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**Teachers as Learners and Curriculum Designers in  
the Context of Modeling-Centered Scientific  
Inquiry**

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A Dissertation Submitted in Partial Fulfillment of the  
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# APPROVAL PAGE

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## Abstract

This thesis aimed at examining the impact of a strategically designed Professional Development Course (PDC) on teachers' development of modeling ability, content knowledge (CK) about models and modeling, and curricular knowledge (CuK) for modeling-centered scientific inquiry (MCSI). It also sought to identify and describe the characteristics of teachers' created MCSI curriculum designs in an attempt to investigate the types of transformations that were enacted by the participants in their effort to apply the theoretical perspectives of MCSI approach for the design of their own curriculum materials.

The thesis documents the absence of a framework from existing research that would provide information about the constituent components of learners' *modeling ability*, and suggests a theoretical framework for addressing this gap. The framework emerged from a synthesis of disparate research literatures on learning and teaching science through modeling, and entailed five modeling skills, as well as, two types of knowledge (metacognitive knowledge and meta-modeling knowledge), that were considered as essential for an individual to effectively and successfully engage within MCSI instructional settings. The framework served as a guide for the design and implementation of a sequence of MCSI activities in the context of 1-D elastic collisions, and it was empirically tested through the analysis of the data collected from the several assessment tasks designed and administered at the beginning and the end of the PDC.

Additionally, the design of the PDC was informed by the findings from prior related research that revealed teachers' limited understandings of the nature and role of models and modeling in science, and the lack of knowledge and skills to enact science instruction through modeling. The PDC was implemented within a science education master class and the participants were twenty teachers (16 elementary school teachers, 3 physics and 1 chemistry teachers). Both their prior experience with modeling during their undergraduate studies and their prior teaching experience regarding modeling were very limited.

The course was organized into 13 three-hour sessions and was split in two consecutive phases. During Phase 1, a curriculum titled "Modeling 1-D collisions" was implemented, through which the teachers (working in dyads) were engaged in multiple cycles of model development and deployment of elastic collision phenomena. Specifically, the teachers as *learners* observed collision phenomena, created models with the use of Stagecast Creator to represent the observed phenomena, revised their models, compared their models with their peers' models, and validated their models by applying them in new collision phenomena. During Phase 2, teachers initially studied the underlying design principles of curricula that were grounded on the MCSI perspective, and then, taking the role of *curriculum designers*, were asked to re-design an existing unit from their science curriculum to foster the development of understanding of the unit's concepts through a MCSI approach.

Multiple data collection instruments were used for capturing teachers' modeling ability, CK about models and modeling, and CuK for MCSI. The data were analyzed through the use of qualitative and quantitative techniques, and rich descriptions about teachers' modeling ability, CK about models and modeling, CuK for MCSI, and their MCSI curriculum designs characteristics emerged for answering each research question.

Both the qualitative and quantitative findings that emerged in addressing the first research question of the study (*How does teachers' modeling ability compare prior to and after*

*their participation in the PDC?*) designate that the PDC had a great impact on the development of all components of teachers' modeling ability in unison. In addition, since the evaluation of teachers' modeling ability, prior to and after the PDC, was accomplished in a variety of content areas that differed to the one experienced during the PDC (e.g., elastic collisions), the findings that were revealed from the analysis of their responses in the modeling ability assessment tasks indicate not only the development of their modeling ability, but also their capability to transfer all components of their modeling ability into new contents. Consequently, the findings of the present thesis indicate that the teachers who engaged as learners in the strategically designed MCSI setting of the PDC developed modeling skills, metacognitive knowledge about the modeling process, and meta-modeling knowledge with respect to the nature and purpose or utility of scientific models, and succeeded on transferring all of these modeling performances across content areas.

As far as the second research question that this study aimed to address is concerned (*How do teachers' CK about models and modeling, and CuK for MCSI change as a result of their participation in the PDC?*), both findings pertaining to teachers' examination of CK about models and modeling, and CuK for MCSI revealed significant changes as teachers transitioned from the beginning to the end of the PDC. These changes can be attributed to several designed elements of the PDC that appeared to influence teachers' knowledge bases in several ways. It was found that the elements of the PDC that fostered the development of their epistemic understandings about the nature of models and modeling and their CuK for MCSI were as follows: (i) the design and implementation of the 1-D elastic collisions activity sequence within the MCSI curriculum; (ii) teachers' collaborative model building of the five 1-D elastic collision phenomena; (iii) the modeling tool that facilitated the dynamic model development and deployment of elastic collision phenomena; (iv) teachers' reflective journals that were completed after the end of each session of the PDC through which they were prompted to reflect on their modeling experiences and the "lessons learned" after each session; (v) peer evaluation of the models emerged from collaborative building during the sessions; (vi) asynchronous discussions in the Blackboard e-Education platform on topics emerged from teachers' reflective journals; and (vii) the theoretical paper that teachers read and focused on the presentation of the modeling ability framework and the analysis of its constituent components.

The findings that emerged in response to the third research question of this study (*What are the characteristics of teachers' modeling-centered curriculum designs?*) indicate that teachers' curriculum designs can contribute to our understanding of how to better monitor teachers' knowledge bases that evolve as a result of their participation in PDC. Seven dimensions were considered as critical to guide the identification and description of the characteristics of teachers' curriculum materials, through which important information was elicited about: (i) teachers' curriculum design orientation; (ii) the degree and type of reconstruction of the national curriculum unit that teachers followed; (iii) the types of the activities they designed and the role of modeling in their curriculum designs; (iv) the integration of the modeling ability framework within their curriculum designs; (v) model's progression; (vi) the nature of the suggested models; and (vii) the format of the evaluation of students' learning gains. In addition, the characteristics that emerged for each dimension were clustered along three levels of increased sophistication revealing that the teachers who were engaged in the same PDC for MCSI and followed the same learning pathways during developing and deploying models in the context of 1-D collisions have conceptualized in diverse ways the underlying principles of the MCSI approach.

This study can contribute to the research field of science education in two main ways. The first relates to the main objective of this study, which was to suggest a framework for

teachers' professional development in MCSI. Despite the fact that the value of this objective is highlighted in the literature, examples of PDCs to designate what design principles should be considered when designing and implementing such training programs are insufficient. This thesis contributed to the development of a framework for the effective preparation of teachers to enact science instruction through MCSI, whose originality lies in the two distinct roles which teachers performed during their professional development. Specifically, positioning teachers in the role of *active learners* and letting them experience themselves the same learning journeys that their students are expected to follow, appeared to be beneficial for their professional development in various ways. For instance, teachers as learners were given the opportunity to inquire themselves of (i) what they know and what they do not know about a specific subject matter (that is their *conceptual understanding* status), (ii) what type of skills or abilities need to be applied for the development of their understanding of subject matter (that is their *procedural understanding* status), and (iii) what epistemic considerations they need to think of for assessing the validity of the acquired knowledge and the process that has been followed for the development of this knowledge (that is their *epistemic understanding* status). The second role that teachers were assigned to was that of *curriculum designer*. This role is important, because engaging teachers in constructing a public artifact (e.g., their own curriculum) served as a productive way to support their learning and also, through such an approach teachers were offered appropriate scaffolding when transforming their personal learning experiences into pedagogically potent curriculum designs. Additionally, given that engaging teachers in the process of curriculum development is recommended in literature, we need to offer them a certain degree of autonomy and power in making pedagogical decisions while designing and implementing their own curriculum materials.

The originality of the framework that teachers' professional development around MCSI was based upon is also exemplified through the methodology used to study the types of transformations that were enacted by the participants in their effort to apply the theoretical perspectives of MCSI approach for the design of their own curriculum materials. Given that in prior research the types of teachers' knowledge transformations were elicited either through written questionnaires or through clinical interviews, this thesis made use of teachers' curriculum materials as a lens for examining these transformations. The rich information obtained through the multiple levels of analysis that were followed, and the description of the characteristics of teachers' MCSI curriculum materials across the levels that emerged, allowed the drawing of essential inferences for both teachers' development of understanding of the design principles that are important to be followed during developing MCSI curriculum materials, and the types and degree of the knowledge transformations applied in the development of these teaching materials. Additionally, as it was claimed in the thesis, teachers' curriculum designs might serve as transparent prisms through which teacher educators can collect rich data about teachers' understandings, their difficulties, and their "genuine" content knowledge, curricular knowledge, and pedagogical content knowledge for MCSI.

The second aspect of the contribution of the present study relates to the development of a theoretical framework for analyzing individuals' modeling ability, which emerged as a response to closing a gap in the literature of what constitutes learners' modeling ability. The framework emerged from a synthesis of disparate research literatures on learning and teaching science through modeling, and entailed five modeling skills, as well as, two types of knowledge (metacognitive knowledge and meta-modeling knowledge) that were considered as essential for an individual to effectively and successfully engage within MCSI instructional settings. The framework served as a guide for the design and implementation of a sequence of MCSI activities in the context of 1-D elastic collisions,

and it was empirically tested through the analysis of the data collected from the several assessment tasks designed and administered at the beginning and the end of the PDC. Based on the findings that emerged, it is suggested the groundings of this modeling ability framework can advance from the theoretical considerations its conceptualization was based on at the outset of this thesis, to a more robust empirical documentation of the content and the connections among its constituent components, because the levels that emerged for each of the modeling ability components can potentially inform, enrich, and help in revising its foundations. Also, the findings with respect to teachers' modeling ability shed light on the relationships and the degree of correlation among the various modeling ability components, as it was found that all modeling ability components relate with each other to some extent, but most importantly, it appeared that meta-modeling knowledge with respect to nature of models is at the heart of the development of all components.



## Περίληψη

Η παρούσα διατριβή απευθύνθηκε σε δύο βασικές επιδιώξεις. Η πρώτη εστιάζει στη μελέτη της επίδρασης ενός στρατηγικά σχεδιασμένου προγράμματος επιμόρφωσης εκπαιδευτικών στην ανάπτυξη τριών αξόνων μάθησης των εκπαιδευτικών: (i) της ικανότητας μοντελοποίησης, (ii) της γνώσης περιεχομένου για τα μοντέλα και τη μοντελοποίηση και (iii) της γνώσης αναλυτικών προγραμμάτων για τη διδασκαλία του μαθήματος των Φυσικών Επιστημών μέσω της προσέγγισης της μοντελοποίησης. Η δεύτερη αφορά στη μελέτη των χαρακτηριστικών του διδακτικού υλικού που αναπτύσσουν οι συμμετέχοντες με στόχο την εξέταση των μετασχηματισμών των αξόνων μάθησης που επιτελούνται κατά το σχεδιασμό διδακτικού υλικού στηριζόμενου στη μοντελοποίηση.

Στη διατριβή τεκμηριώνεται η απουσία από την υφιστάμενη βιβλιογραφία ενός πλαισίου που να αφορά στις συνιστώσες που συνθέτουν την ικανότητα μοντελοποίησης των μαθητών, γεγονός που αποτέλεσε το έναυσμα για να αναπτυχθεί ένα θεωρητικό πλαίσιο ανάλυσης και περιγραφής των συνιστωσών της ικανότητας μοντελοποίησης. Αυτό το θεωρητικό πλαίσιο καθοδήγησε στη συνέχεια τόσο το σχεδιασμό του διδακτικού υλικού ανάπτυξης της ικανότητας μοντελοποίησης που ενσωματώθηκε στο πρόγραμμα επιμόρφωσης, όσο και τον καταρτισμό δοκιμίων αξιολόγησης της ικανότητας μοντελοποίησης των εκπαιδευτικών.

Επιπρόσθετα, το πρόγραμμα επιμόρφωσης, που σχεδιάστηκε και υλοποιήθηκε στο πλαίσιο της παρούσας διατριβής, έλαβε υπόψη τα πορίσματα αντίστοιχων προσπαθειών επιμόρφωσης εκπαιδευτικών στο ίδιο θέμα, τα οποία κατεδείκνυαν την ελλιπή κατανόηση της φύσης των μοντέλων και των στόχων της μοντελοποίησης, καθώς και την ανεπάρκεια των εκπαιδευτικών να διδάξουν το μάθημα των Φυσικών Επιστημών μέσω της προσέγγισης της μοντελοποίησης. Το πρόγραμμα επιμόρφωσης υλοποιήθηκε στο πλαίσιο ενός μεταπτυχιακού μαθήματος του προγράμματος «Μάθηση στις Φυσικές Επιστήμες» και σε αυτό συμμετείχαν είκοσι εκπαιδευτικοί (16 εκπαιδευτικοί Δημοτικής Εκπαίδευσης και 4 εκπαιδευτικοί Μέσης Εκπαίδευσης). Τόσο οι προϋπάρχουσες γνώσεις των εκπαιδευτικών σε σχέση με τα μοντέλα και τη μοντελοποίηση, όσο και οι διδακτικές τους εμπειρίες σε σχέση με τη διδασκαλία του μαθήματος των Φυσικών Επιστημών μέσω της προσέγγισης της μοντελοποίησης ήταν πολύ περιορισμένες.

Το πρόγραμμα επιμόρφωσης υλοποιήθηκε σε δύο φάσεις. Στην πρώτη φάση οι εκπαιδευτικοί κλήθηκαν ως *μανθάνοντες* να ακολουθήσουν το διδακτικό υλικό για τη μελέτη διαφόρων πειραμάτων μονοδιάστατων ελαστικών κρούσεων, για το καθένα από τα οποία δημιουργούσαν μοντέλα με τη χρήση ενός λογισμικού μοντελοποίησης. Στη δεύτερη φάση, οι εκπαιδευτικοί αρχικά κλήθηκαν να μελετήσουν το διδακτικό υλικό που χρησιμοποίησαν με στόχο να κατανοήσουν τη φιλοσοφία και τις αρχές σχεδιασμού που καθοδηγούν την ανάπτυξη διδακτικού υλικού στηριζόμενου στην προσέγγιση της μοντελοποίησης ως μέσου επιστημονικής διερώτησης. Στη συνέχεια, ως *δημιουργοί διδακτικού υλικού* κλήθηκαν να αναδομήσουν μια υφιστάμενη ενότητα από το αναλυτικό πρόγραμμα των Φυσικών Επιστημών Δημοτικής ή Μέσης Εκπαίδευσης, με τρόπο ώστε η προώθηση των μαθησιακών στόχων της ενότητας να επιτυγχάνεται μέσω της προσέγγισης της μοντελοποίησης.

Τα δεδομένα που προέκυψαν από τη χρήση ποικίλων οργάνων συλλογής δεδομένων έτυχαν συστηματικής επεξεργασίας μέσα από την εφαρμογή κατάλληλων μεθόδων ποιοτικής ανάλυσης δεδομένων και στατιστικών τεχνικών, στοιχεία τα οποία επέτρεψαν την πλούσια και εμπειριστατωμένη περιγραφή των πορισμάτων που ανέκυψαν για την απάντηση του κάθε ερευνητικού ερωτήματος.

Συγκεκριμένα, τα πορίσματα της διατριβής σε σχέση με το πρώτο ερευνητικό ερώτημα (*Πώς συγκρίνεται η ικανότητα μοντελοποίησης των εκπαιδευτικών πριν και μετά τη συμμετοχή τους στο πρόγραμμα επιμόρφωσης;*) κατέδειξαν ότι το πρόγραμμα επιμόρφωσης επέδρασε καταλυτικά όχι μόνο στην ανάπτυξη όλων των πτυχών της ικανότητας μοντελοποίησης των εκπαιδευτικών, αλλά και στην ικανότητά τους να μεταφέρουν επιτυχώς όλες τις πτυχές της μοντελοποίησης για τη μελέτη άγνωστων συγκεκριμένων. Επιπρόσθετα, για την κάθε πτυχή της ικανότητας μοντελοποίησης προέκυψαν διαβαθμισμένα επίπεδα ανάπτυξης, τα οποία χρησιμεύουν ως δείκτες κατάταξης των μανθανόντων σε επίπεδα ανάλογα με την ικανότητα μοντελοποίησης τους.

Τα αποτελέσματα που προέκυψαν από την ανάλυση των δεδομένων σχετικά με το δεύτερο ερευνητικό ερώτημα (*Πώς αλλάζει η γνώση περιεχομένου για τα μοντέλα και τη μοντελοποίηση και η γνώση αναλυτικών προγραμμάτων για τη διδασκαλία του μαθήματος των Φυσικών Επιστημών μέσω της προσέγγισης της μοντελοποίησης των εκπαιδευτικών κατά τη διάρκεια συμμετοχής τους στο πρόγραμμα επιμόρφωσης;*) έδειξαν ότι τόσο η γνώση περιεχομένου για τα μοντέλα και τη μοντελοποίηση, όσο και η γνώση αναλυτικών προγραμμάτων για τη διδασκαλία του μαθήματος των Φυσικών Επιστημών μέσω της προσέγγισης της μοντελοποίησης των εκπαιδευτικών βελτιώθηκαν αισθητά, συγκρινόμενες στην αρχή και τέλος του προγράμματος επιμόρφωσης. Στοιχεία του προγράμματος επιμόρφωσης όπως τα αναστοχαστικά ημερολόγια που συμπλήρωναν οι εκπαιδευτικοί μετά το τέλος της κάθε συνάντησης, οι ετερο-αξιολογήσεις των μοντέλων των εκπαιδευτικών από άλλους εκπαιδευτικούς, οι ασύγχρονες συζητήσεις των εκπαιδευτικών στην διαδικτυακή πλατφόρμα Blackboard σε θέματα που προέκυπταν από τα αναστοχαστικά τους ημερολόγια ή τις αξιολογήσεις των μοντέλων τους, η ακολουθία των δραστηριοτήτων στην οποία στηριζόταν ο σχεδιασμός του διδακτικού υλικού στο συγκείμενο των ελαστικών κρούσεων, καθώς και το ανάγνωσμα ενός άρθρου που αφορούσε στην ικανότητα μοντελοποίησης και στις συνιστώσες της, βρέθηκαν να συνεισφέρουν σημαντικά στη βελτίωση της γνώσης περιεχομένου για τα μοντέλα και τη μοντελοποίηση, όσο και της γνώσης αναλυτικών προγραμμάτων για τη διδασκαλία του μαθήματος των Φυσικών Επιστημών μέσω της προσέγγισης της μοντελοποίησης των εκπαιδευτικών.

Όσον αφορά στο τρίτο ερευνητικό ερώτημα της παρούσας διατριβής (*Ποια είναι τα χαρακτηριστικά του στηριζόμενου στην προσέγγιση της μοντελοποίησης διδακτικού υλικού που αναπτύσσουν οι εκπαιδευτικοί;*), φάνηκε ότι μέσα από τη μελέτη των χαρακτηριστικών του διδακτικού υλικού των εκπαιδευτικών μπορεί να προκύψει χρήσιμη πληροφόρηση σχετικά με τις σχεδιαστικές αρχές που διέπουν το διδακτικό τους υλικό, των τύπων αναδόμησης του υφιστάμενου διδακτικού υλικού από το αναλυτικό πρόγραμμα που ακολουθήθηκε, τα είδη των δραστηριοτήτων που σχεδιάστηκαν σε συνδυασμό με το ρόλο της μοντελοποίησης στο διδακτικό υλικό, του βαθμού ενσωμάτωσης του θεωρητικού πλαισίου μοντελοποίησης στο διδακτικό υλικό, τη φύση των μοντέλων που δυνητικά θα αναπτυχθούν από τους μανθάνοντες σε πιθανή εφαρμογή του διδακτικού υλικού, την εξέλιξη της διαδοχής των μοντέλων στο διδακτικό υλικό, καθώς και τη φύση και το ρόλο της αξιολόγησης των μαθησιακών επιτευγμάτων των μαθητών στο διδακτικό υλικό.

Η συνεισφορά της διατριβής στο ερευνητικό πεδίο μάθησης και διδασκαλίας στις Φυσικές Επιστήμες αναδεικνύεται μέσα από δύο σημαντικά στοιχεία. Το πρώτο στοιχείο αφορά στην κύρια επιδίωξη της διατριβής να διαμορφώσει ένα πλαίσιο επιμόρφωσης εκπαιδευτικών για διδασκαλία του μαθήματος των φυσικών επιστημών μέσω της προσέγγισης της μοντελοποίησης. Παρά το γεγονός ότι η αξία αυτής της επιδίωξης αναγνωρίζεται στην ερευνητική βιβλιογραφία, δεν υπάρχουν επαρκή παραδείγματα που να αναφέρονται στις σχεδιαστικές αρχές που πρέπει να λαμβάνονται υπόψη κατά το

σχεδιασμό και υλοποίηση τέτοιων προγραμμάτων επιμόρφωσης. Η συγκεκριμένη διατριβή οδήγησε στην δημιουργία ενός πλαισίου επιμόρφωσης εκπαιδευτικών, του οποίου η αποτελεσματικότητα και πρωτοτυπία έγκειται στους δύο διακριτούς ρόλους τους οποίους οι εκπαιδευτικοί κλήθηκαν να αναλάβουν στο πλαίσιο της επιμόρφωσής τους. Συγκεκριμένα, μέσα από την εμπλοκή των εκπαιδευτικών ως *μανθάνοντες* στο πλαίσιο επιμόρφωσής τους, σε συνδυασμό με τη συμμετοχή τους σε αυθεντικές διεργασίες μοντελοποίησης παρόμοιες με αυτές που αναμένεται οι ίδιοι να εμπλέξουν σε κατοπινό στάδιο τους μαθητές τους, τους δίνεται η ευκαιρία να αξιολογήσουν την επάρκειά τους σε σχέση με το εννοιολογικό περιεχόμενο της ενότητας με την οποία έρχονται σε επαφή, να προβληματιστούν για τα είδη των συλλογιστικών στρατηγικών που κρίνονται αναγκαίες να εφαρμοστούν για το συγκείμενο που μελετούν, καθώς και να αποφασίσουν για ζητήματα επιστημολογικής φύσεως. Ο δεύτερος ρόλος που κλήθηκαν οι εκπαιδευτικοί να αναλάβουν ήταν αυτός του *δημιουργού διδακτικού υλικού*. Ο ρόλος αυτός κρίνεται σημαντικός, γιατί αφενός μεν είναι συμβατός με θεωρίες μάθησης που αναφέρονται στη δημιουργία τεχνουργημάτων από τους μανθάνοντες ως ένα παραγωγικό τρόπο υποστήριξης και καθοδήγησής της μάθησής τους, αφετέρου δε μέσα από την πρόκληση της ανάπτυξης του δικού τους διδακτικού υλικού τους δίνεται η δυνατότητα να μετασχηματίσουν τις προσωπικές μαθησιακές τους εμπειρίες σε διδακτικές αλληλουχίες δραστηριοτήτων. Επιπρόσθετα, η εμπλοκή των εκπαιδευτικών σε διαδικασίες ανάπτυξης διδακτικού υλικού αποτελεί μια από τις συστάσεις της σύγχρονης βιβλιογραφίας, αφού συχνά γίνονται εισηγήσεις οι εκπαιδευτικοί να έχουν ενεργό δράση και εμπλοκή σε διαδικασίες εφαρμογής, αναθεώρησης και μεταρρύθμισης των αναλυτικών προγραμμάτων και επομένως θα πρέπει να τους δίνεται σημαντικός βαθμός αυτονομίας και ενίσχυσης καθώς λαμβάνουν παιδαγωγικές αποφάσεις κατά το σχεδιασμό και υλοποίηση του δικού τους διδακτικού υλικού.

Η πρωτοτυπία του πλαισίου επιμόρφωσης των εκπαιδευτικών διαφαίνεται και μέσα από τη μεθοδολογία που ακολουθήθηκε για τη μελέτη των ειδών των μετασχηματισμών των γνώσεων των εκπαιδευτικών σε σχέση με τα μοντέλα, τη μοντελοποίηση και τη διδασκαλία του μαθήματος των φυσικών επιστημών μέσω της προσέγγισης της μοντελοποίησης. Ενώ σε προηγούμενες έρευνες τα είδη των μετασχηματισμών των γνώσεων των εκπαιδευτικών μελετούνταν είτε μέσω γραπτών ερωτηματολογίων είτε μέσω κλινικών συνεντεύξεων, στην παρούσα διατριβή χρησιμοποιήθηκε το διδακτικό υλικό που σχεδίασαν οι ίδιοι οι εκπαιδευτικοί ως το μέσο εξέτασης αυτών των μετασχηματισμών. Η πλούσια πληροφόρηση που προέκυψε μέσα από τα πολλαπλά επίπεδα ανάλυσης που χρησιμοποιήθηκαν, καθώς και η περιγραφή των χαρακτηριστικών γνωρισμάτων του διδακτικού υλικού των εκπαιδευτικών σε κάθε επίπεδο ανάλυσης, επέτρεψε την εξαγωγή χρήσιμων συμπερασμάτων τόσο για την ανάπτυξη της κατανόησης των εκπαιδευτικών για τις σχεδιαστικές αρχές που είναι σημαντικό να ακολουθούνται κατά την παραγωγή διδακτικού υλικού στηριζόμενου στην προσέγγιση της μοντελοποίησης, όσο και για τα είδη και το βαθμό των μετασχηματισμών των γνώσεων των εκπαιδευτικών που διενεργήθηκαν στο πλαίσιο της ανάπτυξης του διδακτικού τους υλικού. Επιπρόσθετα, υποστηρίχθηκε μέσα από τη διατριβή ότι αυτή η προσέγγιση μπορεί να συνεισφέρει στην υφιστάμενη γνώση για το πώς μπορεί να μελετηθεί ενδελεχώς η παιδαγωγική γνώση περιεχομένου των εκπαιδευτικών για τη διδασκαλία μέσω μοντελοποίησης.

Το δεύτερο στοιχείο που αναδεικνύει τη συνεισφορά της διατριβής στο ερευνητικό πεδίο μάθησης και διδασκαλίας στις Φυσικές Επιστήμες αφορά στην πρόταση για διαμόρφωση ενός θεωρητικού πλαισίου ανάλυσης της ικανότητας μοντελοποίησης, η οποία προέκυψε μετά τη διαπίστωση απουσίας από την υφιστάμενη βιβλιογραφία ενός πλαισίου που να αφορά στις συνιστώσες που συνθέτουν την ικανότητα μοντελοποίησης των μανθάνοντων. Η παρούσα διατριβή απευθύνθηκε σε αυτό το κενό, διατυπώνοντας αρχικά ένα θεωρητικό

πλαίσιο περιγραφής και ανάλυσης των συνιστωσών που συνθέτουν την ικανότητα μοντελοποίησης των μανθανόντων (πέντε δεξιότητες μοντελοποίησης, μεταγνώση για τη διαδικασία μοντελοποίησης και επιστημολογική επάρκεια για τη φύση και το ρόλο των μοντέλων στη μάθηση), το οποίο καθοδήγησε στη συνέχεια τόσο το σχεδιασμό του διδακτικού υλικού ανάπτυξης της ικανότητας μοντελοποίησης που ενσωματώθηκε στο πρόγραμμα επιμόρφωσης, όσο και τον καταρτισμό δοκιμίων αξιολόγησης της ικανότητας μοντελοποίησης των εκπαιδευτικών. Αυτό το θεωρητικό πλαίσιο έτυχε εμπειρικής θεμελίωσης και εγκυροποίησης μέσα από πορίσματα της παρούσας διατριβής, αφού τα επίπεδα ανάπτυξης της κάθε συνιστώσας της ικανότητας μοντελοποίησης των εκπαιδευτικών οδήγησαν αφενός μεν σε βελτιωτικές ρυθμίσεις σε επίπεδο διατύπωσης λειτουργικών ορισμών για την κάθε συνιστώσα, αφετέρου δε στον εντοπισμό των σχέσεων που υφίστανται μεταξύ των συνιστωσών της ικανότητας μοντελοποίησης. Βρέθηκε, για παράδειγμα, ότι η επιστημολογική επάρκεια για τη φύση των μοντέλων συνδέεται με όλες τις υπόλοιπες συνιστώσες της ικανότητας μοντελοποίησης, εύρημα το οποίο είναι πρωτότυπο και προσθέτει στην υφιστάμενη γνώση για τις διαδικασίες ανάπτυξης της ικανότητας μοντελοποίησης.

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To Soteroula and Nicholas

Marios Papaevripidou

Marios Papaevripidou



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## List of Abbreviations

BeEP:	<b>B</b> lackboard <b>e</b> - <b>E</b> ducation <b>P</b> latform
CK:	<b>C</b> ontent <b>K</b> nowledge
CuK:	<b>C</b> urricular <b>K</b> nowledge
MCSI:	<b>M</b> odeling- <b>C</b> entered <b>S</b> cientific <b>I</b> nquiry
PDC:	<b>P</b> rofessional <b>D</b> evelopment <b>C</b> ourse
PCK	<b>P</b> edagogical <b>C</b> ontent <b>K</b> nowledge
SC:	<b>S</b> tagecast <b>C</b> reator

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## CHAPTER 1: INTRODUCTION

*“Student learning of science depends on teachers having adequate knowledge of science... Currently, K-8 teachers have limited knowledge of science and limited opportunities to learn science.... In order for K-8 teachers to teach science as practice, they will need sustained science specific professional development in preparation and while in service.”*  
(Duschl, Schweingruber, & Shouse, 2007, p. 296)

### 1.1. Teachers’ professional development in science

Teachers are considered to be the “linchpin” in any effort to change science education across nations (National Research Council, 2012), and thus perennial emphasis has been placed on enhancing their professional development. Reform documents in science education have underlined the increasing importance of preparing effective teachers, who will play key roles in guiding students through cognitive activities centered on *inquiry*, including: student-generated questioning; designing and carrying out scientific investigations; use of technology to enhance investigations and communications; formulating and revising scientific explanations and models using logic and evidence; recognizing and analyzing alternative explanations and models; and communicating and defending a scientific argument (Crawford, 2005; NRC, 1996). In order to design instructional settings through which such cognitive activities would be fostered, it is essential to move beyond considering science as encapsulated in “cookbook” type of activities that point to a single correct answer, and present science as a process of revision and substitution of knowledge claims (Duschl, 1990) or, alternatively, “as an activity whose purpose is to develop, interpret, or evaluate explanatory models for the phenomena being investigated” (Raghavan & Glaser, 1995, p. 38). Duschl (1990) argues that failing to succeed on this direction, we run two risks. Firstly, to develop in students the perception that ‘scientific knowledge growth is governed by the addition of new ideas, facts and theories to old ones’ (p.54) and, secondly, to portray science as an activity on which scientists always agree. This stance is also highlighted by Abd-el-Khalick & Lederman (2000) who claimed that many elementary teachers understand science as a collection of facts rather than as a tentative and creative endeavor.

A successful design and implementation of science instructional settings, however, signals two interconnected requirements for teachers; teachers should develop sufficient

knowledge of new curriculum contents and methods, and at the same time they should be competent enough to teach them (Van der Valk & de Jong, 2009). We cannot continue to expect teachers to carry out inquiry-based curricula without figuring out how to support them in understanding the philosophies underlying these curricula (Crawford, 1999; Crawford, 2000). Consequently, “this puts new demands on the professional development of science teachers” (p. 829), as Van der Valk and de Jong (2009) assert. Well-designed opportunities incorporated within Professional Development Courses (henceforth called PDC) may result in scaffolding teachers in the production of desired changes in their classroom practices. This can enhance their capacity for continued learning and professional growth, and can in turn contribute to improvements in student learning.

In order to succeed on facilitating the professional development of teachers, we need to “...understand the process by which teachers grow professionally and the conditions that support and promote that growth” (Clarke & Hollingsworth, 2002, p. 947). It is also essential to understand and value the personal knowledge and beliefs that teachers develop within their participation in PDCs, because teacher knowledge influences instructional practice (Clark & Peterson, 1986; Duffee & Aikenhead, 1992). In doing so, there is an emergent need to identify the role of teachers within these courses and ask ourselves a critical question: ‘How can we best prepare teachers to learn *how to do science* and to *know science*?’

Prior research (e.g., Clarke & Hollingsworth, 2002; Crawford, 2005; de Jong, Van Driel & Verloop, 2005; Justi & Gilbert, 2005) indicates that positioning teachers in the role of *active learners* and letting them experience themselves the same learning journeys that their students are expected to follow, could be beneficial for their professional development in various ways. Firstly, teachers as learners are given the opportunity to inquire themselves of (i) what they know and what they do not know about a specific subject matter (that is their *conceptual understanding* status), (ii) what type of skills or abilities need to be applied for the development of their understanding of subject matter (that is their *procedural understanding* status), and (iii) what epistemic considerations they need to think of for assessing the validity of the acquired knowledge and the process that has been followed for the development of this knowledge (that is their *epistemic understanding* status). Secondly, situating teachers as learners will allow them to directly experience and become aware of the various types of learning difficulties (e.g., conceptual, procedural, epistemic) that their students might be confronted with during their exposition

in similar learning situations and thus to take them into consideration for the design of their latter instructional settings. Thirdly, teachers will appear more ready and confident in their own field of practice for scaffolding their students' learning pathways through their own robust proficiency of both the content and the pedagogy (or their *pedagogical content knowledge*) that they might have effectively developed as a result of their participation in a PDC, which placed an emphasis on them as active learners.

Apart from situating teachers as learners in PDCs, it is also equivalently important to give teachers the authority to act as *designers* of their own science curriculum materials. This is because engaging teachers in constructing a public artifact (e.g., their own curriculum) is a productive way to support their learning (Papert, 1991) and the transformation of their personal learning experiences into pedagogically potent curriculum designs. Teachers should take the role of active participants in any implementation or instructional reform we seek to achieve, and thus we need to offer them a certain degree of autonomy and power in making pedagogical decisions while designing and implementing their own curriculum (Mishra & Koehler, 2006). The idea of teachers as *curriculum designers* is based on the stance that teachers are "an integral part of the curriculum constructed and enacted in classrooms" (Clandinin & Connelly, 1992 p. 363), since their effort of curriculum development undergoes an organic process of iterative design, refinement and negotiation of a balance between technology, pedagogy, and content (Mishra & Koehler, 2006).

Accordingly, situating teachers as *learners* and *curriculum designers* in the context of modeling-centered scientific inquiry (henceforth called MCSI), and investigating the impact of a PDC on the development of teachers' *modeling ability, content knowledge about models and modeling* and *curricular knowledge for MCSI* was the main objective of this thesis. The rationale behind focusing on MCSI as the context of the PDC departs from three directions. First, there is ample evidence from prior research indicating that teachers' content knowledge, curricular knowledge and pedagogical content knowledge about models and modeling is inadequate or incomplete (Justi & van Driel, 2005; Crawford & Cullin, 2004; Windschitl & Thompson, 2006). Second, evidence from studies (e.g., Crawford & Cullin, 2004; De Jong & Van Driel, 2001; Windshittl & Thomas, 2006) that sought to scaffold the preparation of teachers to teach science through modeling and thus to appreciate the multiple advantages of such an approach on students' learning revealed that even after structured interventions teachers failed in changing their teaching practices by adopting a modeling-centered approach in their instruction. Third, prior studies that

aimed at reporting on the format and the ways that designed interventions attempted to reshape teachers' understandings and views about models and modeling and prepare them to enact science through MCSI are very limited. All three arguments that this thesis builds upon are elaborated in detail in Chapter 2.

## **1.2. Modeling-centered scientific inquiry and modeling ability**

Building, refining, revising, testing, evaluating and validating scientific models, reflecting on the cyclical and iterative process that scientific modeling entails, as well as learning about the nature, purpose and utility of scientific models are viewed as essential aspects of "modeling-centered scientific inquiry" (Duschl, Schweingruber, & Shouse, 2007; Nelson & Davis, 2011; Passmore, Stewart, & Cartier, 2009; Penner et al., 1997; Schwarz & White, 2005; Schwarz & Gwekwerere, 2006; Snir, Smith, & Raz, 2003; Windschitl, Thompson, & Braaten, 2008a, 2008b). Understanding how to help students accomplish learning within MCSI has been one of the central challenges in science education, and a difficult one, because learners often view science as a body of factual knowledge, and learning science as a matter of receiving information (Hammer, 1994). Hence, a major challenge for science educators is to design learning environments through which learners will be scaffolded on developing understanding about the process of scientific modeling itself as a learning tool, as well as accomplishing learning through the modeling process. This type of inquiry provides opportunities for science education research to "escape" from the narrow focus of conceptual change, and examine the wider cognitive and epistemic aspects involved in learning science through modeling.

Although inquiry has become a central focus in the science classroom (NRC, 2000), there is ample evidence in the literature which testifies that modeling is not routinely practiced in schools at all (Coll et al., 2005; Crawford, 2005; Duschl, Schweingruber, & Shouse, 2007; Franco et al., 1999; Raghavan & Glaser, 1995; Snir, Smith, & Raz, 2003; Stephens, McRobbie & Lucas, 1999). Schwarz and Gwekwerere (2006) attributed this failure to either "...the persistence of theories of education that focus on simple, component skills for young children and a graduation to complex forms of reasoning only for older and more capable students ... or, to a lack of existing information, frameworks, and structures for guiding teachers in engaging children in model-based inquiry practices" (p. 2). In addition, research on MCSI neither defined nor explored in depth so far what should be learned when students are engaged in the process of scientific modeling. Put it differently,

there is a lack of sufficient knowledge of the constituent components of learners' *modeling ability* (that is, their ability to (i) build, refine, revise, test, evaluate and validate scientific models, (ii) reflect on the cyclical and iterative process that scientific modeling entails, and (iii) demonstrate informed understandings about the nature, purpose and utility of scientific models) and how these should be fostered within MCSI learning environments, because research in this domain has often treated aspects of the modeling ability as discrete. For example, although in the study of Schwarz and White (2005) the participants were engaged in the process of building models of force and motion phenomena through their Model-Enhanced ThinkerTools Curriculum, the assessment of their learning that related to their modeling ability was concentrated solely on the epistemic aspect of models (e.g., role, purpose, utility of models).

While seeking for a theoretical framework in the existing literature on models and modeling that focuses on the analysis of modeling ability in its constituent components and getting an insight on how these could be interwoven in curriculum designs and be assessed, I did not succeed in spotting such a theoretical framework. Instead, the literature review enabled me to identify five interrelated lines of research that enriched my understanding about several critical issues related to MCSI. Specifically, the first cluster of research encompasses studies that investigated students' or teachers' understanding of the epistemic nature of models and modeling (e.g., Danusso, Testa, & Vicentini, 2010; S. Gilbert, 1991; Grosslight et al., 1991; Justi & Gilbert, 2002a; Justi & Gilbert, 2002b; Justi & Gilbert, 2003; Schwarz et al., 2009; Schwarz & White, 2005; Treagust et al., 2002; Van Driel & Verloop, 2002). The second cluster of research focused on the cognitive strategies and reasoning that learners use or apply while they are involved in computer-based modeling tasks (e.g., Louca & Zacharia, 2008; Sins et al., 2005; Stratford et al., 1998; Zhang et al., 2002). The third cluster of research investigated the impact of modeling-centered teaching on the development of conceptual understanding in various domains, e.g., in Newtonian mechanics (Halloun & Hestenes, 1987; Schwarz & White, 2005; White, 1993), in human biology [human elbow] (Penner et al., 1997); in particulate model of matter (Snir, Smith, & Raz, 2003); in plant biology (Ergazaki et al., 2005); in evolutionary biology (Passmore & Stewart, 2002); in genetics (Johnson & Stewart, 2002; Rotbain et al., 2006), in properties of materials (Acher et al., 2007). The fourth cluster of research focused on teachers' preparation to teach science through modeling (e.g., Crawford & Cullin, 2004; De Jong, Justi, & Van Driel, 2005; Justi & Van Driel, 2006; Schwarz & Gwekwerere, 2006; Van Driel & Verloop, 2005; Windschitl & Thomson, 2006). The last cluster of research coped

with theoretical and epistemological considerations regarding models and modeling (e.g., Develaki, 2007; Etkina et al., 2006; Gericke & Hagberg, 2007; Gilbert, Boulter, & Rutherford, 1998a; Gilbert, Boulter, & Rutherford, 1998b; Halloun, 2007; Harrison & Treagust, 2000; Koponen, 2007; Matthews, 2007; Oh & Oh, 2010; Portides, 2007).

Thus, grounded in contemporary perspectives on learning science as a process of model building (S. Gilbert, 1991; Stewart, Cartier, & Passmore, 2005; Stewart, Hafner, Johnson, & Finkel, 1992) and built upon the abovementioned considerable amount of research, I will attempt in this thesis to address the need, and thus to propose, a theoretical framework (see Chapter 2 for further details) that emerged through my synthesis of disparate research literatures on learning and teaching science through modeling. Through this modeling ability framework, I seek to analyze the modeling ability into its constituent components and provide detailed descriptions about the nature and characteristics of each component. The proposed modeling ability framework offers a new perspective on what should be learned when students are engaged in the process of scientific modeling. It addresses the types of knowledge and modeling skills that students must eventually acquire to be considered as “good modelers” when doing and learning about science. I postulate that such a theoretical framework that focuses on the analysis of modeling ability in its constituent components might have a positive impact to science teaching and learning in several ways. Firstly, it will help research to bring out what scientific modeling is, how this differentiates from mental modeling (see Nersessian (1999) for further review) and how the two are related. Secondly, it will empower the foundations of modeling-centered inquiry instruction research by informing curriculum design and practice of how each aspect of the modeling ability could potentially be interwoven in curriculum designs and, also, be assessed. Thirdly, it will be used as a “benchmark” for the design and implementation of PDCs for both pre-service and in-service teachers that aim at enhancing not only the development of teachers’ modeling ability, but also their content knowledge about models, modeling and the development of learners’ modeling ability.

### **1.3. Research objectives, research questions, significance and importance of the study**

The purpose of this thesis was twofold. Firstly, this thesis aimed at examining the impact of a strategically designed PDC on teachers’ development of modeling ability, content knowledge (henceforth called CK) about models and modeling, and curricular knowledge



(henceforth called CuK) for MCSI. Secondly, this thesis sought to identify and describe the characteristics of teachers' created MCSI curriculum designs in an attempt to investigate the types of transformations that were enacted by the participants in their effort to apply the theoretical perspectives of MCSI approach for the design of their own curriculum materials.

The research questions that this thesis aimed to address are as follows:

1. How does teachers' modeling ability compare prior to and after their participation in the PDC?
2. How do teachers' CK about models and modeling, and CuK for MCSI change as a result of their participation in the PDC?
3. What are the characteristics of teachers' MCSI curriculum designs?

More information regarding the research questions (e.g., definitions of the terms used in the formulation of the research questions, how these questions were answered in the context of the present thesis, etc.) are provided in Chapters 2 and 3.

The importance of the current research lies in the fact that it draws from research in MCSI (Crawford, 2005a; Crawford, 2005b; Crawford & Cullin, 2004; Danusso, Testa, & Vicentini, 2010; De Jong, Schwarz, & Gwekwerere, 2006; Gilbert, 1991; Grosslight et al., 1991; Halloun & Hestenes, 1987; Justi & Gilbert, 2003; Justi & Van Driel, 2005; Justi & Van Driel, 2006; Nelson & Davis, 2011; Schwarz & White, 2005; Stewart, Cartier, & Passmore, 2005; Stewart, Hafner, Johnson, & Finkel, 1992; Treagust et al., 2002; Van Driel & Verloop, 2002; Van Driel and Verloop, 2005; White, 1993; Windschitl & Thomson, 2006), and makes use of a theoretical framework developed for the purposes of this thesis for analyzing the modeling ability of teachers. This study is significant, because it provides empirical evidence about teachers' modeling ability, content knowledge and curricular knowledge about models and modeling, and suggests a research method for studying their intertwined elements. Also, the teachers who participated in the PDC that focused on MCSI would have been benefited, because they were given the opportunity to expand their previously developed knowledge about MCSI and inform their practice with elements of scientific modeling that were obtained throughout the course. Additionally, by gaining an insight into the modeling and learning pathways that the participating teachers went through during the PDC, and by examining their learning outcomes (e.g. their MCSI curriculum designs), teacher preparation programs could identify the kinds of experiences

that are critical for both the development of teachers' modeling ability, as well as CK about models and modeling and CuK for MCSI.

This study aims to extend the findings of prior similar research attempts in the same field (e.g., Crawford & Cullin, 2004; de Jong & Van Driel, 2001; Justi & Van Driel, 2005; Schwarz & Gwekwerere, 2006; Windschitl & Thompson, 2006) by further investigating the potential of a strategically designed PDC on teachers' modeling ability, content knowledge and curricular knowledge about models and. This study differs from (i) the De Jong and Van Driel (2001) and Windschitl and Thompson (2006) studies, in that the participating teachers were directly engaged in the act of building, testing, refining, and validating of models through the use of a computer-based modeling medium (namely Stagecast Creator); (ii) the de Jong and Van Driel (2001), Crawford and Cullin, (2004), Justi and Van Driel (2005), Windschitl and Thompson (2006) and Schwarz and Gwekwerere (2006) studies, in that it did not only examine teachers' development of the various knowledge bases (e.g., content knowledge, curricular knowledge, etc), but also the overall development of their modeling ability which encompasses modeling skills, metacognitive knowledge about the modeling process and meta-modeling knowledge about the purpose and utility of models; (iii) the Schwarz and Gwekwerere (2006) study, in that the participants did not receive from the beginning of the course an instructional framework about the various phases that a learner needs to go through when engaged in MCSI. Instead the participants engaged with MCSI activities as *active* learners for an extended period of time, in order to experience at firsthand how MCSI looked like in practice, and what the focus and the nature of the various modeling activities that they underwent through was. Then they had the opportunity as *thinkers* of MCSI curricula to identify and reflect on the critical components of MCSI instruction and thus to express their own evolved modeling ability frameworks. At the end they were given the modeling ability framework that is presented in Chapter 2 to compare and contrast their understandings, and thus to resolve any misunderstandings or inconsistencies.

In what follows (Chapter 2), theoretical perspectives are presented and analyzed in an attempt to contextualize the present study.

## CHAPTER 2: THEORETICAL PERSPECTIVES

### 2.1. The nature and purpose of scientific models

Meaningful learning in science can be thought of as a dynamic process of building, organizing and elaborating knowledge about the natural world. According to Constantinou (1999), science can be characterized as a complex and dynamic network of models interrelated by a system of theoretical principles. Models are units of structured knowledge used to represent observable patterns in physical phenomena. Schwarz and White (2005) define a model as a cluster of representations, rules and reasoning structures that permit the generation of predictions, provide a basis for interpretive frameworks, and serve as a platform for the expression of scientific theories. In a more recent conceptualization of scientific models, Schwarz et al. (2009) asserted that models are “productive tools for generating and representing explanations and predictions about scientific phenomena” (p. 639). Consequently, a model is an external representation of a phenomenon that provides a mechanism for that phenomenon, and can also be used to make predictions about future behavior of the phenomenon.

Models are constructed in an attempt to improve our understanding of an object, a phenomenon or a system whose mechanism is inaccessible through direct observation. In other words, by simply observing them we fail to get a clear picture of how events, objects or processes operate within them. For example, some objects, phenomena or systems are either too small or too large (Rotbain, Marbach-Ad, & Stavy, 2006), too fast, too old, too distant (in space or time) or too complex (Crawford & Cullin, 2004), and, therefore, models may mediate either the understanding of specific parts, patterns or aspects of them or the understanding of them as a whole. As a result, one might construct a family of models to capture different aspects of the phenomena of interest. In a study with elementary students who were prompted to create models of the human elbow, Penner et al. (1997) highlight this issue by asserting that “there is no one right model of one’s elbow; instead some models may focus on the elbow’s range of motion, while others include its motive force or its properties as a lever” (p. 127).

Representation is one of the crucial roles of models in science (Giere, 1999; Morrison and Morgan, 1999; Nersessian 1999), since entities, phenomena, and ideas need to be

represented in order to further being investigated and help scientists with the production of knowledge. The functionality of a model is strongly related to the representation medium that is used to model a phenomenon under study (Louca & Zacharia, 2008). There is a wide range of available means to construct and communicate a model to others, such as drawings, mathematical equations, graphs, three-dimensional structures, computer-programming and modeling environments or even verbal descriptions. The selection of appropriate means for model representation depends on the availability of the representation medium, its usability (e.g., the learner's familiarity with the representation medium) or its capability (e.g., whether the representation medium is appropriate for modeling the specific phenomenon).

Irrespective of the communication medium that is used for the expression of a model, scientific models are essentially conceptual in nature (Driver & Oldham 1986; Hestenes 1997). Scientific models are epistemological constructs of the natural sciences that enable the description of natural systems in an operational mode. For instance, they are interpretive representations with predictive capability (Louca, 2004).

Models are created and used not only in physical sciences but in several domains, such as geography, economics, social anthropology, etc. The following extract provides an interesting example of how models are created and used by members of different communities to make sense of the Gulf Coast hurricane that stroke New Orleans in 2005.

*“In late August 2005, millions of Americans turned on their televisions to see an ominous whorl of color advance across the Gulf of Mexico toward New Orleans. But they were not watching the storm itself; what they were seeing was a model, a carefully constructed way of representing selected features of this natural occurrence (areas of changing wind velocity across a two-dimensional space). Scientists used similar atmospheric models to “virtually manipulate” variables such as air and water temperature in an attempt to predict the trajectory of the storm, the time of landfall, and its strength. After the storm, demographic models (in the form of coded maps) suggested that the most devastated human populations were also the poorest and helped explain, in turn, why evacuation models (systems of instructions directing how communication, law enforcement, and logistical support were to be mobilized) were based on faulty assumptions about people’s ability to transport themselves out of harm’s way.” (Windschitl and Thompson, 2006, p. 785)*

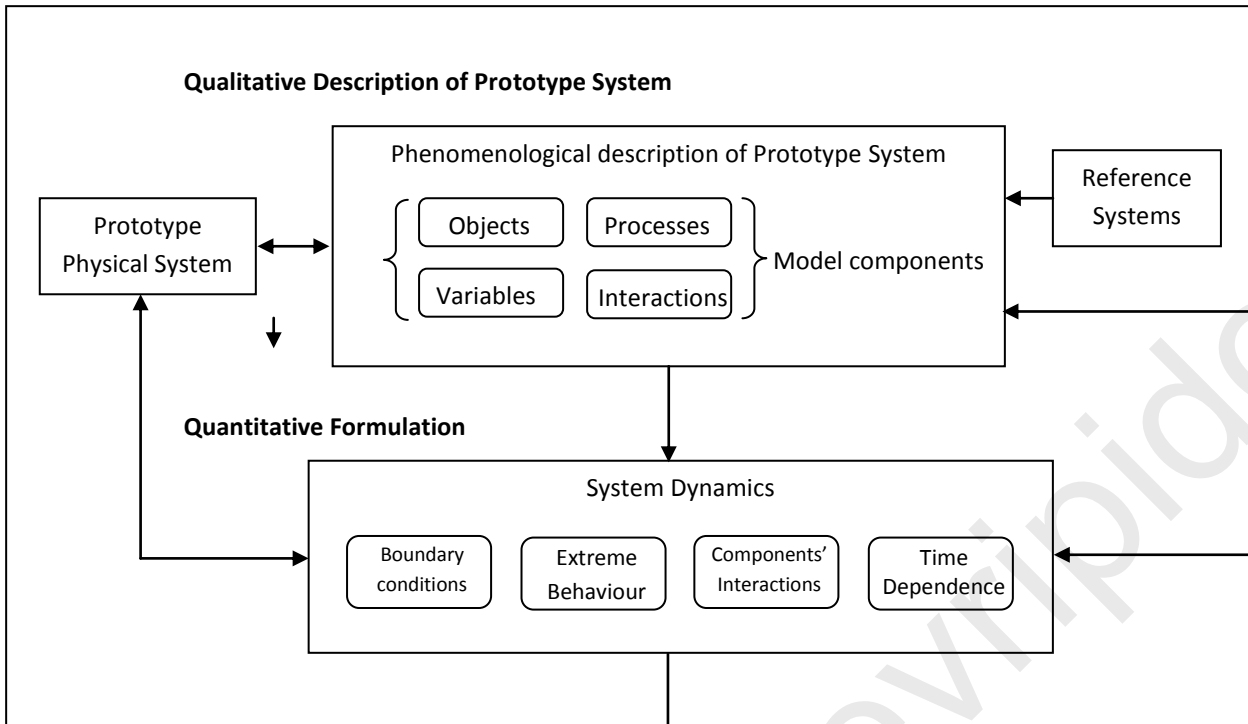
## 2.2. The process of scientific modeling

Researchers identify that the process of scientific modeling involves two major stages: the *Model Formulation stage* and the *Model Deployment stage* (Hestenes, 1997; Constantinou, 1999) (see Figure 1). Additionally, there is consensus that the modeling approach to learning is iterative, in that it involves continuous comparison of the model with the reference physical system with the express purpose of gaining feedback for improving the model so that it accurately represents as many aspects of the system as possible. It is also cyclical, in that it involves the generation of models of various forms until one can be found that successfully emulates the observable behavior of the system (Constantinou, 1996; Lehrer & Schauble, 2000; Penner et al., 1997).

During the Model Formulation stage, the learners are exposed to the observation of a natural phenomenon (or an object or a system) that is of interest, with the explicit purpose of creating a model that describes as many aspects of the behavior of the phenomenon as accurately as possible. Therefore, learners are prompted to identify the various parts constituting the phenomenon, the processes that guide its operation, the interactions between its various constituents, and the variables pertaining to the behavior of the phenomenon. Creating a model involves various activities, such as identifying variables, making connections among variables, and verifying the accuracy of the model (Buckley, 2000; Fretz et al., 2002; Harrison & Treagust, 2000). Hestenes (1992) asserted that creating a model also involves the identification and representation of objects, as well as the definition of interactions and relationships between them.

Once learners have constructed a model that accounts for their observations, they are asked to examine the relation of the constructed model with the studied phenomenon. This examination propagates an iterative cycle of comparisons between the model and the physical phenomenon, with continuous refinements of the model, until students are satisfied that their final model accounts for all of their observations and represents the various aspects of the phenomenon they are interested in. Typically, students will construct a number of models of different forms before they can successfully complete the *Model Formulation stage*. These cycles of model generation, revision and evaluation have been described in greater detail elsewhere (Mandinach, 1989; Penner et al., 1997; Stewart et al., 1992). At this stage, an anticipated learning outcome of the MCSI refers to the development of epistemological awareness of learners towards the underlying scope of model refinement; learners are expected to appreciate the continuous evaluation and

### I. Model Formulation



### II. Model Deployment

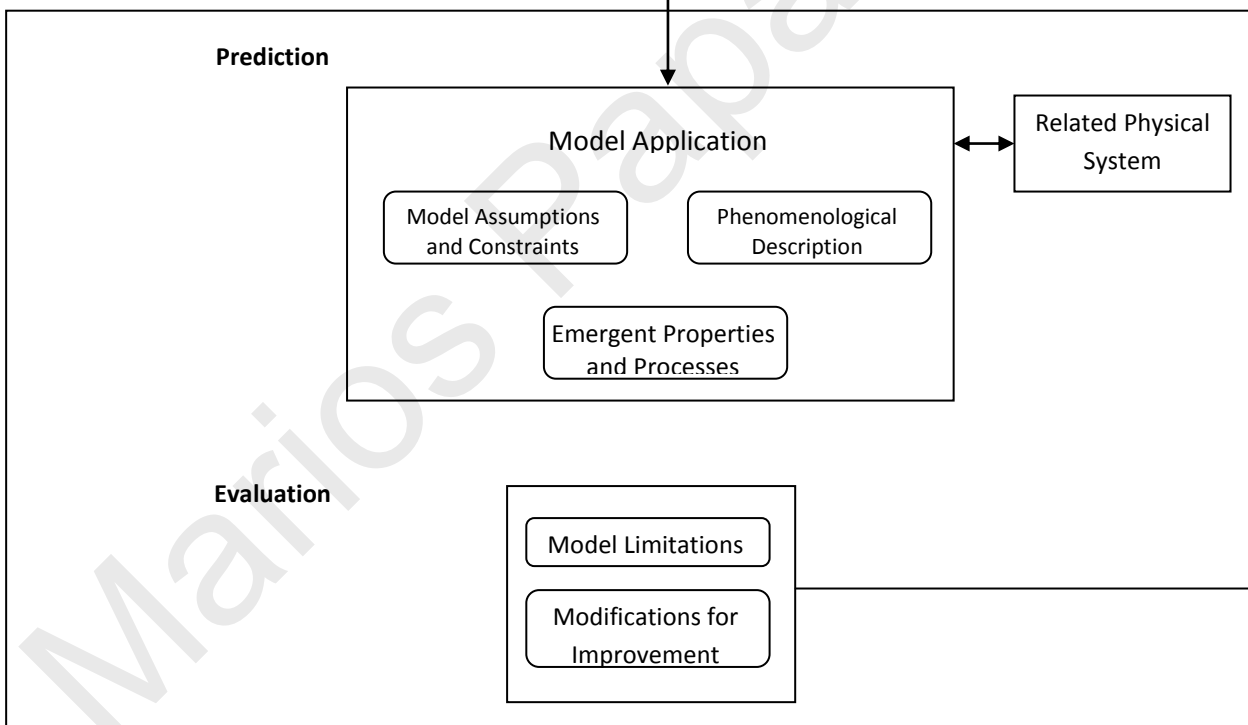


Figure 1. The Process of Scientific Modeling (adapted from Constantinou, 1999)

reformulation that their models go through as an integral part of the model-building process and not as a mere process of repair implemented to fix errors, inconsistencies or deficits (Penner et al., 1997).

The second stage of the scientific modeling process, the *Model Deployment stage*, emerges as soon as learners have finalized the process of formulation of what they consider an initial satisfactory model. Through appropriate instruction, learners are prompted to abstract their model from the prototypical phenomenon and apply it in a new situation. In doing this, they need to make explicit their model's assumptions and constraints as a means to recognize the limitations of their model. In the beginning, new situations could be different states of the same phenomenon. In subsequent cycles, they could be different phenomena of the same class. The process of applying their model to new situations provides the opportunity to learners to use their model for interpreting new phenomena, as well as to make predictions for the behavior of the new phenomena. In addition, through this process students receive valuable feedback for further improving their model so as to progress from a model of restricted applicability to a more powerful version. Finally, through a series of carefully sequenced activities relating to different phenomena, the students can be empowered to formulate more general laws and theories that transcend any single phenomenon (Constantinou, 1999).

Engaging students in the cyclical processes of model development and evaluation can serve to reveal fundamental aspects of the epistemology of modeling and of science in general. This notion is also aligned with the statement of White and Frederiksen (1998) that "...complex theories in science are developed through a process of successive elaboration and refinement in which scientific models are created and modified to account for new phenomena that are uncovered in exploring a domain" (p.7). As a result, learners are empowered in learning how to formulate and deploy models of a phenomenon, and, at the same time, to develop a more refined epistemological awareness towards the evolution of scientific theories. The development of students' epistemologies about science as an important aspect of science learning and teaching has been highlighted in other studies (Abd-El-Khalick et al., 1998; Abd-El-Khalick & Lederman, 2000; Akerson, Abd-El-Khalick, & Lederman, 2000; Lederman, Wade, & Bell, 1998; Sandoval, 2005).

## 2.3. The three “faces” of modeling

By summarizing the value and significance of models and scientific modeling, I have simultaneously revealed the triple role of modeling in relation to its use and purpose. Firstly, modeling represents an authentic *scientific enterprise*, since scientists develop models in order to build and elaborate their own understanding about their research domains. Secondly, modeling could be viewed as an *instructional approach*, when used as a platform to help students develop understanding of the content, the process, and the epistemology of science through building, testing, refining, and validating models of observed phenomena or complex systems. Thirdly, modeling could be considered as an *ability* that is developed during learners’ exposition to MCSI settings. I portray the three “faces” of modeling in detail below.

### 2.3.1. Modeling as a *scientific enterprise*

*“Scientists develop models and representations as ways to think about the natural world. The kinds of models that scientists construct vary widely, both within and across disciplines. Nevertheless, in building and testing theories, the practice of science is governed by efforts to invent, revise, and contest models. Using models is another important way that scientists make their thinking visible.”*  
(Michaels, Shouse, & Schweingruber, 2008, p. 109)

Modeling is an authentic scientific activity through which scientists “study precisely those phenomena that are not easily perceivable, timely, or of the right scale” (Hmelo, Holton, & Kolodner, 2000, p. 290). Scientists create and use models to portray their current understanding of a system (or parts of a system) under study, to aid in the development of questions and explanations, and to communicate ideas in public (NRC, 2012). Modeling has been an integral part of the scientific enterprise from its origins, as experimentation and the broader enterprise of inquiry are profoundly situated in model building, testing, and revising (Duschl & Grandy, 2008; Giere, 1988; Kitcher, 1993; Longino, 1990). In their book *Fearful Symmetry*, Stewart and Golubitsky (1992) portrayed the way scientists use modeling in their everyday work:

*“Scientists use mathematics to build mental universes. They write down mathematical descriptions—models—that capture essential fragments of how they think the world behaves. Then they analyze their consequences. This is called ‘theory.’ They test their theories against observations: this is*



*called 'experiment.' Depending on the result, they may modify the model and repeat the cycle until theory and experiment agree. Not that it's really that simple, but that's the general gist of it, the essence of the scientific method"(p. 2).*

Accordingly, through modeling scientists aim to test their ideas against observations in the real world and to assess the adequacy of their formulated models against standards of evidence (Windschitl, Thompson, & Braaten, 2008a). It has also been claimed that "modeling is the scientists' main activity, and of physicists in particular, for the generation and application of scientific theories" (Greca & Moreira, 2000, p. 7). Being a participant observer in molecular biology and immunology laboratories, Dunbar (1999) declared that model building was most important and most common in instances where scientists were confronted with a series of unexpected findings. It was at this point that he observed a major shift in their mode of reasoning; scientists sought to draw analogies to different types of mechanisms and models in other organisms. Rather than making analogies to the same organism, they attempted to generalize over the series of findings by proposing a general model that accounts for and explains their findings, and they attempted to build a sequence of causal events that could probably provide a more comprehensive model that described and explained the entire biological process.

Consequently, models (the products of modeling) evolve from scientists' perennial and systematic attempts to understand and represent the diverse systems found in real world (Giere, 1988). Models could also serve as tools for scientists' communication of their research findings within the scientific community. Specifically, Nersessian (1992) points out that when scientists aim to communicate the findings of their work, they present them by means of the logic of their mathematical formulae and the conceptual models they have created. Scientific models are expressed in the forms of inscriptions (i.e., textual, pictorial, or graphic expressions such as notations, drawings, diagrams, charts, or maps), analogies, physical constructions, or computer simulations (Latour, 1990). They can represent theoretical structures (as in abstract/conceptual) such as energy flow in thermal conductivity phenomena, or phenomena/systems that are inaccessible to direct observation, such as the dissolution of a substance in a liquid (Windschitl et al., 2008). Anderson (1999) underscored the value of inscriptions created by scientists by stating that it is through the process of creation, sharing and negotiation the meaning of inscriptions that "raw experience is transformed into data and infused with scientific meaning; it is through this

process that scientists create models and theories and use them to interpret the world” (p. 973).

The history of scientific evolutions is dispersed with examples of such scientific endeavors. For instance, in observational astronomy Claudius Ptolemy the Greek built a model in which the earth was at the center (geocentric), while the sun swung around it, but years later Nicolaus Copernicus, Galileo Galilei and Johannes Kepler based on new observations came up with the heliocentric (centered around the sun) model. In physics of light, scientists hypothesized that light energy can behave like a wave as it moves through space (the “wave” model of light), or it can behave like a discrete particle with a discrete amount of energy (quantum) that can be absorbed and emitted (the “particle” model of light). In atomic physics, Bohr and Rutherford proposed a model of the atom in which electrons spin around the nucleus of the atom in their orbits. In molecular biology, James Watson and Francis Crick built scale models of DNA out of wire and wood and used them afterwards to reason whether the real molecule had a double or a triple helix structure (Watson, 1968).

### **2.3.2. Modeling as an *instructional* approach**

As it has been stated in the previous section, scientists create models to test theories and to develop a better understanding of complex phenomena and systems. I argue that students can similarly benefit from this scientific approach. Model building is in line with constructionist theories of learning (Papert, 1991); in order to build an internal, mental model of a particular scientific phenomenon, learners need to construct external representations or artifacts of the phenomenon under study, and as Jackson (1995) put it, “to develop that level of understanding, students need to engage in the activities of modeling, e.g., questioning, predicting, constructing, verifying” (p. 7). Additionally, modeling activities provide opportunities for teachers’ to better monitor students’ progression from their initial and probably naïve understanding of a phenomenon or a concept under study to a more comprehensive and epistemologically acceptable conception of phenomena and concepts.

Before proceeding on describing how an instructional setting that is grounded on the premises of MCSI should look like, it is essential to consider the anticipated benefits and learning gains that modeling activities might proffer to learners. It has been advocated

through previous research that engaging students in the iterative and cyclical processes of model development and deployment would enable them to: (i) express and externalize their own internalized mental models and thus to express their own thinking (Gilbert, 1991; Justi & Gilbert, 2003; Mellar, Bliss, Boohan, Ogborn, & Tompsett, 1994; Windschitl and Thomson, 2006); (ii) visualize their ideas in more organized ways (Izsak, 2000); (iii) examine abstract scientific phenomena in a way that meets their cognitive ability (Clark & Mathis, 2000); (iv) to solve problems (Windschitl and Thomson, 2006); (v) to coordinate and integrate facts with scientific theory rather than passively collect facts and formulas (Halloun & Hestenes, 1987); (vi) to reveal fundamental aspects of their understanding of the epistemology of modeling and of science in general (S. Gilbert, 1991; Gilbert, Boulter, & Rutherford, 1998a; Linn, 2003) and thus to develop epistemic awareness regarding the nature and purpose of science (e.g., scientific knowledge is a human construct, models aid individuals to represent, understand the underlying but “hidden” mechanism of complex systems or phenomena and predict real-world phenomena); (vii) to synchronize models and evidence (Pluta, Buckland, Chinn, Duschl, & Duncan, 2008). Duschl, Schweingruber, and Shouse (2007) also pointed out that students who have developed modeling-centered reasoning are more ready to take on the challenge of investigating, describing, and explaining a host of new phenomena, as well as, re-explaining and more deeply understanding phenomena with which they are already familiar.

In order to be able to design instructional settings through which learners will experience modeling-centered inquiry and, thus, to develop the abovementioned learning gains, a science instructor should obviously need to be acquainted with the various types of activities that should be incorporated within a modeling-centered instruction. Windschitl, Thompson, and Braaten (2008) indicate that successful instructional frameworks that use modeling as a teaching approach should typically guide students through a number of activities, such as:

*“engaging with a question or problem (often through material involvement with a natural phenomenon); developing a tentative model or hypothesis about causal or otherwise associative relationships in the phenomenon; making systematic observations to test these hypotheses; creating models of the phenomena that would account for the observations; evaluating this model against standards of usefulness, predictive power, or explanatory adequacy; and finally, revising the model and applying it in new situations” (p. 5).*

Apart from the activities that focus on the process of scientific modeling and pertain to specific modeling skills that learners should possess or develop during their engagement in modeling activities, Gilbert (2004) and Schwarz and White (2005) underlined the necessity of scaffolding learners' development of epistemic awareness regarding models and modeling. Specifically, Gilbert (2004) suggests that "...students should come to understand the nature and significance of the models that played key roles in the development of particular themes in the sciences. [...] To do so is to participate in the creative aspect of science and to experience its cultural value. (p. 117).

An additional characteristic of a MCSI instruction concerns the perspective from which learners should approach and study a phenomenon. Instead of viewing a phenomenon as a whole, composite and complex organization, Marquez, Izquierdo and Espinet (2006) suggested that learners should view a natural phenomenon as a system constituted by *material*, *dynamic*, and *causal* components. According to these authors, the *parts* or *entities* of the phenomenon constitute the *material* components, the *relationships* among the parts or entities of the phenomenon refer to the *dynamic* components, and the *causes* and *functions* that take place within the phenomenon fall into the category of *causal* components. For example, in the context of 1-D elastic collision phenomena, the colliding bodies and the surface that the bodies move on could be considered as the *material components*, the mass and the velocity of the bodies constitute the *dynamic components*, and the mechanism that describes the functions that take place during the collision of the moving bodies (e.g., the colliding bodies interchange their momentum during collision) could be viewed as a *causal component* of the phenomenon.

To sum up, modeling could be viewed as an *instructional approach* when is used as a platform to help students develop understanding of the content, the processes and the epistemology of science through building, testing, refining and validating models of observed phenomena or complex systems. I postulate that any science educator who is willing to adopt a modeling perspective in his/her instruction needs to be acquainted with both the critical aspects and design principles that shape a modeling-oriented instruction and also with the constituent components of the learners' *modeling ability* in order to design MCSI activities through which the learners' modeling ability will carefully fostered and sedulously practiced. I discuss below how and why modeling could be viewed as an *ability*.

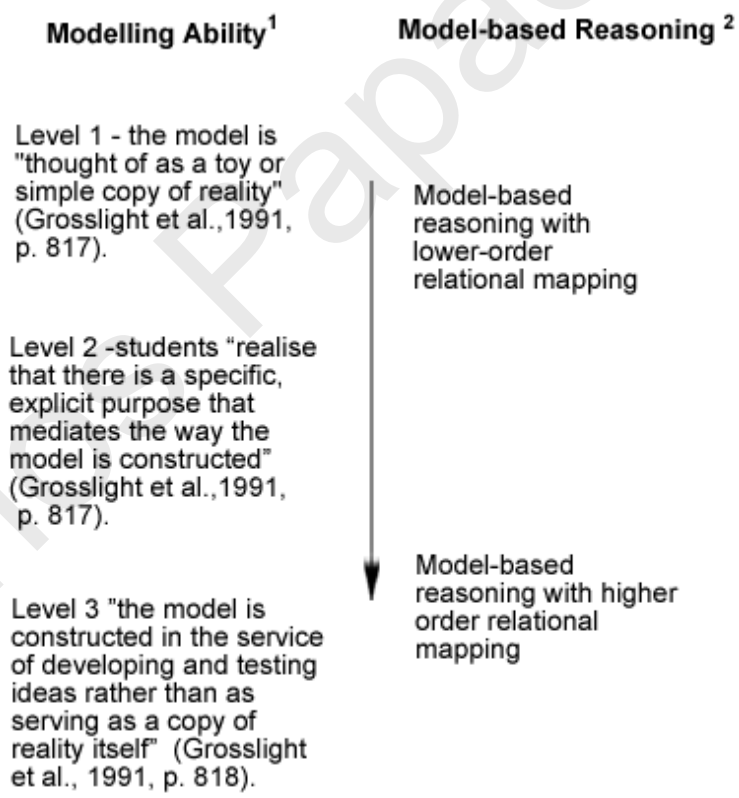
### 2.3.3. Modeling as an *ability*

National Science Standards (1996) revealed -among others- that students need to learn to formulate and revise scientific explanations and models using logic and evidence and also, to recognize and analyze alternative explanations and models. In order to be able to perform these types of tasks, learners should apply *model-based reasoning* (Driver et al., 1996). This type of reasoning moves beyond *phenomenon-based reasoning* (e.g., no clear distinction between a description of a phenomenon and its explanation is made) and *relation-based reasoning* (e.g., explanations derive from the data and because they are articulated in the same language as the data, they appear as statements of the empirical laws which govern the data), in that "...explanations are more than just logical deductions from the data, instead, explanatory models are used to construct explanations based on the mechanism of causation" (Stephens, Mcrobbie, & Lucas, 1999, p. 190). Stephens, Mcrobbie and Lucas confirmed the existence of these types of reasoning in a study conducted with middle school students in the context of electrical resistance and classified students' model-based reasoning into *lower-* and *higher-order relational mapping*. The learners who expressed *model-based reasoning with lower-order relational mapping* used a model as a basis for explaining experimentally-determined relationships but addressed only surface-level similarities or lower order relations between the model (the base) and the real phenomenon (the target), whereas the learners who expressed *model-based reasoning with higher-order relational mapping* used a model to explain experimental results but their reasoning involved higher-order relational mapping between the analog and the target.

Another significant study that sought to investigate student/expert modeling abilities in terms of students' beliefs about models' structure and purpose was conducted by Grosslight et al. (1991). Based on the participants expressed views about models' structure and purpose, Grosslight et al. derived at three hierarchical modeling levels that appear to be linear, age and experience dependent (Duit and Treagust, 2003). Specifically, many lower secondary students were classified in Level 1, because they stressed that there is a 1:1 correspondence between models and reality, e.g., students considered models as replicas of real life objects or incomplete copies of actual objects, they thought that models should be "right", they attributed the incompleteness of a model to the modeler's choice to present the model that way, and they did not search for ideas or purposes in the model's form. Some secondary students were classified in Level 2, where models are considered as real world objects or events rather than representations of ideas, models are incomplete or

different depending on the context, and communication rather than the exploration of ideas is the model's main purpose. The only participants who succeeded in entering Level 3 were the experts, as there were three evident characteristics of models in their expressed beliefs; models should be multiple, their purpose is to serve as thinking tools and can be manipulated by the modeler in a way that satisfies his/her epistemological beliefs. In general, the modeling levels of Grosslight et al. (1991) imply that modeling is an intellectual ability that develops with age, and also with appropriate guidance and experience.

Chittleborough and Treagust (2007) contrasted the two levels of model-based reasoning identified by Stephens, Mcrobbie and Lucas (1995) with the three levels of modeling ability proposed by Grosslight et al. (1991) and declared that lower-order relational mapping and higher-order relational mapping are consistent with Grosslight et al.'s Level 1 and Level 2. This relationship is depicted in Figure 2.



1 (Grosslight et al., 1991 p. 815); 2 (Stephens et al., 1999, p.194).

Figure 2. Comparison of model-based reasoning and modeling ability as proposed by Chittleborough and Treagust (2007, p. 279)

As stated so far, modeling ability is conceived as a thinking skill that, according to Harrison and Treagust (2000), "...cannot be learned like content. Learning to become a skilled modeler is like learning to write creatively: it is only achieved through much practice over a lengthy period" (p. 377). It has also been stated that "modeling ability is a particularly useful tool for identifying changing epistemologies and ontologies during science learning (Duit & Treagust, 2003, p. 678). Other authors referred on modeling ability as a procedural skill that involves a set of modeling practices. For example, Van Driel and Verloop (2002) indicated that modeling abilities can be analyzed into the following: (1) using a given model, students should be able to explain the phenomenon that is represented through the model; (2) students should be able to compare a model and the phenomenon that represents (the target) and identify specific differences between the model and its target; (3) students should be able to revise an initial model in a way that accounts better for their observations; and (4) students should be able to draft a model to explain or describe a certain phenomenon. Stratford et al. (1998) suggested that learners' development of modeling ability should focus on: (1) decomposing a system under study into parts (analysis); (2) exploring how parts of a system are causally related (relational reasoning); (3) ensuring that the model represents the complete phenomenon (synthesizing); and (4) testing the model, trying different possibilities, and identifying problems with its behavior and looking for solutions (testing and debugging). Rogat, Schwarz, and Reiser (2006) analyzed modeling practices into four categories: (1) construct (develop models); (2) use (explain, test, and predict through the use of a model); (3) evaluate (identify limitations, determine explanatory power); and (4) revise (revise a model to strengthen its explanatory power).

Accordingly, there is a gap in the literature on what constitutes modeling ability, because some authors conceived modeling ability as a thinking tool that pertains on several types of knowledge about the nature and purpose of models, and others thought of modeling ability as a procedural tool that involves several modeling practices. Based on the description of the scientific modeling process in a previous section, it became apparent that modeling is a complex process that involves many constituent activities (Justi & Gilbert, 2002a; Justi & Gilbert, 2002b), and thus I sense that it requires *both* specific *skills* and *knowledge* that have to be mastered by learners in order to respond effectively to the various challenges that scientific modeling entails. I address in the subsequent section the need for a framework that unifies what I have learned so far from the literature about modeling

ability's "ingredients", and I propose a framework for developing and assessing learner's modeling ability.

#### **2.4. A framework for developing and assessing learners' modeling ability**

As it was claimed in the preceding section, modeling could be considered as an ability that is developed during learners' exposition to modeling-centered instruction and thus experience MCSI learning. Learning about the nature and purpose of scientific models, reflecting on the process of scientific modeling, and the ability to develop, refine and validate models are core components of human cognition and scientific inquiry (Linn, 2003) and, hence, they are desirable outcomes of science education (Barab et al., 2000; Crawford, 2005c; NRC, 1996; Penner et al., 1997; Schwarz & Gwekwerere, 2006; Schwarz & White, 2005). In this section, I discuss the issue of what constitutes modeling ability with a view to inform an effort to design for its development. In doing so, I draw on prior work in order to arrive at a coherent synthesis that can be used as a framework for promoting modeling ability and monitoring its development.

Before describing the proposed modeling ability framework, I would like to elucidate that this framework differentiates from the "model-based learning" framework that has been used extensively in prior research (e.g., Buckley et al., 2004; Clement, 2000; Gilbert, 1991; Gobert, 2000; Gobert & Buckley, 2000) to denote learning through construction, evaluation and revision of *mental* models. The term "model-based learning" derived from the work of Johnson-Laird (1983) on mental models, according to which the tenets of model-based learning are based on the presupposition that understanding requires the construction of mental models of the phenomena under study, and that all subsequent problem-solving, inferencing, or reasoning are done by means of manipulating or processing these mental models.

In contrary, my proposed "modeling ability framework" concerns the active participation of learners in *modeling-centered* inquiry instruction that engages them in the construction, revision, refinement and validation of *external representations* or *artifacts* that are commonly named as *scientific models*. Hence, I use of the term *modeling-centered inquiry* (and not the term *model-based*) to denote: (i) learning about the nature and purpose of scientific models; (ii) reflection about the process of scientific modeling; and (iii) the capability to develop, refine, compare, and validate models. This framework draws upon



varied literature bases from Cognitive Psychology and Science Education, namely, *constructionism* (Kafai & Resnick, 1996; Papert, 1991; Papert & Harel, 1991), *epistemic awareness of the nature of models and modeling* or “*metamodeling knowledge*” (S. Gilbert, 1991; Grosslight et al., 1991; Justi & Gilbert, 2002a; Justi & Gilbert, 2002b; Justi & Gilbert, 2003; Schwarz & White, 2005; Treagust et al., 2002; Van Driel & Verloop, 2002), *cognitive strategies and reasoning during learners’ engagement in computer-based modeling tasks* (e.g., Löhner et al., 2004; Louca & Zacharia, 2008; Sins et al., 2005; Stratford et al., 1998; Zhang et al., 2006), *modeling-centered science instruction* (Acher et al., 2007; Ergazaki et al., 2005; Halloun & Hestenes, 1987; Johnson & Stewart, 2002; Passmore & Stewart, 2002; Penner et al., 1997; Rotbain et al., 2006, Schwarz & White, 2005; Snir, Smith, & Raz, 2003; White, 1993), and *metacognition* (Brown, 1987; Brown, Bransford, Ferrara, & Campione, 1983; Flavell, 1976; Flavell, 1987).

The description of the scientific modeling process indicates that modeling is a complex process that involves many constituent activities (Justi & Gilbert, 2002a) and requires skills and knowledge that need to be mastered by learners in order to respond effectively to the various challenges that modeling entails. This assertion raises a question pertaining to the types of skills and knowledge that shape the modeling ability that is necessary for the enactment of scientific modeling.

Before proceeding further, I would like to clarify the term ‘skill’. In the scientific community there has been a great deal of confusion about skills. An important discrepancy concerns the issue of whether a skill is an automated procedure that emerges spontaneously or a cognitive attribute that emerges through learning. Concerning the relationship between knowledge and skill, Stokking and Voeten (2000) concluded: ‘All considered, there seems to be good reason to view [declarative and procedural] knowledge and skill as a unity, but at the same time it can be maintained that they are separate constructs’ (p. 103). According to Stokking and Voeten the concept of skill has been used to describe different attributes: “Skills may be defined as the performance of a (socially meaningful) task or activity; the word skill may refer to the proficiency with which someone can do something; it can refer to the automatic execution of procedures [...]; skills may (also) be seen as a hypothetical construct – a non-observable quality that facilitates behaviour” (p. 103). In this thesis, I take a cognitive approach, in which skills are defined as competences or processes (Perkins & Salomon, 1989). I view skills as the proficiency to perform specific activities or processes (Duggan & Gott, 1995). Every skill should form a meaningful unity, embedded

in a context of generating, processing and elaborating knowledge (Shavelson et al., 1993; Stokking & Voeten, 2000).

Based on previous research, I identified a number of skills, as well as, two types of knowledge that are essential for an individual to effectively and successfully engage with the scientific modeling process presented above (see Figure 3). Specifically, the skills that appear to be involved in the scientific modeling process are *model formulation* (Constantinou, 1999; Duschl, Schweingruber, & Shouse, 2007; S. Gilbert, 1991; Lehrer, Horvath, & Schauble, 1994), *identification of model components* (Halloun, 2006; Hestenes, 1997; Stratford et al., 1998), *comparing and contrasting models of the same phenomenon* (Penner et al., 1997; Snir et al., 2002), *model evaluation and formulating ideas for improvement* (Fretz et al., 2002; Schwarz & White, 2005; Snir et al., 2002; Stratford et al., 1998), and *model validation through comparison with phenomena in the same class* (Halloun, 1996; Snir, Smith, & Raz, 2003;). The first type of knowledge that is important for a self-regulated learner engaged in the scientific modeling process concerns the explicit identification and description of the major steps of the scientific modeling process (henceforth called *metacognitive knowledge about the modeling process*). The second type of knowledge that is important for the scientific modeling process is the epistemic knowledge or “meta-modeling knowledge” that corresponds to understanding of the nature of models and appreciation of the purpose and utility of scientific models (Schwarz & White, 2005; Snir et al., 2002).

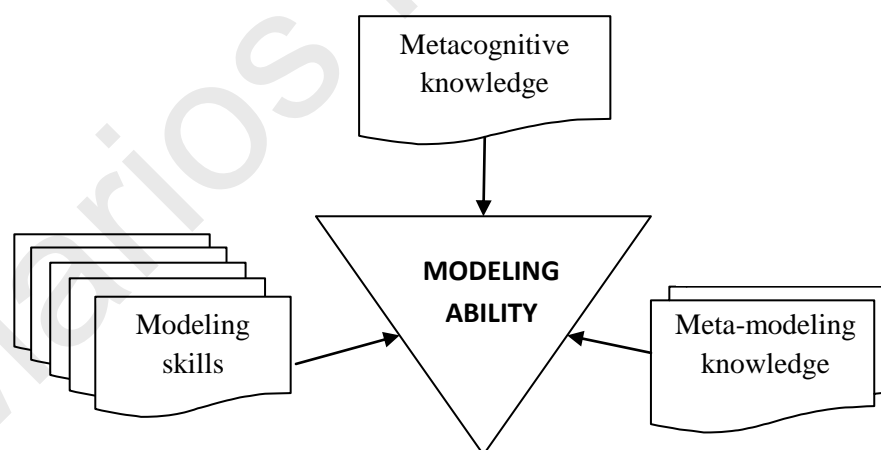


Figure 3. Aspects of the modeling ability

For the purposes of this thesis, I assume that the compilation of these three constituent components amalgamates the modeling ability. I consider that it is not possible for an individual to successfully complete the scientific modeling process without mastering the aforementioned skills and knowledge. Therefore, I propose that the modeling ability emerges through the development of a set of specific *modeling skills*, *metacognitive knowledge about the modeling process* and *meta-modeling knowledge*. I describe below in detail the three broad constituent components that shape the modeling ability.

To begin with, the most fundamental skill that lies at the heart of the *Model Formulation stage* of the scientific modeling process and serves as a pre-requisite for entering the model development stage is *model formulation*. This skill pertains to the ability of a learner to develop an external representation of a physical phenomenon or a system or an object (Constantinou, 1999; Lehrer et al., 1994) after s/he has collected various types of information either by directly observing the reference phenomenon or, indirectly, through making measurements or using secondary sources. In doing this, the learner needs to make major considerations such as “*Which is an appropriate modeling medium, that is available and I am already familiar with, that would enable the representation of the observed phenomenon in the best fashion?*”, “*What types and which of the collected information is appropriate for representing the phenomenon and how are these going to be implemented in the model?*” The answers to these questions will lead the learner to a phenomenological description of the prototype system. I assume that a learner who has already developed the *model formulation* skill is capable of creating representations that include the various system components and deciding how these will be emulated within the model. Of course, this decision depends on and is highly influenced by the strengths and limitations of the selected modeling medium. For example, in a model of a marine ecosystem the *variable* that pertains to the energy level of each species might be implemented using a number below each of the species in a paper-and-pencil model and the modeler might provide a verbal description of how the value of this variable is affected by each of the behaviors of a certain species. In a computer-based model, however, the energy variable might be set up using a mathematical formula and then implemented within a computational rule that will vary its value according to pre-specified criteria.

Even though the *model formulation* skill has not been explicitly stated and described in prior research, a lot of research that fits under the umbrella of modeling-centered inquiry, has considered the ability of constructing models as one of the modeling practices that

learners are engaged with during a modeling task (Fretz, 2002; Justi & Gilbert, 2002a; Lehrer et al., 1994; Schwarz & White, 2005; Stratford et al., 1998; Zhang et al., 2002). I believe that without the acquisition of this skill the learner lacks the ability to engage in the practice of modeling and therefore s/he cannot perform any tasks that are associated with scientific modeling.

A second skill that congregates within the modeling ability and is highly related to *model formulation* is the *identification of the model components*. This skill is developed during the *Model Formulation stage* of the scientific modeling process and pertains to the learner's ability to identify a model's *objects, variables, processes* and *interactions among its constituent components* that correspond to the various identified components of the phenomenon under study. In their modeling framework, Lesh and Doerr (2003) share a similar conceptualization of the constituent components of a model. They declared that a model consists of “elements, relations, operations, and rules governing interactions that are expressed using external notation systems” (p. 10). The elements are the conceptual elements used to represent important aspects of phenomena. Information and ideas about the elements, relations, operations, and rules within the model can derive from observations of the phenomenon under study, and the model must be consistent with the data collected about the phenomena (Schwarz et al., 2009).

It has also been reported that learners extract information from a model when they proceed at the stage of model analysis (Hestenes, 1995). This skill is important for two reasons: firstly, the learner that has already developed this skill is empowered with the ability to perform assessments as to whether her model has reached an adequate level that includes representations of the four major model components; secondly, after searching for any missing components to the model, the learner will re-visit the physical phenomenon in an attempt to collect new evidence to further refine her model. Stratford et al. (1998) have also stated that, at the stage of model synthesizing, students should ensure that the resulting model represents the various aspects of the phenomenon.

These two skills (*identification of model components* and *model formulation*) are highly related, since both of them are developed on the notion of what are thought to be the components of a model. Hence, I conjecture that both skills are simultaneously developed within the *Model Formulation stage* of the scientific modeling process (Figure 1).

Students will typically formulate various models of different forms before they can satisfactorily complete the *Model Formulation stage*. In order to take a critical decision on how and which of the already constructed models should be rejected in favor of the most appropriate model that satisfies a set of specific criteria, students need to be equipped with another skill that refers to *comparing and contrasting models of the same phenomenon*. The importance of this modeling skill has been delineated by Penner et al. (1997) who declared that “understanding the possibility of different models, and thinking about the advantages and disadvantages of various alternatives, might in turn support children’s progress from a primarily descriptive use of models to a beginning recognition that models can serve as instantiations of rival hypotheses” (p. 126). Snir et al. (2002) argued that a phenomenon under study can be modeled in more than one way according to the visual or conceptual tools that have been used to depict different aspects of the same reality. The articulation of this skill implies that learners should support their decision of selecting the most appropriate model that represents the phenomenon under study based on certain criteria. These criteria refer to: (a) plausibility (e.g., the model represents parts of the phenomenon); (b) accuracy (e.g., the model represents the way the phenomenon functions in real life); and (c) allowance of the model to formulate and test predictions (Fortus et al., 2006; Lehrer & Shauble, 2000; Penner et al., 1997; Schwarz & White, 2005). For instance, a learner that has already developed the skill to compare and contrast models of the same phenomenon is expected to reject a flexible plastic straw-model representing how a human elbow functions with the rationale that this model is not accurate (e.g., a flexible straw moves in 360° angle direction whereas a human elbow is allowed to move in an 180° angle direction). It may acknowledge as better a model made of a two sided folding rectangular cardboard on which a piece of rope is attached on its both sides in a way that enables the movement of one side in an 180° angle direction while pulling the rope. The rationale can be that this model is plausible (e.g., the two sided folding rectangular cardboard represents the upper and the lower portions of an arm, the rope represents the tendon), is accurate (e.g., while pulling the rope-tendon the lower portion of the arm rises up or when loosening the rope the lower portion of the arm lowers), and it enables the testing of predictions (e.g., what will happen if the rope/tendon is cut off?) (Penner et al., 1997).

Each time a learner tries to identify the model components that are missing by revisiting the physical phenomenon that is being modelled, s/he spontaneously proceeds to the next stage of the scientific modeling process, the *Model Deployment stage* (see Figure 1), and is engaged in an iterative process of model evaluation. In order to perform this, the learner

needs to have already developed a fourth skill, namely *model evaluation and formulating ideas for improvement*. From my perspective, this type of skill pertains to a learner's capability to: (i) contrast a model with its corresponding phenomenon; (ii) evaluate it on the basis of the presence or absence of a model's basic components (e.g., objects, variables, processes, interactions); (iii) pose ways of how the missing parts could be integrated in the revised model; and (iv) check model's adequacy in representing a particular phenomenon, providing a structural mechanism of the phenomenon, and enabling the formulation and test of predictions. Although this type of skill was not referred explicitly as a "skill" in previous research, it has been highlighted and studied as a modeling practice or a modeling activity that learners are engaged with while dealing with a modeling task (Fretz et al., 2002; Schwarz & White, 2005; Snir et al., 2002; Stratford et al., 1998). Fretz et al. (2002) stated that the modeling practice of evaluating a model involves several actions, such as predicting what would happen, identifying anomalies, critiquing/interpreting the results, identifying/proposing solutions. Similarly, Stratford et al. (1998) asserted that *testing and debugging* are examples of modeling activities that students are engaged in and they involve testing the model, trying different possibilities, and identifying problems with its behavior and searching for solutions. A more sophisticated set of criteria for evaluating a model has been proposed by Snir, Smith, and Raz (2002) who indicated that models are evaluated "according to their power to explain a set of experimental phenomena, their ability to predict the outcome of not-yet-experienced phenomena, and by their internal consistency" (p. 798). I argue that it is essential for the learner to have already developed the skill that refers to *model evaluation and formulating ideas for improvement* in order to fulfill her goal towards this end.

After improving a model through repeatedly contrasting it to the corresponding phenomenon, the learner needs to decide whether her model is "mature" enough to be considered as a completed model. In doing this, the learner needs to abstract her model from the prototypical phenomenon and apply it in a new situation, possibly in phenomena of the same class of the original phenomenon being studied. I suggest that the process of decontextualizing the model from its original context requires another modeling skill from learner, namely the *model validation through comparison with phenomena in the same class skill*. Halloun (1996) asserted that "validation includes different forms of assessment that provide students with opportunities to fulfill a major objective of science education: *critical thinking*" (p. 1028). It has also been claimed that asking students to defend the

validity of their models results in significant improvements in their scientific discourse (Stewart et al., 1992; White & Frederiksen, 1990).

A learner that has already developed this skill would apply a model that has already being evaluated and improved to a new phenomenon of the same class of the original phenomenon that was used as the basis for its construction, test whether the model fits to the new phenomenon, and decide if a new model needs to be built in order to fit in both phenomena of the same class. In case of model's failure to fit in the new phenomenon, the learner needs to formulate a new model that will successfully describe, represent and predict the observable patterns of both phenomena. In order to underscore the necessity for validating a model, Snir et al. (2003) pointed out that "students should understand the standards used in science for evaluating the validity of a model by examining the facts it explains and the model's internal consistency" (p. 803).

Although model's validation is of great importance during the modeling process, because it serves as a "certificate of viability" or a "certificate of mortality" of learner's model, it is often ignored during instruction (Halloun, 1996). This instructional unawareness might be attributed either to the complex character of the model validation process or to the developmental inadequacy of the learners to develop the abovementioned skill that is required during the model validation process or both.

So far, I have described five modeling skills that I consider as crucial for learners to be able to engage in various modeling practices during the *Model Formulation* and *Model Deployment* stages of the scientific modeling process. Even though the mastery of these skills might be considered as a necessary prerequisite for learners to enact autonomous modeling of phenomena, I argue that they do not amount to a sufficient presupposition. I propose that a self-regulated learner performing modeling tasks also requires *metacognitive knowledge about the modeling process*. Metacognitive knowledge, as defined by Flavell (1979), entails knowledge of general strategies that might be applied for different types of tasks, knowledge of the conditions under which these strategies might be used, and knowledge of the extent to which these strategies are effective. Likewise, *metacognitive knowledge about the modeling process* refers to the capability of a learner to explicitly describe and reflect on the major steps followed during modeling a phenomenon under study. For instance, one starts with observing the phenomenon that is of interest, collects information from the phenomenon, formulates a model by implementing the collected

information, contrasts the formulated model with the phenomenon as a means of evaluating the model, revises the model in light of new information that has not been implemented during the original formulation, repeats the previous steps in an iterative and cyclical manner with the purpose of refining the model to make it consistent and rigorous and to be able to use it to test hypotheses and make predictions. I view this component of the modeling ability as a challenging type of knowledge since it requires reflective appreciation of the various stages of the modeling process, and how they fit together. It is a type of metacognitive knowledge that enables the learner to reflect on the modeling process, to plan future steps, to monitor the evolution and gradual refinement of a model under construction and to evaluate the whole process. It enables the learner to regulate the application of individual skills at different stages of the scientific modeling process. This stance is in line with Bamberger & Davis (2011) who claimed that the “development of metacognitive knowledge can be encouraged by a teaching strategy of applying the same practices on several scientific content areas, along with reflection on the practice” (p.23).

Apart from modeling skills and metacognitive knowledge about the modeling process that are basic requirements for learners to meaningfully engage in the practice of modeling, I propose that modeling ability also involves well developed epistemic knowledge or “meta-modeling knowledge” that corresponds to *understanding of the nature of models* and *appreciation of the purpose and utility of scientific models*. The term “meta-modeling knowledge” was derived from the work of Schwarz and White (2005) who designed and implemented an inquiry-oriented physics curriculum for secondary students aiming at developing four aspects of meta-modeling knowledge. These aspects referred to: (i) the *nature of models* (e.g., What is a model? What do models represent? Can there be different models to represent the same object or phenomena? Do models represent absolute reality?); (ii) the *nature or process of modeling* (e.g., What is involved in the modeling process? How are models constructed? Would a scientist ever change a model?); (iii) the *evaluation of models* (e.g., Is there a way to decide whether one model is better than another? What kinds of criteria are used to evaluate models?); and (iv) the *purpose or utility of models* (e.g., What are models for? How can models be useful for scientists or students in science classes? What is the purpose of having multiple models of the same phenomena or object?). I share the view about the necessity of developing students’ meta-modeling knowledge and agree that engaging students in simply developing models is not enough to develop epistemological awareness towards models and modeling, but “one needs to add a ‘meta-modeling layer’ to a modeling curriculum, which enables students to develop not only scientific models but also explicit theories about the nature of models



themselves” (Schwarz & White, 2005, p. 167). However, in the framework that I propose, I have organized the constituent components of modeling ability somewhat differently. Specifically, I have sought to distinguish between metacognitive knowledge about the modeling process (which is metacognitive knowledge about how to construct and validate scientific models) and meta-modeling knowledge (which is epistemic knowledge about the *nature* and *purpose* of models in science). As far as the *nature of models* is concerned, I concur with the view expressed by Snir et al. (2002) that “... for scientists, a model is not a true description of a system, but rather a set of assumptions that include theoretical entities and relations among them, that are designed to help them think about how to explain some aspect of reality” (p. 797).

Consequently, *meta-modeling knowledge about the nature of models* entails a definition of models in terms of their *representational completeness* (e.g., does the model entail all necessary aspects of the phenomenon under study that facilitate its representation?), their *interpretive potential* (e.g., does the model entail a mechanism that explains how and why the phenomenon functions the way it does?), and their *predictive power* (e.g., does the model allow the formulation and testing of predictions for new aspects of the phenomenon it represents?). Likewise, *meta-modeling knowledge about the purpose and utility of models* entails epistemic understanding about the various purposes that scientific models play in science. For instance, models: (i) serve as sense-making tools for constructing knowledge; (ii) are used as communication platforms for conveying understanding or knowledge; (iii) can be used to develop new understandings by predicting new aspects of phenomena; and (iv) are used to illustrate, explain, and predict phenomena (Schwarz et al., 2009).

In summary, I advocate that the development of modeling ability emerges through the development of the three broad constituent components described above (Table 1). I also propose and concur with Lehrer and Schauble (2000) that the modeling ability is not likely to develop through short term instruction, but it unfolds over the course of continuous and persistent instructional attempts. The various components may fail to develop in unison unless modeling ability is carefully fostered and sedulously practiced. To understand how modeling ability develops in practice, there is an emergent need to carefully design and implement instructional approaches that are grounded on the premises of the scientific modeling process (see Figure 1) and test their effectiveness through evaluating the learning outcomes achieved by learners.

Table 1. Description of the components of the modeling ability

Component	Description
<u>I. Modeling skills</u>	
• <i>Model formulation</i>	It pertains to the learner's capability to develop an external representation ("a model") of a physical phenomenon which consists of <i>objects, variables, processes and interactions</i> among these components.
• <i>Identification of model components</i>	It pertains to the learner's capability to identify a model's <i>objects, variables, processes and interactions among the constituent components of the model</i> .
• <i>Comparing and contrasting models of the same phenomenon</i>	It pertains to the learner's capability to select the most and the least appropriate model that represents a phenomenon under study based on certain criteria; (i) <i>plausibility</i> , (ii) <i>accuracy</i> , and (iii) <i>allowance of the model to formulate and test predictions</i> .
• <i>Model evaluation and formulating ideas for improvement</i>	It pertains to the learner's capability to (i) contrast a model with its corresponding phenomenon, (ii), check model's adequacy in representing the phenomenon, providing a structural mechanism of the phenomenon, and enabling the formulation and test of predictions, and (iii) pose ways of how the missing parts could be integrated in the revised model.
• <i>Model validation through comparison with phenomena in the same class</i>	It pertains to the learner's capability to apply a model that has already built to a new phenomenon, test whether the model fits to the new phenomenon and decide if a new model needs to be built in order to fit in both phenomena of the same class.
<u>II. Metacognitive knowledge about the modeling process</u>	It pertains to the learner's capability to explicitly describe and reflect on the major steps of the modeling-centered cycle.
<u>III. Meta-modeling knowledge</u>	
▪ <i>Nature of models</i>	It pertains to the learner's development of epistemic awareness regarding the nature of models as this is illuminated in responses to questions like " <i>What is a model?</i> ", " <i>What do models represent?</i> ", " <i>Can there be different models to represent the same object or phenomena?</i> ", " <i>Do models represent absolute reality?</i> "
▪ <i>Purpose or utility of models</i>	It pertains to the learner's development of epistemic awareness regarding the purpose or utility of models as this is illuminated in responses to questions like " <i>What are models for?</i> ", " <i>How can models be useful for scientists or students in science classes?</i> "

## 2.5. What is the current situation with modeling-centered inquiry in science classrooms and science curricula?

*“Teaching practices rarely include modeling activities and do not emphasize the development of scientific knowledge as a continuous process of producing and revising models” (Justi & van Driel, 2005, p. 550).*

The abovementioned statement is in line with numerous reports in the literature that revealed the absence of modeling as a teaching practice both at the elementary and middle school level (e.g., Coll et al. 2005; Duschl, Schweingruber, & Shouse, 2007; Franco et al., 1999; Snir, Smith, & Raz, 2003; Stephens, McRobbie & Lucas, 1999). Particularly, Duschl, Schweingruber, and Shouse (2007) reported that modeling has been omitted entirely so far from science instruction by stating that *“almost totally absent from science classrooms is any systematic use of modeling or model-building activities that call for students to use new representational tools (including relevant mathematical tools and understandings) to make predictions that are tested against observations and iteratively revised”* (p. 8-20). Similarly, Berenfeld et al. (2003) argued that students rarely have the opportunity to build and use even physical models, and even in instances that they use models, these models *“...serve largely to illustrate rather than expand upon the content on which students are working* (p. 23). As a result, their models do not serve as vehicles for prediction and discovery.

Although many secondary education science textbooks contain examples of scientific models, these models are usually presented as static facts or as final versions of our knowledge of matter (Erduran, 2001; Van Driel & Verloop, 2002). Additionally, activities that welcome students the active construction, testing, or revising their own models as part of the learning process are totally absent from these textbooks (Barab, Hay, Barnett, & Keating, 2000). In line with these findings are the inferences made by Snir, Smith, and Raz (2003) who, while reviewing some science textbooks aiming to get insight on how the particle model is presented to students, they detected that in most curricula students were not engaged with explicit metaconceptual discussions of the nature of models nor involved in activities with considering alternative models. Instead the particle model was presented as a “known fact” and also the idea that “a model is an abstract construct of science”, was usually omitted from discussions or was only mentioned briefly in a few sentences. Thus,

they assumed -and I concur with their assertion- that this point of view forfeits students from developing an understanding of what type of thing the particulate theory really is (i.e., an abstract model, not a set of facts) and, thus, to appreciate its tremendous power and scope. Likewise, Franco et al. (1999) conveyed that a frequent habit within the practice of science education is to present the scientific laws in isolation with the models which provide meaning for them. This kind of reductionism, according to Franco *et al.* “is one of the most common pitfalls of science curricula, for which model based teaching and learning can be great assistance” ( p. 290).

Given the current situation with modeling-centered inquiry in science classrooms and curricula, one might plausibly argue that learners would hold naive conceptions of the nature, the role and the purpose of models and therefore these conceptions will impede their effective use of models during instruction. Based on a summary of research reports about learners’ different types of difficulties that were encountered during their participation in modeling-centered settings, Coll et al. (2005) identified several factors that hinder learners’ effective use of models and, at the same time, serve as indicators of their level of expertise. Their summary is provided below:

- *some learners may learn the model rather than the concept that it is meant to illustrate;*
- *pupils may lack awareness of the boundary between the model and the reality the model is representing;*
- *unshared attributes are often a cause of misunderstanding for learners;*
- *when given a range of models, some pupils continue to use the least sophisticated one;*
- *some pupils lack the necessary visual imagery;*
- *some pupils find it difficult to apply the model in different contexts;*
- *pupils may mix their models; for example, they may have the concept that heat makes molecules expand.*

(p. 186)

As stated above, students’ difficulties and naive conceptions concerning models and modeling may have their origins in the mode of instruction; either a typical science instruction that ignores the potential of modeling as an instructional approach to facilitate important learning goals or a science instruction that incorporates models in a very surface level might reveal the same results. Another major factor that is highly correlated with instruction is certainly the science teacher. It has been reported in the literature that science teachers also hold naive conceptions about models and modeling which in turn impact on their views about how to enact science instruction through modeling. I present in the next

section a summary of findings reported in the literature about teachers' understandings and views about models, modeling and modeling as an instructional approach.

## **2.6. Prior research on teachers' understandings and views about models and modeling, and modeling as an instructional approach**

*“The progressive introduction of students to the art of modeling requires that their teachers have, as a necessary condition for success, an appropriate understanding of what modeling as a process entails” (Justi & Gilbert, 2002a, p. 374).*

In this section a review of prior research pertaining to teachers' understandings and views about models and modeling, and modeling as an instructional approach is provided as an attempt to get useful insights on what is learned so far from existing literature on this particular domain of research.

Smit and Finegold (1995) explored novice teachers' perceptions of models in general, and of models specifically related to optical phenomena. To explore participants' views on models they used a questionnaire comprised of statements regarding physics models in general and specific models in optics. For each statement, the participants were asked to indicate whether they agreed with, or disagreed with or were unsure of the statement and they were also prompted to explain the reasoning behind their selection. The results of this study indicated that most participants' level of knowledge of models was limited. For example, the participants (i) confused scientific models with the “manufacture” models used by engineers in technological development; (ii) believed that a model should be depicted as similar as possible to the target that it represents; (iii) considered the function of a model to promote a better understanding of reality to be relatively unimportant; (iv) viewed the primary function of a model as a tool to help someone understand a phenomenon, explain complex and abstract things, and to demonstrate how something works.

Van Driel and Verloop (1999) investigated the knowledge of experienced science teachers about models and modeling in science through the use of two types of questionnaires; an open-ended questionnaire comprised of seven items that was completed by 15 teachers,

and a Likert-type scale questionnaire consisting of 32 items that was completed by 71 teachers. The themes of the open-ended questionnaire derived from the work of Grosslight et al. (1991) and referred to (i) the types of representations of models; (ii) the goals and functions of models in science; (iii) the characteristics of models; and (iv) modeling in science, with a focus on the design and revision of models. The same themes were used as the basis for the formulation of statements incorporated in the Likert-type scale questionnaire. The analysis of teachers' responses from the open-ended questionnaire revealed the following:

1. The teachers expressed a variety of beliefs regarding the *representational modes* of scientific models, but all agreed that the *interpretive potential* of the different representations that have been presented with was the major criterion to qualify a representation as a scientific model.
2. The teachers acknowledged the *explanatory* and *descriptive* function of models, and not their *predictive* power.
3. The teachers mentioned different *characteristics* of models, e.g., a model (i) relates to a target that is represented by the model; (ii) is a research tool that facilitates the collection of information about a target that cannot be observed or measured directly; (iii) always differs in certain respects from the target; (iv) needs to be kept as simple as possible; (v) is developed through an iterative process, and so on.
4. The majority of teachers stated that different models can co-exist for the same target, a belief that implies a *constructivist orientation* about science, whereas a minority of teachers reasoned in terms of *logical positivism* as they thought that a model needs to be as close to reality as possible.

As far as the Likert-type scale questionnaire is concerned, the respondents' statements were grouped in three clusters that reveal three distinctive aspects of models and modeling in science. The first aspect refers to the relations between models and a target in a positivist way, e.g., a model is a simplified reproduction of reality which enables causal explanations of phenomena, model formulation is a straightforward, rational process. The second aspect pertains to the physical appearance of models, e.g., a model can be represented with the use of drawings, pictures, analogies, or scale models. The third aspect concerns the use and construction of models in a social context and the idea that models are the products of human thought, creativity and communication.

In addition, Van Driel and Verloop (2002) undertook another study again with experienced science teachers aiming to gain insight of teachers' knowledge of teaching and learning of models and modeling. Teachers' knowledge was investigated in two consecutive steps. First, semi-structured interviews with seven experienced teachers were performed in order to explore teachers' practical knowledge about teaching models and modeling in science. Second, a Likert-type scale questionnaire was administered to 74 science teachers to inquire teachers' use of specific activities with respect to models and modeling in the teachers' current classroom practice, and teachers' knowledge of students' views of models and modeling abilities. The analysis of the responses provided during the interviews revealed a dichotomy between the participating teachers. One subgroup appeared to be in favour of mostly *teacher-directed* teaching activities and expressed that they paid more attention on discussing and reflecting on the *content* of the models that they provided to their students. On the other hand, the other subgroup focused on the *design* and *development* of models by students, gave emphasis not on the content but on the *nature* of models, and, thus, they appeared to be in favor of *student-directed* teaching activities. As far as the results obtained from the analysis of data obtained from the questionnaire are concerned, the teachers were divided in two subgroups according to the use of modeling activities. Specifically, the teachers who were grouped in the first subgroup indicated that they used relatively few teaching activities focusing on models, whereas the second subgroup stated that they use all possible types of teaching activities more frequently. Another finding that emerged from the analysis of the questionnaire indicated that the use of teaching activities seemed only loosely related to the teachers' knowledge of their students' views of models and modeling abilities.

Justi and Gilbert (2002a) sought to identify the knowledge and skills that science teachers consider as prerequisites to produce a model successfully. In doing this, they interviewed 39 Brazilian science teachers using a semi-structured interview. Teachers' responses were grouped into several categories based on a "model of modeling" framework they came up with to analyse the data collected. The most important<sup>1</sup> categories that pertain on the knowledge and skills that science teachers thought of necessary for the production of a model are as follows:

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<sup>1</sup> I use the term "important", because some of the categories that Justi and Gilbert (2002a) identified in their work appear somehow unsupported or irrelevant according to their descriptions or the participants' quotes they chose to support their claims. For example, one category is labeled "the construction of mental models" and what the reader reads below this category does not directly linked with what the label intimates.

<sup>2</sup> The teachers were enrolled in a selective master's science education course, within which the PDC was

1. *Purpose for modeling.* Teachers declared that in order to produce a successful model, a modeler must (i) have a clear purpose in producing a model (e.g., what are my aims for producing a specific model, which ideas am I trying to express and explain through the model), (ii) keep in mind the characteristics of the recipient audience (e.g., what are the needs and the existing knowledge the model recipients), (iii) decide of the level of similarity of the model with the phenomenon/object being modeled and model's comprehensiveness (some teachers thought that a model should be as similar to the phenomenon as possible, whereas others thought that only the main aspects of the phenomenon need to be represented)
2. *Personal experience, knowledge and attributes of the modeler.* Teachers stressed that modeler's (i) prior experience with the phenomenon being modeled, (ii) experiences with other phenomena and models, (iii) active interest in building the model, (iv) creativity, and (v) determination might have a positive impact on the successful development of a model.
3. *The selection of the source from which the model is developed.* Teachers recognized the importance of the use of analogy, both between phenomena and models and between sources of models (e.g., when building an orrery, it is important to use balls that they can move because these are essential aspects of the phenomenon).
4. *The selection of an appropriate mode of representation.* Teachers appeared to be aware of the several modes of representation, namely two- and three-dimensional models, visual models, mathematical models and verbal-expressed models. In addition, their statements indicated that the teacher (and not the learner) would act as a modeler and therefore the teacher himself would select the most appropriate mode of representation to create a model that would facilitate learners' understanding of the phenomenon being modeled.
5. *Designing and performing an empirical test.* Teachers identified four sets of personal skills a modeler need to be acquainted with during model formulation. Specifically, they reported that a modeler should: (i) have good manual skills (e.g., be able to manipulate materials to create a model), (ii) be a good observer, (iii) perform abstract thinking, and (iv) perform logical thinking (e.g., the modeler should have some organization of thought, some logic, in order to think in a series of steps).

In another study, Justi and Gilbert (2002b) used a semi-structured interview to enquire into the knowledge of the role of models in science teaching held by 39 Brazilian teachers. The questions used during the interview focused on teachers' views on the use of models and



modeling in the teaching and learning of science. The ideas expressed by the participants were classified in three groups, as follows:

- i. *The status and value of models in science education.* Teachers' ideas regarding the use of models in science education were thought to originate from: (a) their perceptions of the relationships that were possible between teaching models and scientific models *per se*; and (b) their perceptions of the characteristics of models that make a valuable contribution to science teaching and learning. Examples of the alternatives proposed by the interviewees that relate to the first origin are: 1) the integrity of the original scientific/historical models is signified them as "truisms" and hence no changes are allowed to be made when incorporated in science instruction; 2) a scientific model could be simplified by removing those aspects that are not aligned with the learning objectives of the instruction; and 3) teachers create their own models for the purposes of their instruction. Examples of the alternatives proposed by the interviewees that relate to the second origin are: 1) teaching science becomes more interesting through the use models; 2) models are useful for teaching because they provide a framework through which scientific knowledge and scientific language becomes more concrete and comprehensible for students and also because they facilitate the construction of explanations; 3) models serve as a medium for teacher to judge students' level of conceptual understanding; 4) models make abstract more concrete and hence visualizable, and therefore students improve their understanding about microscopic phenomena; 5) models serve as platforms for conceptual change to occur; and 6) through model building students improve their understanding about the nature of science.
- ii. *The translation of teachers' beliefs into classroom practice.* This group refers to teachers' (a) beliefs about their students' understanding of the nature of models; and (b) valuation of modeling activities undertaken by their students. Specifically, teachers stressed that a student may perceive a model as 1) the reality of a phenomenon; 2) a representation of some aspects of reality; 3) an example of a phenomenon; 4) a concrete object like a toy; 5) something that refers to the everyday meaning of the word model (e.g., a top model or a car model); 6) something to be copied; 7) something that cannot be changed; 8) something that is true; 9) a way to think about something; and 10) something complicated. Some teachers also stated that their students may not be able to understand what the term "model" entails, and some others appeared to be unaware of what their students thought of the concept of model. As far as teachers' valuation of modeling

activities undertaken by their students is concerned, 59% of teachers were positive in their valuation of modeling activities by students and used the following judgments to explain their position: modeling activities can be a way of 1) reconstructing students' prior knowledge; 2) causing students to reinvent scientists' models; 3) supporting active learning; and 4) providing a basis for experimental work.

- iii. *Teachers' responses to the outcomes of students' modeling activities.* Teachers' responses to the outcomes of students' modeling activities were clustered in two main categories according to the activities they proposed that relate to this theme. Activities like *asking students to explain their models, using models for prediction or experimentation, discussing the scope and limitations of students' models, producing a class consensus model from those presented, and discussing the roles of models in science* were grouped under the umbrella of using the outcomes of modeling as *a bridge to an understanding of scientific methodology*. Activities like *discussing all students' models, but allowing only those similar to the scientific/historical model to be used further, reinventing the scientific consensus model from parts of those put forward by students, and discussing and then overruling students' models, followed by introducing the historical/scientific model* were clustered under the umbrella of using the outcomes of modeling as *a bridge to a scientific consensus model*.

To sum up, it is clear from the aforementioned literature review that there exists a major problem which, in turn, becomes a challenge for teacher preparation programs designers and teacher educators – that of how best to support the development of teachers' scientifically accepted views of models and modeling. The apparent inadequate level of teachers' knowledge of models and modeling in science creates a “demand”, according to Crawford and Cullin (2004), to “provide robust experiences in order to alter unscientific understandings” (p. 1385). A review of examples of research reports aligned to this goal is provided in the subsequent section.

## 2.7. Attempts to reshape teachers' understandings and views about models and modeling: a review of existing literature

*“We almost know nothing of how they [the teachers] respond to instruction designed specifically to enhance their understanding of models and, in particular, of the key role of these representations play in inquiry”* (Windschitl and Thompson, 2006, p. 784).

The abovementioned statement is in line with what I was confronted with while seeking in the existing literature on how different research groups attempted to reshape teachers' understandings and views about models and modeling through structured interventions. Consequently, there is a limited number of studies that sought to attend to this issue. The studies that I reviewed are provided below.

De Jong and Van Driel (2001) developed a pre-service course module to change participants' focus of teaching from the content of scientific models to the nature of models. Beginning chemistry teachers participated in various activities, such as discussing articles from journals on modeling, discussing intentions to teach about scientific models, examining model-dominant chemistry curricula, and reflecting on their own pre-service experiences. Based on the results of their work, teachers failed to develop pronounced content knowledge about models and modeling (e.g., they did not come to understand that models are used to make and test predictions), but they showed some changes in their pedagogical content knowledge regarding their understanding of students' difficulties associated with the learning of models and modeling.

Crawford and Cullin (2004) explored how computer modeling experiences that prospective secondary science school teachers have been engaged with during a course influenced their understanding and intentions of teaching about models and modeling. During the course, the participants were engaged in the design of an open-ended investigation of a plant, soil and water system and later built computer models in *Model-It* of the relevant environmental phenomena. Multiple data sources (e.g., pre-module and post-module questionnaires, semi-structured interviews of purposefully selected participants, and journal responses) were used to capture teachers' development of understanding and

intentions of teaching about models and modeling. The findings of this study indicated the following:

1. The prospective science teachers initially possessed uniformed views of the role of models and modeling in science. For instance, they stressed that scientific models are created by someone who understands an object or a phenomenon (the target) and is willing to explain their function to someone who does not. Crawford and Cullin characterized this view as a “pedagogical” one, according which scientific models are perceived as “final form devices, used to communicate or explain a concept that is already understood” (p. 1393). In addition, although prospective teachers expressed the idea that scientists change a model in light of *new information*, they did not, however, articulated the informed view that models serve as platforms for the development of new *ideas*, or that scientists may change a model as a result of interpreting the same data in new ways.
2. After instruction, the prospective teachers shifted from the pedagogical view of models (e.g., use of models as explanatory tools in instances that the modeler as “the one who knows” seeks to help “someone who doesn’t know” to understand a phenomenon through the use of a model) to the view that the modeler him/herself can be benefited from model building because s/he can use the model to *understand* the phenomenon being modeled. Additionally, a shift in the kind of language used by the participants was also revealed after instruction. Specifically, the participants used modeling “terminology” in their responses in the post-module questionnaire that was never mentioned in the pre-module questionnaire. This finding, according to Crawford and Cullin, implies that these prospective teachers became more articulate with the language of modeling as a result of their engagement in a rich modeling experience.
3. Although prospective teachers declared that models could help learners to develop conceptual understanding about scientific concepts, they did not seem to appreciate the role of models in helping students to understand the process of both the development and the use of models in science. Hence, no substantial progress in their intentions to teach *about* models within their everyday teaching practices was made. Factors that were identified by the participants that hinder their decision making on adopting a modeling perspective in their instruction were *time*, *curriculum* and *technological constraints*.

Justi and van Driel (2005) investigated how beginning science teachers’ content knowledge (CK), curricular knowledge (CuK) and pedagogical content knowledge (PCK)

changed after their participation in a teacher's training program on models and modeling and, also, after they conducted a research project in their classes that focused on models and modeling. The main aspects related to models and modeling that these researchers incorporated in the teachers' training program were: (i) the nature and purposes of models in everyday life and in science; (ii) the use of different modes of representation; (iii) the production and use of two-dimensional, three-dimensional, and pseudo-three-dimensional (computerized) teaching models in science teaching; (iv) the advantages and limitations of each type of teaching model; (v) the use of analogies as teaching models in science teaching; (vi) the characteristics of the modeling process; and (vii) the use of modeling activities in science teaching. The training course was divided in four meetings of 3 hours each that were held over a period of six weeks. The analysis of the data collected during the enactment of the training program (e.g., teachers' written responses to a questionnaire, transcriptions of the three interviews conducted with each teacher, written material produced by each teacher in each of the learning activities in which they were involved during the meetings, the transcriptions of the discussions that occurred during the meetings, the written research project planning produced by each teacher, and the written research reports produced by each teacher) revealed the following:

1. Prior to their engagement in the training program, teachers did not have a comprehensive understanding of *the nature of the modeling process, the roles of models and modeling in the development of scientific knowledge, and the use of both teaching models and modeling activities in science teaching.*
2. The integration of teaching models from textbooks within the teachers' training program enabled them to reflect on: (i) characteristics of other teaching models presented by different instructional materials (textbooks, simulations, etc) that did not think about before; (ii) their personal teaching experiences regarding model introduction and use; (iii) the importance of discussing the limitations of the presented models.
3. Evidence from the discussions organized within the training program by the instructors revealed that these discussions had an influence on teachers' PCK about models and modeling.
4. Positioning the teachers' in the role of student during the modeling activities and thus confronted with difficulties similar to those encountered by their students enabled them to become more sensitive to both the questions they should ask their students and the importance of taking students' ideas into account.

5. Teachers' implementations of their research projects in their classes enabled them to test new ideas and probe new questions that might have been created during their participation in the program.
6. Teachers benefited from their research reports that were prepared after the implementations of their projects, because they enabled them to reflect on: (i) the aspects of the activity they designed for their students and were relevant for their learning; (ii) the learning outcomes of their students; (iii) the reasons that the activity has generated different learning outcomes; and (iv) modifications of the activity that would better facilitate their learning objectives in a future implementation.

Windschitl and Thompson (2006) examined how a series of activities implemented within a secondary science methods course influenced 21 preservice secondary teachers' understanding of the epistemic roles that models, theory, and argument play in scientific inquiry. The activities included the following: (i) immersion in investigative experiences with live fish through which students were prompted to make observations, pose their own questions, collect data, and present their results to their peers; (ii) presentation and debriefing of the requirements of a project pertaining to an authentic scientific investigation that would be undertaken by students throughout the course and presented to their peers at the end of the course; (iii) introduction to models through micro-teaching (the instructor involved students in using materials to create a model, in the form of rule-based statements, of mechanical advantage, and then, taking advantage of the experiences provided to students through this activity, he inserted and elaborated on the term *model* in a classroom discussion; (iv) use of computer-based simulations through which students explored natural systems by manipulating their variables and observing the consequent results; (v) reading and discussion of models and argumentation paper; and (vi) final presentations of investigations. Data collection sources were questionnaires, students' inquiry journals, transcripts from whole-group and small-group conversations during classes, responses to a model-based technology assignment, videotapes of participants' presentations of their investigations, participant-developed unit plans to be used for student teaching, and informal conversations that took place throughout the course. The findings of this study are summarized as follows:

1. The majority of the participants advanced their ideas about the nature of models, the function of models, or both after their participation to the course. For example, most of the participants who originally believed that models were representations of only "entities", expanded their views by referring to models of processes during their

discussions with their peers and, additionally, they appeared to consider models as predictive tools.

2. Participants appeared to be resistant to change their beliefs that models represent an objective reality. This view was evidenced in their statements about models as being imperfect representations of the “real thing”. However, according to Windschitl and Thompson, the term “real thing” as it was used by the participants did not imply an objective reality, but referred to humans’ experiences of reality.
3. At the end of the instruction, more than half of the participants included modeling strategies in their designs of the unit plans that would be used during their upcoming teaching practicum. This important finding might be attributed, according to the authors, either to the *teachers as learners* approach that was adopted during the course through which students were positioned at the role of the learner and prompted to construct models of mechanical advantage using actual materials or to the repeated integration of model discourse.
4. The informative paper that the researchers prepared and administered for review and reflection to the participants appeared to be the most valuable intellectual resource to influence and foster students’ conceptual change about important aspects related to models and modeling. On the other hand, the inquiry journal that students prepared as part of the requirements of the course seemed to serve primarily a reporting rather than a reflective function and therefore, it did not impact on changing participants’ thinking about models and investigations.
5. Even though participants appeared to be able to elaborate on the idea of models in advanced ways if given contextualized examples, evidence from their teaching units’ designs revealed that they failed to develop theoretical models to ground empirical investigations or employ model-based reasoning to make sense of their findings.
6. Participants’ prior experiences with research and with the “scientific method” resulted in hindering their advancement of more sophisticated understandings of models and their roles in empirical investigations.

Schwarz and Gwekwerere (2006), explored the effect of a using a guided inquiry and modeling instructional framework and accompanying science methods instruction on 21 preservice elementary teachers’ science lesson design skills, scientific model use, and teaching orientations. The science methods course consisted of three different types of endeavors: (i) reading, reflecting on, and discussing ideas about science, learning, and teaching within small or large class discussion, (ii) science inquiry activities, and (iii)

group work on lesson plans and preparation for teaching science lessons. The analysis of the data collected (e.g., preservice teachers' pre–posttests, classroom artifacts, peer interviews, and lesson plans throughout the semester) indicated that:

- the participants learned and used the framework in their lesson plans and teaching.
- in posttest lesson plans the participants gave emphasis on engaging students in scientific inquiry using several kinds of models.
- two thirds of the class moved their teaching orientations away from discovery or didactic approaches toward reform-based approaches such as conceptual change, inquiry, and guided inquiry.

## **2.8. Types of knowledge that teachers need to acquire in order to enact science instruction through modeling**

It has repeatedly been claimed that science teachers across the world have not been adequately equipped with knowledge and skills to enact science instruction through modeling (e.g., Crawford & Cullin, 2004; Justi & van Driel, 2005; Schwarz & Gwekwerere, 2006; Windschitl and Thompson, 2006). This can be attributed to the absence of teaching practices within their professional development that emphasize the development of scientific knowledge as a continuous process of building and refining models (Justi & van Driel, 2005). Even in cases where teachers have been participated in instructional programs that focused on enhancing their knowledge about models and modeling, they failed in changing their teaching practices by adopting a modeling-centered approach in their instruction, because teachers' prior knowledge and experiences about models and modeling were not taken into account when they participated in such programs (Justi & van Driel, 2005). In addition, Justi and van Driel (2005) argued that another factor that accounts for this failure relates to the content and the nature of these programs; in most cases it appeared that even though teachers received information about how to integrate modeling principles in their science instruction, they were neither became committed to such approaches nor felt that their instruction would be more effective and productive by applying them.

As it has been advocated for years, a major challenge for science teachers is to translate their accumulated undergraduate and precollege learning experiences into the design and enactment of effective science instruction. In fact what is actually needed, as Windschitl and Thompson (2006) suggest, is not a mere translation of their prior experiences but



rather a reinvention of their understanding of what science is and what science instruction entails. This is because: (a) teachers should be able to provide opportunities to their students to develop an informed understanding of what science is through learning environments that emulate the “disciplinary pursuits” of scientists, (b) these “disciplinary pursuits” of scientists are thought to be methodologically and epistemologically more complex compared to the dominant views of inquiry, e.g., inquiry is perceived as a universally applicable protocol that encompasses a certain sequence of activities such as observe, develop question, create hypothesis, design experiment, collect and analyze data, draw conclusions, develop new questions, and (c) the majority of teachers are more likely to have been exposed a passive instruction about models and modeling during their academic studies and, hence, they did not appreciate the fundamental contribution of models and modeling to the generation of new knowledge (Windschitl & Thompson, 2006).

Consequently, teachers’ knowledge about science teaching and learning is of pivotal importance in the design and implementation of innovative curriculum materials that may contribute to the enhancement of students’ understanding of science concepts (Justi & Van Driel, 2005). There is ample evidence that teachers’ content knowledge, curricular knowledge and pedagogical content knowledge about models and modeling is inadequate or incomplete (Justi & Van Driel, 2005).

### **2.8.1. Content knowledge about models and modeling**

In general, content knowledge is the understanding of subject matter *per se* (Shulman, 1987), which includes an understanding of conceptual knowledge, an understanding of issues about history, philosophy and methodology of science, and an ability to take part in activities that result in the acquisition of scientific knowledge (Justi & Van Driel, 2005). According to Justi and Van Driel, content knowledge about models and modeling incorporates a comprehensive understanding of the scientific models to be taught, and of models and modeling in general. In addition, content knowledge about models and modeling is analysed, according to these authors, into two aspects: (i) *teachers knowledge about models* (e.g., what a model is, the use to which it can be put, the entities of which it consists, and its stability over time); and (ii) *teachers knowledge about the modeling process* (e.g., steps to be followed in the modeling process and factors on which the modeling process depends). I argue that both factors relate to two of the constituent

components of the modeling ability framework provided in a previous section. Specifically, the first factor relates to the “meta-modeling knowledge” component, whereas the second factor relates to the “metacognitive knowledge about the modeling process” component of the proposed modeling ability framework.

### **2.8.2. Curricular knowledge about models and modeling**

An important aspect of teachers’ knowledge base is *curricular knowledge*. This type of knowledge pertains to teachers’ understanding of curriculum materials and their use in practice, standards and learning goals, and the sequencing of subject matter and opportunities for learning over time (Magnusson, Krajcik, & Borko, 1999; Shulman, 1986; Zembal, Starr, & Krajcik, 1999). This definition implies that teachers should possess an understanding of the specific learning objectives that each unit of school science curriculum promotes, the activities that are incorporated within each unit of school science curricula, the materials that are associated with these activities, and the assessment tasks that are used to assess the learning objectives of each unit. In the field of modeling-centered inquiry, *curricular knowledge about models and modeling* includes *when, how, and why* the general idea of models and of specific scientific or historical models should be introduced to their classes (Justi & van Driel, 2005). According to these authors, curricular knowledge is analysed into two aspects: (i) *knowledge about curricular models* (e.g., the need to introduce them in science teaching and their nature as simplifications of scientific (consensus or historical) models; and (ii) *knowledge about the introduction of modeling activities in science teaching* (e.g., when and why? what is the need? what is the purpose of such an attempt?).

### **2.8.3. Pedagogical Content Knowledge about models and modeling**

As it has been advocated extensively, the act of teaching is a complex cognitive activity that requires the transformation (Wilson, Shulman, & Richert, 1988) of teacher knowledge from diverse domains, such as, subject matter knowledge, general pedagogical knowledge, and knowledge of context. Teachers’ interpretations and transformations of subject-matter knowledge in the context of facilitating student learning (Van Driel, Verloop, & de Vos, 1998) have been encapsulated in a new type of teacher knowledge and named as *Pedagogical Content Knowledge* (PCK). Shulman (1986) first introduced PCK as a specific category of teacher knowledge “which goes beyond knowledge of subject matter

per se to the dimension of subject matter for teaching” (p. 9). In his own words, Shulman (1987) defined PCK as

*“that special amalgam of content and pedagogy that is uniquely the providence of teachers, their own special form of professional understanding ... Pedagogical content knowledge ... identifies the distinctive bodies of knowledge for teaching. It represents the blending of content and pedagogy into an understanding of how particular topics, problems, or issues are organized, represented, and adapted to diverse interests and abilities of learners, and presented for instruction. Pedagogical content knowledge is the category most likely to distinguish the understanding of the content specialist from that of the pedagogue.”*  
(p. 8)

On the one hand, PCK differentiates from content knowledge, because of the emphasis on the communication between teacher and student, and from general pedagogical knowledge, and on the other hand, because of the direct relationship with subject matter (Verloop, van Driel & Meijer, 2001). In trying to unpack the elements of PCK, Magnusson et al. (1999) identified five components that were thought to shape PCK. These were the following: (i) orientations toward science teaching; (ii) knowledge and beliefs about science curriculum; (iii) knowledge and beliefs about students’ difficulties with specific science concepts; (iv) knowledge and beliefs about assessment in science; and (v) knowledge and instructional strategies for teaching science (p. 110).

While PCK is typically conceptualized as topic-specific, teachers also need discipline-specific knowledge about how a discipline works (Davis, Nelson, & Beyer, 2008; Nelson & Davis, 2011). For example, as Davis, Nelson and Beyer advocated, science teachers need PCK for scientific inquiry and PCK for scientific modeling. In the context of scientific modeling, Justi and Van Driel (2005) delineate PCK as the type of knowledge that includes teachers’ ability to develop good teaching models; their ability to conduct modeling activities in their classes; their understanding of how their students construct their own mental models; and how the resulting expressed models should be dealt in class. PCK aspects were defined as: (i) *teaching models-purposes of their use* (what are the main purposes of the use of teaching models), (ii) *teaching models-production* (the nature of the models employed in their production and points that the teacher should take into account in producing different kinds of teaching models), (iii) *teaching models-use in science teaching* (ways in which the notion of teaching models is deployed by the teacher), (iv) *conducting of modeling activities in science teaching* (teacher’s role, characteristics of the discussion of students’ models and teachers’ previous experience), (v) *knowledge of*

*students' ideas about models and modeling* (the status of a teacher's knowledge about students' ideas and difficulties associated with models and modeling) (Justi & Gilbert, 2002b).

A different conceptualization of the elements that constitute teachers' PCK about models and modeling was proposed in a recent study undertaken by Henze et al., (2007). Henze et al. defined PCK about models and modeling as the amalgam of four elements. These elements are as follows: i) *knowledge about instructional strategies* (refers to teachers' knowledge about (a) the type of activities and the sequence of the activities that students are engaged with within a specific topic, and (b) their role as teachers); ii) *knowledge about students' understanding* (refers to teachers' knowledge about (a) students' prerequisite knowledge for engaging in a specific context, (b) evidence that indicates which activities were successful, and (c) the difficulties students were confronted with during instruction); iii) *knowledge about ways to assess students' understanding* (refers to teachers' knowledge about (a) on what and how they assessed their students and (b) the learning gains obtained by their students and what is the evidence of these gains); and iv) knowledge about goals and objectives of the topic in the curriculum.

A third proposal of what PCK for scientific modeling entails was provided by Nelson and Davis (2011). According to their proposal, PCK for scientific modeling encompasses teachers' knowledge of:

- orientations toward science teaching using scientific modeling
- knowledge and beliefs about scientific modeling in science curriculum
- knowledge and beliefs about students' understanding of scientific modeling
- knowledge and beliefs about assessment in science using scientific modeling
- knowledge and beliefs about instructional strategies in science using scientific modeling

## **2.9. Summary**

The emphasis of this chapter has been on presenting models and scientific modeling, and their place within science and science education. Specifically, the nature and purpose of scientific models have been discussed, the process of scientific modeling has been presented and an interpretation of the term "modeling" (that is, modeling as *a scientific enterprise, an instructional approach, and an ability that is developed*) has been proposed.

Next, the rationale and the need for a framework for developing and assessing learners' modeling ability have been explained, followed by the proposal of a theoretical framework to address this gap in the related literature. Additionally, an attempt was made to portray the current situation with MCSI in science classrooms and science curricula. The emergent "picture" of scientific modeling as the "neglected child" of science instruction was complemented with insights from prior research on teachers' understandings and views about models, scientific modeling and modeling as an instructional approach. Subsequently, research attempts to reshape and scaffold teachers' understandings and views about models and modeling have been presented, followed by the types of knowledge that teachers need to acquire in order to enact science instruction through modeling.

Through this chapter, it became apparent that there is an emergent need to explore possible ways to design instructional settings that would better support teachers' professional development in MCSI learning. I concur with Crawford (2005a) that *if* teachers are given the opportunity to gain an understanding of the importance of models and modeling in science through active participation in MCSI settings, *then* this can create a gestalt shift in their philosophy of teaching science, in which students are at the center of constructing their own explanations through building and using explanatory models. Hence, in order to make a progress on *how* to help teachers overcome specific barriers and, thus, develop informed understandings of models and modeling and of science in general, we need to proceed on making changes in two directions; *science curricula* and *teachers' preparation* programs. The purpose of this thesis is to respond in the latter direction, as it is described in the subsequent chapter.

Marios Papaevripidou

## CHAPTER 3: METHODS OF INQUIRY

### 3.1. Introduction

The purpose of this thesis was twofold. Firstly, this thesis aimed at examining the impact of a strategically designed PDC on teachers' development of modeling ability, CK about models and modeling, and CuK for MCSI. Secondly, this thesis sought to identify and describe the characteristics of teachers' created MCSI curriculum designs in an attempt to investigate the types of transformations that were enacted by the participants in their effort to apply the theoretical perspectives of MCSI approach for the design of their own curriculum materials.

A constructivist qualitative/interpretivist perspective was followed for undertaking the research within the present thesis. Creswell (2003) portrays qualitative/interpretivist research as an approach to understanding that is based on the use of open-ended questioning where participants express their own views about a world, making sense of it from a subjective historical and social perspective. Meaning from the constructivist perspective is socially constructed as humans interact and engage with the world around them (Creswell, 2003). Meaning therefore is varied and multiple, requiring the researcher to look for a complexity of views. Constructivist qualitative/interpretivist research abstains the quantification of learning and focuses instead on the categorization of true nature and diversity of individual understanding. By nature the research is inductive with meaning emergent from data collected in the field.

Accordingly, an experimental design was not used for this study, since this study did not aim at controlling behavioral events, or at focusing on some aspects of the implementation (Yin, 2003), but it aimed at examining how the PDC was implemented in practice, to what extent it was proven to be successful or not, and what were the characteristics of the implementation that might explain why it was proven to be successful or not. More specifically, the focus of the study was not the curriculum materials that were implemented within the course, but the entire PDC; that is the amalgamation of the MCSI curriculum ("Modeling 1-D elastic collision phenomena"), the modeling tool (namely Stagecast Creator), the discussion topics that the participants were encouraged to participate in, and the assignments that were prepared throughout the course, the specific instructor, and the specific participating teachers. Moreover, the researcher was not interested to study the

effect that the modeling tool *per se* might had on the development of teachers' modeling ability, CK about models and modeling, and CuK for MCSI, but was willing to examine the effect of the combination of the modeling tool, the curriculum materials, the topic of study, the different types of assignments, and participants' individual characteristics on the desired learning outcomes. Hence, by following a constructivist qualitative/interpretivist perspective the researcher sought to study all the aspects of the problem (that was, how to better support the development of teachers' modeling ability, CK about models and modeling, and CuK for MCSI), and theorize about the multiple variables of the problem.

## **3.2. Design of the study**

### **3.2.1. Participants: setting the scene**

The participants were twenty teachers who were enrolled in a PDC<sup>2</sup> at the University of Cyprus about the design of software-based curricula. Sixteen were elementary school teachers who had specialization in science teaching, and four were middle school teachers (3 physics teachers and 1 chemistry teacher). Fifteen teachers had a limited teaching experience (e.g., they taught very few science lessons within their school practicum program during the final year of their undergraduate studies or taught physics classes during working in afternoon private clubs), whereas the other five were at the time in their first year at school carrying a full teaching load. Teachers' prior experience with modeling during their undergraduate studies was very scarce, since only two teachers reported that they received explicit instruction about models and modeling during their undergraduate studies. Moreover, their prior teaching experience regarding modeling varied; ten of them did not use any modeling activities in their lessons, six of them used once analogical modeling with their students, and the rest four designed and applied a few modeling activities within their instruction.

The PDC was organized into 13 three-hour sessions. The instructor of the PDC met with the researcher on a weekly basis to discuss several issues regarding the design and implementation of the PDC on MCSI. Before proceeding to provide details about the design and organization of the PDC, a presentation of the theoretical underpinnings that guided the design of the course is presented.

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<sup>2</sup> The teachers were enrolled in a selective master's science education course, within which the PDC was implemented.



### 3.2.2. Theoretical underpinnings guiding the design of the PDC

In the subsequent subsections, a discussion of the theoretical underpinnings that guided the design of the PDC that was implemented for the purposes of this thesis is provided. Each subsection begins with descriptions of the lines of research that inform the design of the PDC, followed by illustrative references of the links between these theoretical considerations and specific aspects of the PDC.

#### 3.2.2.1. Teachers as Learners

Clarke and Hollingsworth (2002) stressed that the central focus of current teachers' professional development efforts should be aligned with the perspective of what they called "*change as growth or learning*". This view moves beyond the more traditional interpretations of teachers' professional development that conceive teachers' change as *training* (e.g. change is something that is done to teachers), *adaptation* (e.g., teachers adapt their practices to changed conditions), *personal development* (e.g., teachers "seek to change" in an attempt to improve their performance or develop additional skills or strategies), *local reform* (e.g., teachers "change something" for reasons of personal growth) or *systemic restructuring* (e.g., teachers enact the "change policies" of the system). Instead, teachers' professional growth programs that are grounded on the premises of the "*change as growth or learning*" perspective aim to "... change teachers to teachers as active learners [by] shaping their professional growth through reflective participation in professional development programs and in practice" (Clarke & Hollingsworth, 2002, p. 948).

Advocates of the *Teacher as Learner* approach emphasized the importance of designing PDCs through which teachers should be offered "...opportunities for learning from teaching, rather than learning of teaching" (De Jong, Van Driel & Verloop, 2005, p. 6). For example, Crawford (2005a) reported that teachers should be situated as active *learners of content* rather than primarily learners of pedagogy, because this *teacher as learner* approach moves beyond the traditional teacher preparation tradition through which teachers learn how to write good lesson plans or act as (passive) receivers of information about the various strategies of how to teach, as it places the teacher directly in the role of inquirer in simulated research experiences. In their study, Windschitl and Thompson (2006) also underlined the value of this approach, as they attributed teachers' change in considering using models in their own teaching to the *teacher as learner* approach.

In a similar way, Justi and Van Driel (2005) declared that in order to facilitate the development of teachers' knowledge about models and modeling, it is essential to design instructional activities through which teachers would be involved in situations analogous to those that students experience in their classes. The following extract underscores this notion:

*“During one of our meetings, the teachers were involved in a modeling activity as if they were students learning a new scientific content. They were asked to produce a model that explained how glue works. This phenomenon was chosen because one of the aims of the activity was to make the teachers experience the same kinds of difficulties that students have when they are asked to model something that is unknown to them. They were asked to express their models in any mode of representation they wished and to explain all the steps they had followed during the proposal of the model. The discussion of this activity was conducted from two perspectives. Initially, the researcher tried to act in the same way the teachers may act with their students; that is, by asking each of them to express her/his model, by asking them to compare the models, and by making them think about important aspects related to models — such as, the nature of a model as a partial representation, the non-existence of something as a ‘right’ model, the limitations imposed by the process of expressing their mental models, and the need to test their models in order to make them acceptable to a given community. The aim was to involve them in an exemplary situation of how modeling activities may be discussed in classes.” (p. 562).*

In the present thesis, the tenets of the *Teacher as Learner* approach were adopted for the design and implementation of the first phase of the PDC (see Figure 6). Specifically, the participating teachers, working in pairs, were engaged in multiple cycles of model development and deployment of five elastic collision phenomena. For instance, the teachers *as learners* were expected to

- make observations and collect data of the first collision phenomenon (a cart moving with a constant velocity collides with a stationary cart of the same mass),
- create a model in paper to represent the observed phenomenon,
- revise their model by applying new data collected from the phenomenon,
- improve their model by using a software tool (Stagecast Creator) in which they will create a new dynamic model,
- compare their model with the model created by another pair of teachers through discussing with their peers the advantages and disadvantages of each model,
- name their model based on the underlying mechanism that they used for creating their model, and

- validate their model by applying it in a new collision phenomenon (e.g., two equal mass carts move in opposite directions with the same constant velocity collide).

The abovementioned cyclical and iterative procedure was followed for each of the five collision phenomena. Teachers uploaded each of their final models in the Blackboard e-Education Platform (henceforth called BeEP) and they were asked to evaluate another pair of teachers' model using the Discussion forum of the BeEP. Their peers' comments, suggestions and critique were into account for further revising and improving their models in the next course meeting.

During the first phase of the PDC, the role of the instructor changed from one of telling participants correct answers to guiding and facilitating teachers as learners activity, as teachers engaged in the modeling process (Vygotsky, 1978). The teachers were considered active participants in the learning process, setting their own learning goals (in relation to the task) and forging meaningful relations.

### **3.2.2.2. The Interconnected Model of Professional Growth**

As it has been repeatedly reported in the literature, professional development programs that seek to succeed on teachers' change of classroom practices and behaviors through changing their beliefs and attitudes are inevitably confounded to failure. Clarke's and Hollingsworth's (2002) response to this critical issue is illuminated in their proposal of a teachers' professional growth model, namely, the Interconnected Model of Teacher Professional Growth (IMTPG). This model (as shown in Figure 4) suggests that:

*"...change occurs through the mediating processes of "reflection" and "enactment", in four distinct domains which encompass the teacher's world: the personal domain (teacher knowledge, beliefs and attitudes), the domain of practice (professional experimentation), the domain of consequence (salient outcomes), and the external domain (sources of information, stimulus or support)." (p. 950)*

## The Change Environment

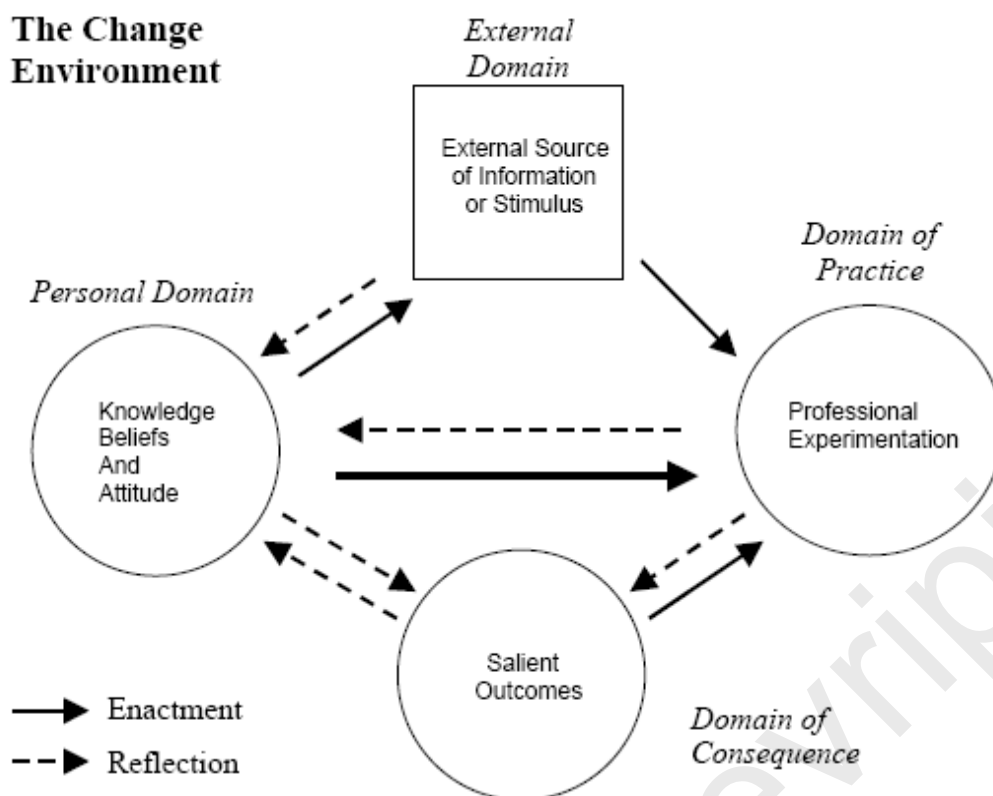


Figure 4. The Interconnected Model of Professional Growth (Clarke & Hollingsworth, 2002)

What distinguishes this model from others reported in the literature is, according to the authors, its non-linear nature, the crystallization of the complexity of teachers' professional growth through the identification of multiple growth pathways between its four domains, its recognition of professional growth as an inevitable and continuous process of learning, and the identification of the mediating processes of reflection and enactment as the mechanisms by which change in one domain propagates the change in another.

Because the abovementioned characteristics of the IMTPG model are in line with the view that teachers should be offered opportunities to be actively engaged in a process of knowledge building in order to develop their personal knowledge bases, I decided to use the IMTPG model as the basic framework for the design and enactment of the PDC of the present thesis. Specifically, the purpose of this thesis that pertains to the investigation of the effect of a designed PDC on teachers' development of modeling ability, CK about models and modeling, and CuK for MCSI is in line with the view expressed by the creators of the IMTPG model, who advocated that:

*“...teacher growth becomes a process of the construction of a variety of knowledge types (content knowledge, pedagogical knowledge, and pedagogical content knowledge) by individual teachers in response to their participation in the experiences provided by the professional development program and through their participation in the classroom.”* (Clarke & Hollingsworth, 2002, p. 955).

In order to illustrate how the IMTPG model was aligned with the purposes of this thesis, it is important to demonstrate how the domains of this model were translated in this thesis. It is also important to state that the study of Justi and van Driel (2005), that used the same framework for both the design of their PDC and the analysis of the data collected, was used as a supplementary source for unpacking the definitions of the four domains of the IMTPG model. Hence, the realization of the four interconnected domains of teachers' professional growth is briefly represented in Figure 5 and described below.

1. *External domain.* This domain encompasses all learning activities that teachers participated in during the meetings of Phase 1 and Phase 2. Specifically, the 1-D elastic collision curriculum (e.g., activity sheets, assessment tasks and assignments) during Phase 1 and the Modeling Ability Framework paper during Phase 2 were thought as the *external source of information or stimulus* that fell under the umbrella of this domain.
2. *Domain of practice.* According to Clarke and Hollingsworth (2002), the domain of practice is “conceived as encompassing all forms of professional experimentation, rather than just classroom experimentation” (p. 950). Hence, for the purposes of this study, the domain of practice incorporated all learning situations in which teachers used or expressed their knowledge during the PDC. Examples of these situations are the 1-D elastic collision curriculum activities (e.g., discussions and completion of activity sheets, construction of models in Stagecast Creator), the different types of assignments (e.g., evaluation of modeling-centered curricula, identification of the components of modeling ability framework from modeling-centered curricula, etc), the reflective diaries and the journal report, the peer evaluation of uploaded models in BeEP, and the asynchronous discussions in BeEP.
3. *Domain of consequence.* This domain includes the outcomes that were revealed as a result of teachers' participation in the PDC. A major outcome that illuminates teachers' development of professional growth of modeling-centered inquiry was their modeling-centered curriculum designs that were prepared during Phase 2 of the course.
4. *Personal domain.* In order to capture teachers' personal domain, several sources of data were collected. These were teachers' responses in: (1) the modeling ability tests (both

pre- and post-tests); (2) the CK and CuK tests (both pre- and post-tests); (3) the reflective diaries and journal report; and 4) the asynchronous discussions in BeEP peer evaluation of uploaded models in BeEP.

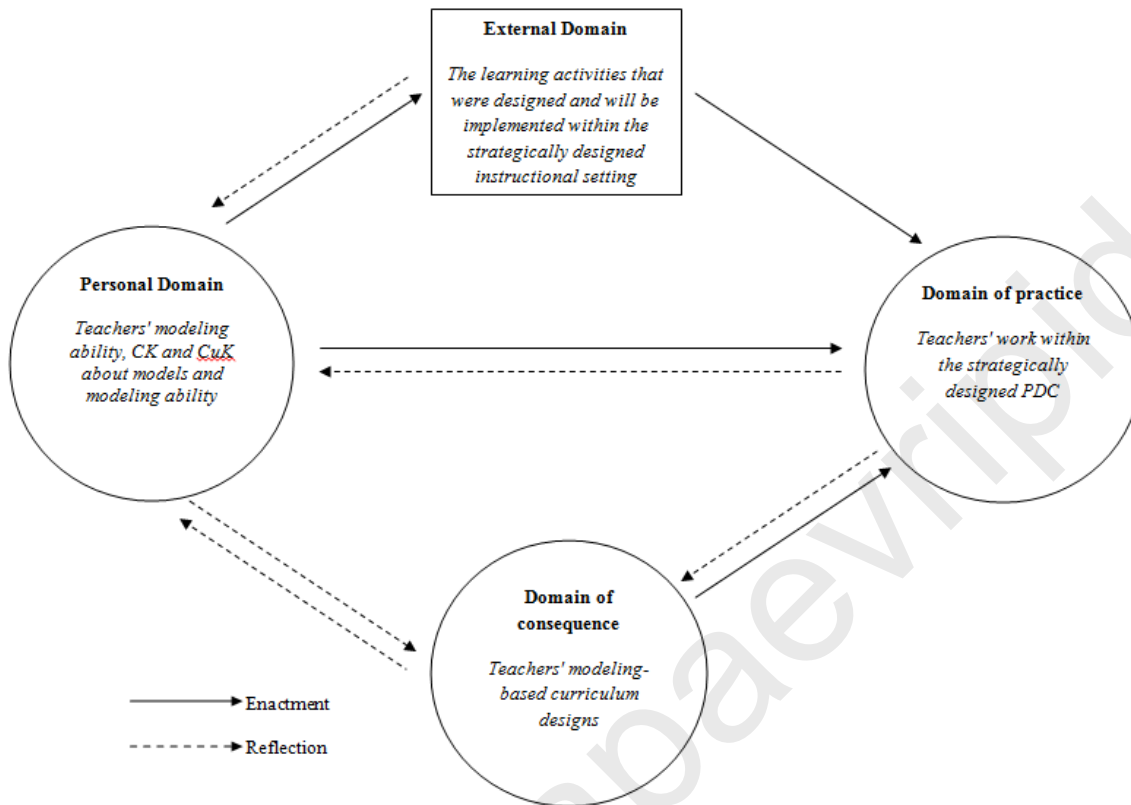
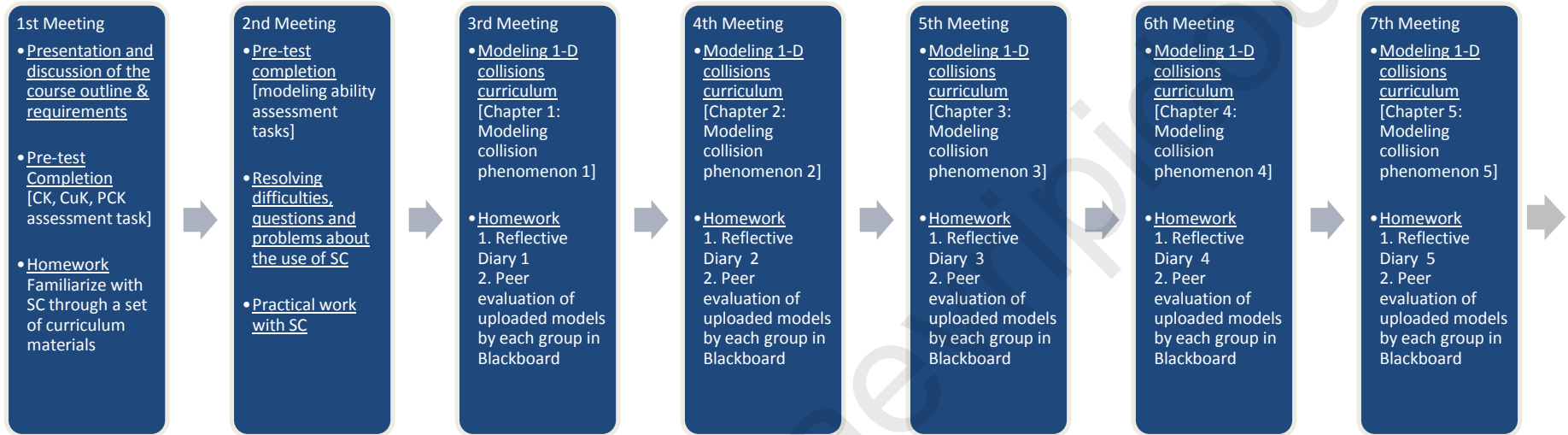


Figure 5. Adaptation of the IMTPG model for the purposes of this thesis

### 3.2.3. Outline of the PDC

The PDC was organised in two phases, the “*Teachers as Learners*” Phase (Phase 1) and the “*Teachers as Thinkers and Designers of Modeling-Centered Curriculum Materials*” (Phase 2). An overview of the course is provided in Figure 6 and a brief description of the two phases is provided below.

### Phase 1: Teachers as Learners



### Phase 2: Teachers as Thinkers and Designers of Modeling-Based Curriculum

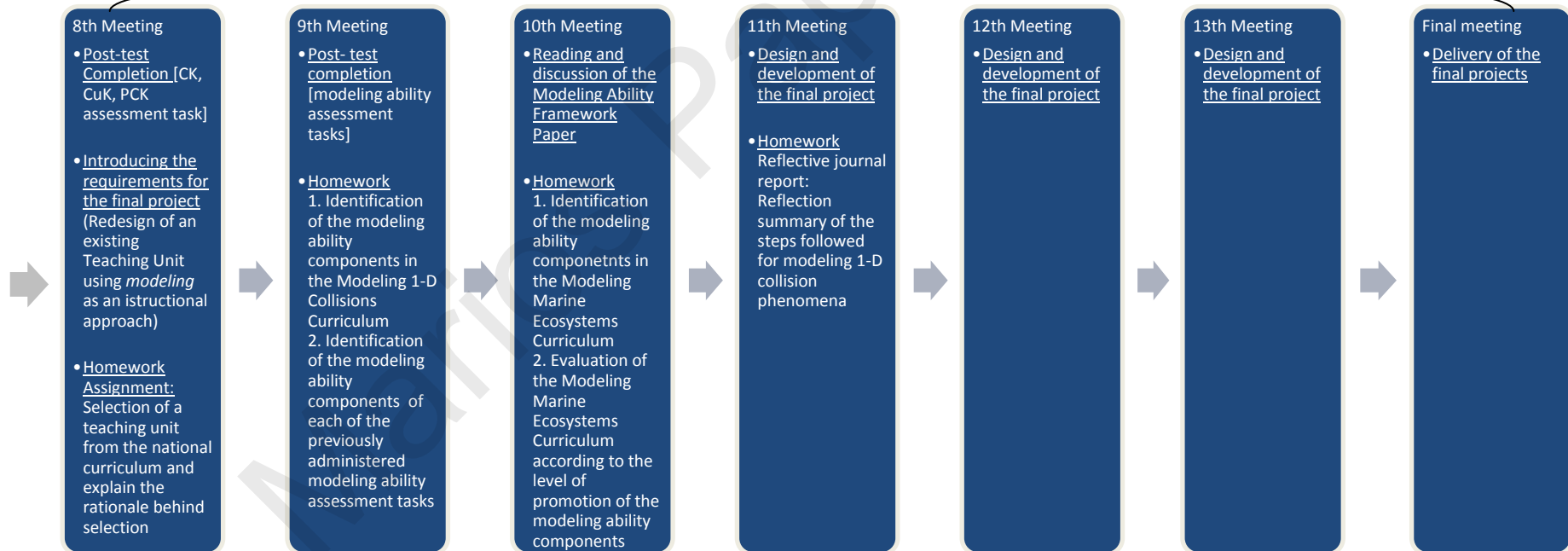


Figure 6. Timeline of the implementation of the proposed research project

### 3.2.3.1. Phase 1: Teachers as Learners

During the first meeting, the instructor introduced the participants to the course and informed them about the outline of the course, its scope and its requirements. The participants were asked to complete three sets of pretests; the *CK Test*, the *CuK Test* and the *Modeling Ability Test A* (see Data Collection section for details about these tests). As soon as the pre-tests completion was finished, the instructor administered to the participants a curriculum through which they would familiarize themselves with Stagecast Creator (henceforth called SC), the computer-based modeling medium that was used for modeling the various collision phenomena in the subsequent meetings. A copy of the SC was given to the participants to install it at their personal pcs at home. Because of the strict time limits of the course, the participants were asked to complete this curriculum at home as a homework, and prepare a list with the difficulties or problems that might have encountered during familiarizing themselves with SC and brought it at the next meeting in order to resolve them with the help of the instructor.

At the beginning of the second meeting, the *Modeling Ability Test B* was administered to the participants and after its completion, the instructor tried to resolve any difficulties, questions or problems that the participants were confronted with during completing the SC curriculum. In order to better scaffold participants in familiarizing themselves with the capabilities of SC, additional practical activities were given to the participants to work with during the second meeting.

Throughout meetings 3, 4, 5, 6 and 7 the curriculum titled “Modeling 1-D elastic collisions” (see next section for details about the activity sequence that this curriculum was based on) was implemented. The participants formed groups of two and completed this curriculum electronically. Specifically, the curriculum was comprised of several word documents in which text boxes for typing a response were provided. During the implementation of the curriculum, the participants were engaged in multiple cycles of model development and deployment of five elastic collision phenomena. For example, during the first meeting each group of participants made observations and collected data of the first collision (a cart moving with a constant velocity collided with a stationary cart of the same mass), created a model in paper to represent the observed phenomenon, revised their model by applying new data collected from the phenomenon, improved their model through using the SC for creating a new dynamic model, compared their model with the model created by another pair of teachers through discussing with their peers the



advantages and disadvantages of each model, named their model based on the underlying mechanism that they used for creating their model, and validated their model by applying it in a new collision phenomenon (e.g., two equal mass carts moving in opposite directions with the same constant velocity collide). The abovementioned cyclical and iterative procedure was followed for each of the five collision phenomena. At the end of this activity sequence, the participants uploaded each of their final models in the BeEP and were asked to evaluate a model created by a pair of teachers using the Discussion platform of the BeEP. Their peers' comments, suggestions and critique were taken into account for further revising and improving their models in the next course meeting.

Apart from the model evaluation assignment that was anticipated to be completed as homework, the participants were asked to prepare reflective journals on a weekly basis, and participated in asynchronous discussions of topics related to the work undertaken during the meetings.

Phase 1 ended with the administration of the modeling ability tests (Test A and Test B) and the CK and CuK tests.

### ***3.2.3.2. Phase 2: Teachers as Thinkers and Designers of Modeling-centered Curriculum***

During phase 2, the participants were asked to (i) change their participation perspective in the course by shifting from *learners* to *thinkers* of the underlying design principles of curriculum that was grounded on the MCSI perspective, and (ii) re-designed an existing unit from the National Curriculum to foster the development of understanding of the unit's concepts through a MCSI approach. To better scaffold teachers' work, various reflective activities were organized: (1) teachers were asked to revisit the curriculum that were engaged with during Phase 1, identify the learning objectives of each set of activities and classify them into those that were related to the conceptual understanding of collisions and those that fostered the development of the learners' modeling ability (e.g., modeling skills, meta-modeling knowledge with respect to the nature, purpose and utility of models, metacognitive knowledge about the modeling process); (2) teachers were given a theoretical paper prepared by the researcher that focused on various theoretical underpinnings related to models, modeling and the development of learners modeling ability and were asked to reflect on how the reading of paper helped them in resolving

several issues related to their understanding of MCSI, (3) teachers were asked to select a science teaching unit from the National Curriculum that the development of conceptual understanding of its concepts could be facilitated in a more advanced way through the use of the MCSI approach and provide the rationale behind their selection. As part of the requirements for their curriculum designs, the participants were asked to prepare the following: (i) formulate learning objectives for both the conceptual understanding part and the modeling ability part of their curriculum; (ii) organize the activity sequence of their curriculum in a map; (iii) provide descriptions of the design and the implementation of each activity and state explicitly what learning objectives were fulfilled through each activity; (iv) design activity sheets based on their activities' descriptions; and (v) design assessment tasks to evaluate their learning objectives.

#### **3.2.4. Modeling 1-D elastic collision phenomena: a description of the activity sequence of the modeling-based curriculum**

The activity sequence that was followed for the design and implementation of the MCSI curriculum during Phase 1 (*Teachers as Learners*) emerged from a prior study (Papaevripidou, Hadjiagapiou, & Constantinou, 2005) which was accomplished within a European funded project, namely "Weblabs" (<http://www.weblabs.eu.com>). The description of the activity sequence is provided below.

At the beginning of the activity sequence, learners observe from a video file the event of a perfectly elastic collision of two carts of equal mass, one moving with constant horizontal velocity and one being at rest, on a horizontal table. Afterwards, they describe how the phenomenon appears visually, determine the factors that should be included in a model and construct a model in Stagecast Creator, possibly a "transfer" model (cart 1 transfers its velocity to cart 2) to explain the situation.

Afterwards, learners observe the second video of a perfectly elastic collision of two carts of equal mass, moving in opposite direction with equal velocities, on a horizontal table. At this point learners test the "transfer" model created in the previous activity and recognize the inconsistency: in this collision the right cart does not transfer its velocity to the left cart. In this way they check the model's validity. Due to the inconsistency of the "transfer" model with this second collision phenomenon, learners have to construct a new model.

This model would possibly be a “reflect” model, in which the two carts simply change direction after collision.

At this point, learners test the “reflect” model in Experiment 1 and again recognize the inconsistency, because in Experiment 1 the moving cart does not reverse its velocity after its collision with the stationary cart. In this way, they check the new model’s validity and appreciate the importance of developing a third model that is consistent with both classes of collisions. Learners observe the event of a perfectly elastic collision of two carts of equal mass, moving in opposite direction with unequal velocities, on a horizontal table.

Learners test both the *velocity transfer* and the *velocity reflect* models with respect to Experiment 3 where, even though the two carts change direction after the collision, they have unequal velocities. Now, learners have to construct a new model for Experiment 3. This model will possibly be a “swap” model, in which the two carts just swap velocity during collision. Learners observe experiment 4 of a perfectly elastic collision of two carts of equal mass, moving in the same direction with unequal velocities, on a horizontal table. They test the “swap” model created in the previous activity, which accurately produces the desired behavior in this case as well. They also test the “swap” model in Experiments 1 and 2. This model describes accurately the behavior of the carts in these cases too.

Learners create representations of classification in order to display the three models and in each case they declare whether they describe correctly the four collisions or not. They are able to report that although the collision events in the different classes appear different visually, the same underlying model (carts swapping velocity) determines their behavior. Next, the learners are prompted to calculate the sum of the velocities of the carts prior to collision A and compare it to the sum of the velocities after the collision. They follow the same procedure for all the observed experiments and decide that the sum of the velocities remains the same. In this way, they should formulate the “velocity conservation law”.

As a final activity, the learners are presented with a perfectly elastic collision of two carts of unequal mass, one moving with constant horizontal velocity and one stationary, on a horizontal table. They are challenged to test the “swap” model as well as the velocity conservation law in this case, and they find that neither the velocity swapping model nor the velocity conservation law hold in Experiment 5, because the two carts have unequal mass. Through a series of activities, they are guided to calculate the product of mass and

velocity of each cart in Experiment 5. Then they calculate the sum of the products prior to and after collision, compare and define the conservation of momentum law. After the definition of the conservation of momentum law, learners have to construct a new model for Experiment 5. This model should be the conservation of momentum model, which describes accurately the behavior of the carts in each observed experiment.

The “Modeling 1-D elastic collision phenomena” curriculum appears in Appendix I.

### **3.2.5. Stagecast Creator: a description of the modeling tool embodied in the modeling-centered curriculum**

During the implementation of the modeling curriculum, the participants extensively used SC to construct the different collision models described in the previous section. SC is a programming environment that enables the design of microworlds (Smith & Cypher, 1999), and hence the building of models, even though it has not been explicitly designed to be used as a modeling tool. The architecture of SC combines two technologies, *programming by demonstration* and *visual before-after rules*, and therefore it eliminates the need for any syntactic language during program construction (Smith, Cypher, & Tesler, 2000). To demonstrate a rule, the user presses the create-a-rule button and then selects the character being programmed. Immediately, the Rule Maker window opens with the character shown in its current state. The user then enacts the behaviour s/he wishes to set for this character, for example dragging the character to a new position. From a programming perspective, this type of rule construction is translated to a script which is monitored and modelled by the program, and this script can be performed by the program when the criteria of its original design are met. Figure 7 shows the creation of a rule in SC.

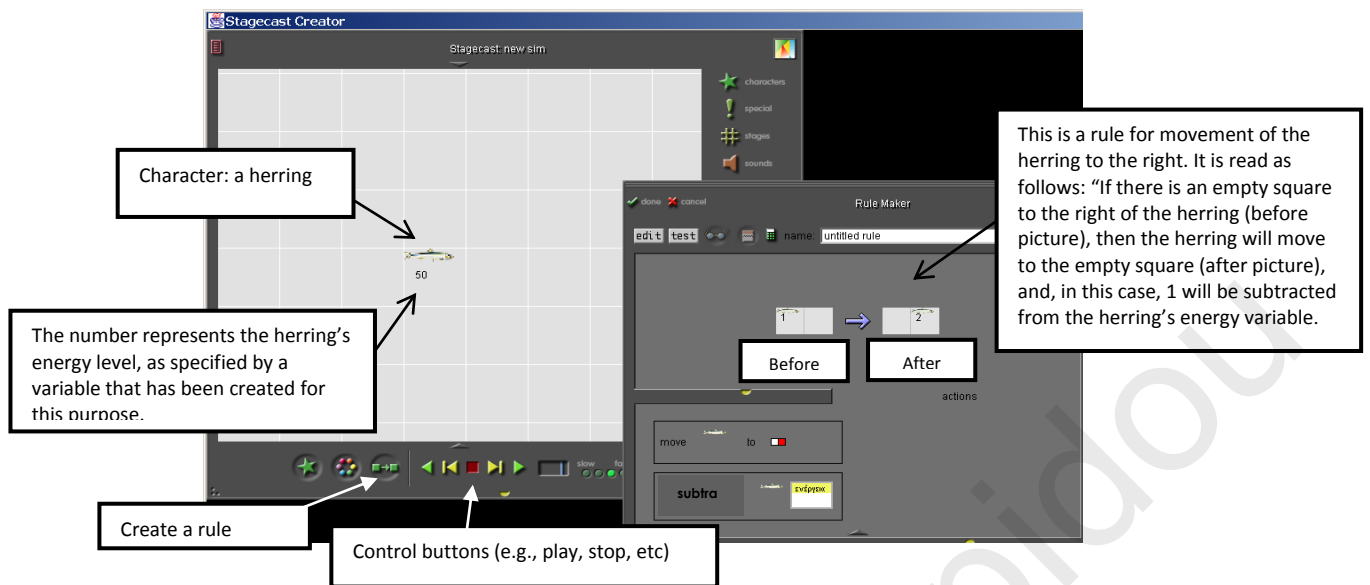


Figure 7. A move to the right rule for a herring character in Stagecast Creator

The rule in Figure 7 is executed by pressing the “play” button and will continue to be executed unless the presupposition “if there is an empty square to the right” is violated. If this character encounters another character to its right, the rule will stop being executed and the program will look for another rule that satisfies the new precondition of neighboring characters in order to set the character’s behavior in this case.

Another important characteristic of SC is its use of variables. A variable in SC is useful when it is implemented in the creation of a rule either in association with or to control a specific action. In the example in Figure 3, the user has already created a variable for the herring character which she named as “energy”. In creating the move-to-the-right rule, she specified that anytime this character moves one square to the right, one unit of energy will be subtracted from its energy variable.

### 3.3. Data collection

For the purposes of this study, eight different sources of data were collected: (a) teachers’ responses in the two modeling ability tests; (b) teachers’ responses to the CK test; (c) teachers’ responses to the CuK test; (d) teachers’ assignments; (e) reflective diaries; (f) peer evaluation and comments of uploaded models in BeEP; (g) asynchronous discussions in BeEP; and (h) teachers’ modeling-centered curriculum design projects. Table 2 below

presents the relations among the sources of data and the research questions, followed by detailed descriptions of each data source.

Table 2. Relation of research questions and data collection tools

Research questions	Data collection
1. How does teachers' modeling ability compare prior to and after their participation in the PDC?	Modeling ability tests A and B (all pre- and post-): <ul style="list-style-type: none"> <li>• Modeling skills (5x2 tests)</li> <li>• Meta-modeling knowledge (2x2 tests)</li> <li>• Metacognitive knowledge (1x2 tests)</li> </ul>
2. How do teachers' CK about models and modeling and CuK for MCSI change as a result of their participation in the PDC?	Content Knowledge test (CK test) Curricular Knowledge test (CuK test) Reflective diaries (after every meeting) Asynchronous discussions in BeEP on issues revealed from the reflective journals or classroom discussions/observations Assignment: <i>Selection of a teaching unit from the national curriculum and explain the rationale behind the selection</i> Assignment: <i>Identification of the modeling ability components in the Modeling 1-D Elastic Collisions Curriculum</i> Assignment: <i>Identification of the objectives of each of the administered modeling ability assessment tasks</i> Assignment: <i>Identification of the modeling ability components in the Modeling Marine Ecosystems Curriculum</i> Assignment: <i>Evaluation of the Modeling Marine Ecosystems Curriculum according to the level of promotion of the modeling ability components</i> Assignment: <i>Reflection on the modeling ability framework – what I knew prior to reading the paper about the modeling ability framework and what I learned after reading it about models, scientific modeling, and the components of the modeling ability of learners</i>
3. What are the characteristics of teachers' modeling-centered curriculum designs?	Modeling-centered Curriculum Design Projects

### 3.3.1. Modeling ability tests

Each component of the modeling ability framework (see Table 1 in Chapter 2 for details) was evaluated through a set of two assessment tasks (see Table 3 below). Both assessment tasks for each modeling ability component had the same structure. They consisted of a scenario and open-ended questions. Both the scenarios and the questions were comprised of short and simple statements. The assessment tasks were grouped in two different tests, Test A (see Appendix II) and Test B (see Appendix III), in a way that each modeling ability component was evaluated by one task. The purpose for designing and administering two tasks for each of the components of the modeling ability framework was to explore whether modeling ability is *content dependent* or not. I claimed that if

modeling ability is content independent, then teachers' performance in each of the assessment tasks that evaluate the same modeling ability component would be equivalent.

Table 3. Modeling ability assessment tasks

Component of the modeling ability	Context of the Assessment Task
<u>I. Modeling skills</u>	
A. <i>Model formulation</i>	A1. Horizontal projectile and free fall A2. Cubic expansion
B. <i>Identification of model components</i>	B1. Image formation in the eye model B2. Soccer game model
C. <i>Comparing and contrasting models of the same phenomenon</i>	C1. Substance dilution models C2. Simple electric circuit models
D. <i>Model evaluation and formulating ideas for improvement</i>	D1. Spinning wheel motion model D2. Seeds growth model
E. <i>Model validation through comparison with phenomena of the same class</i>	E1. Sinking-floating model E2. Refraction model
<u>II. Metacognitive knowledge</u>	
	F1. Moon phases F2. Water cycle
<u>III. Meta-modeling knowledge</u>	
G. <i>Nature of models</i>	G1. Color vision G2. Cell division
H. <i>Purpose or utility of models</i>	H1. Color vision H2. Cell division

To ensure the *construct validity* (Nonda et al., 2000) of the designed assessment tasks, an examination of the *content validity*, *face validity*, and *translational validity* was undertaken. These three types of validity that are thought to shape the construct validity, according to Sampson & Clark (2006), of the designed assessment tasks are presented below.

- (a) *Content validity*: This type of validity measures if the constructs in the assessment tasks are well defined and based on a theoretical framework. The constructs in the assessment tests are associated with modeling ability (modeling skills, metacognitive knowledge about the modeling process, meta-modeling knowledge). In order to define the constructs, the modeling ability framework that was designed for the purposes of this study was used. It is argued that the constructs are based on a sound theoretical framework (that is discussed in detail in Chapter 2) and hence the assessment tasks are valid in terms of content validity.

- (b) *Face validity*: This type of validity measures if the participants ascribe the same meaning to the items as the researchers do. For the purposes of the current study, six teachers who participated in a previous implementation of a similar PDC that was grounded on the premises of scientific modeling were interviewed to verify if they understood the assessment tasks as intended.
- (c) *Translational validity*: This type of validity measures if the constructs are accurately translated into operational items based on expert opinion. For this part, two experts in modeling read the assessment tasks to see if the items were articulated in a way that accurately reflects the theoretical constructs.

The modeling ability assessment tasks were refined based on the abovementioned validity tests and were administered within Test A and Test B at the beginning and the end of Phase 1 (*The Teachers as Learners*, see Figure 6) of the study. Each of the tests were administered separately within one week interval.

### **3.3.2. Content Knowledge test (CK test)**

The CK test encompassed several open-ended questions through which elements of teachers' CK about models and modeling were evaluated. These elements are presented in Table 4 and are accompanied by representative questions that were incorporated in the CK test. Both the conceptualization of the elements that constitute teachers' CK about models and modeling, as well as the content of the questions that were incorporated in the CK test, were informed by the work of Grosslight et al. (1991), Crawford and Cullin (2004), Justi and van Driel (2005) and Henze et al. (2008).

To ensure the construct validity (Nonda et al., 2000) of the questions of the CK test, the same methodology that was followed for the modeling ability tests to examine the content validity, face validity, and translational validity was followed.

The CK test was administered to the participants at the beginning and the end of Phase 1 (*Teachers as Learners*, see Figure 6) during the 1st and the 8th Meeting respectively. The purposes of this test were to establish a baseline of teachers' CK about models and modeling (pretest), and to elucidate areas of teachers' understanding and confusion following instruction on MCSI (posttest).



Table 4. Elements of teachers' CK and their evaluation through the CK test

CK element	Examples of questions from the CK test
Content knowledge about	
<i>a. Models</i>	<ul style="list-style-type: none"> <li>• In natural sciences, what does the term “model” refer to?</li> <li>• Can there be different models that represent the same phenomenon? Explain.</li> <li>• Do models represent the “absolute” reality? Explain.</li> <li>• What criteria are used for evaluating a model?</li> </ul>
<i>b. Modeling</i>	<ul style="list-style-type: none"> <li>• In natural sciences, what does the term “modeling” refer to?</li> <li>• What is the process that is followed for creating a model in Natural Sciences? Make a diagram to represent the steps of this process.</li> <li>• Does the term “modeling” refer to an <i>ability that can be developed</i>, a <i>scientific enterprise</i> or an <i>instructional approach</i>? Explain.</li> </ul>

### 3.3.3. Curricular Knowledge test (CuK test)

The CuK test shared the same format as the CK test. It entailed several open-ended questions through which elements of teachers' CuK for MCSI were evaluated. These elements are presented in Table 5, in conjunction with representative questions that were incorporated in the CuK test. Both the conceptualization of the elements that constitute teachers' CuK for MCSI, as well as the content of the questions that were incorporated in the CuK test were informed by the work of Justi and van Driel (2005) and Henze et al. (2008).

To ensure the construct validity (Nonda et al., 2000) of the questions of the CuK test, the same methodology that was followed for the modeling ability tests to examine the content validity, face validity, and translational validity was followed.

The CuK test was administered to the participants at the beginning and the end of Phase 1 (The Teachers as Learners, see Figure 6) during the 1st and the 8th Meeting respectively. The purposes of this test were to establish a baseline of teachers' CuK for MCSI (pretest) and to elucidate areas of teachers' understanding and confusion following instruction on MCSI (posttest).

Table 5. Elements of teachers' CuK and their evaluation through the CuK test

CuK element	Examples of questions from the CuK test
Curricular knowledge about	
a. <i>the development of modeling ability of learners</i>	<ul style="list-style-type: none"> <li>• What type of activities a science teaching unit should entail if its focus is on the development of the modeling ability of learners?</li> <li>• Are there any science teaching units that are more suitable than others to be used for the development of modeling ability of learners? If your response is positive, please provide examples of such teaching units and explain why you choose these units as exemplars for the development of learners' modeling ability. If your response is negative, please explain why the development of learners' modeling ability could be fostered through any science unit of science curriculum.</li> </ul>
b. <i>the assessment of learners' development of modeling ability</i>	<ul style="list-style-type: none"> <li>• If you are willing to design assessment tasks to evaluate students' modeling ability, what would be the objective of each task?</li> </ul>

### 3.3.4. Assignments

Several assignments were administered to the participants throughout the course through which the development of their CuK was monitored and evaluated. The themes of these assignments are provided below.

- *Selection of a teaching unit from the national curriculum and explain the rationale behind the selection*
- *Identification of the modeling ability components in the Modeling 1-D Elastic Collisions Curriculum*
- *Identification of the objectives of each of the administered modeling ability assessment tasks*
- *Identification of the modeling ability components in the Modeling Marine Ecosystems Curriculum*
- *Evaluation of the Modeling Marine Ecosystems Curriculum according to the level of promotion of the modeling ability components*
- *Reflection on the modeling ability framework – what I knew prior to reading the paper about the modeling ability framework and what I learned after reading it about models, scientific modeling, and the components of the modeling ability of learners*

### 3.3.5. Reflective diaries and journal report

Following the recommendations provided by Justi and van Driel (2005) that during their participation in professional development settings, teachers should be "...provided with

opportunities to analyze their new experiences and to reflect on their own development” (p. 568) and that “...researchers should mediate the teachers’ reflection processes at distinct points of time...[through] providing teachers with both new elements and different perspectives to support a deeper analysis of their practice” (p.570), teachers’ development of knowledge bases in this study were captured via frequent reflective diaries that were prepared at distinct points of time throughout the course. For the purposes of this study, the participants prepared 5 reflective diaries during the “Teachers as Learners” phase (see Figure 6), one after every meeting. The reflective diaries encompassed questions that appeared on a permanent basis (e.g., “What did you learn in this lesson about modeling? Do you feel that you have learned something new? If your response is yes, what did you learn?”), and themes that emerged from classroom observations, discussions between the pairs of teachers working together to complete the activity sheets or during their work in Stagecast Creator, teachers’ reflections in previously submitted reflective journals, and so on.

The format, as well as, the questions and prompts of the reflective diaries were prepared by the instructor and uploaded in the BeEP one day after each meeting. The teachers had one week ahead to complete them and upload them back in the BeEP.

### **3.3.6. Peer evaluation and comments of uploaded models in BeEP**

As shown in Figure 6, teachers working in pairs created five models in SC for each of the five 1-D elastic collision phenomena that studied during the PDC. As soon as a model was finalized, one member from every pair uploaded in the BeEP his/her pair’s final model and another pair of teachers (assigned by the instructor) evaluated their peers’ model according to their own criteria or criteria for model evaluation that emerged from the activities of the 1-D elastic collisions curriculum. Their evaluation, as well as comments, questions, suggestions or reservations related to their peers’ model were uploaded in BeEP and the receiving pair was obliged to respond to their peer’s evaluation. After their peers’ evaluation and comments, the receiving pair was free to proceed in modifying and improving their model in a way that fulfilled their peers’ evaluation and comments. The teachers were encouraged to remain engaged with this task until they reached a consensus about the quality of their models.

The abovementioned procedure was followed for each of the uploaded models of all pairs. For every iteration, the instructor explicitly assigned which two pairs would collaborate with.

### **3.3.7. Asynchronous discussions in BeEP**

During teachers' engagement with the curriculum materials (e.g., completion of activity sheets, group discussions and whole class discussions, construction of models in Stagecast Creator, teachers' reflective journals, etc) several issues were revealed about teachers' evolved CK about models and modeling, possible difficulties while engaging with the curriculum materials, and the ways they responded to specific tasks throughout the course. In order to help teachers resolve these issues in a way that they, as members of a community of learners, would have the opportunity to collaboratively share, negotiate and discuss their ongoing understandings and knowledge growth, these issues were transformed in topics for asynchronous discussion in BeEP. The teachers were asked to (i) respond to these topics by expressing their views and (ii) comment, agree or disagree, ask for clarifications, pose new questions, etc. based on their peers' responses.

An example of a topic emerged from teachers' reflective diaries and was used as a discussion topic in the BeEP discussion forum appears in Figure 15 in the Findings Chapter.

### **3.3.8. Modeling-centered Curriculum Design Projects**

At the beginning of the course, the participants were informed that, as part of the requirements for completing the course, they needed to undertake a project which would focus on modeling-based curriculum design, but more specific details for this requirement were by the end of Phase 1 (*Teachers as Learners*). During Meeting 8<sup>th</sup> (see Figure 6) the instructor recalled the requirements for the curriculum design project, explained the rationale for undertaking this project and provided details about the structure and the deliverables of the project. Specifically, teachers' MCSI curriculum designs encompassed the following:

1. Selection of a teaching unit and describe the rationale behind this selection.
2. Formulation of learning objectives.
3. Mapping the activity sequence.

4. Design and detailed description of the activities proposed in the activity sequence section.
5. Design of activity sheets.
6. Design of assessment tasks.
7. Models in SC that are expected to be developed by the students in a possible future implementation.

The purpose of this project-based assignment (as one of the requirements of the course) was to provide teachers with the opportunity to transform their experiences, knowledge, and skills that were expected to gain throughout the course while redesigning the selected teaching unit from the national curriculum to make it fit with the principles of the MSCl. Another anticipated outcome of this project, was to shed light on teachers' efforts to design curriculum materials through which learners' modeling ability would be fostered and assessed. Hence, teachers' MCSl curriculum designs served as a transparent prism through which transformations of their modeling ability, CK about models and modeling, and Cuk for MCSl were investigated.

### **3.4. Methods of analysis**

In this section, the methods and methodology that were applied in order to answer each research question are presented.

#### **3.4.1. Research question 1: How does teachers' modeling ability compare prior to and after their participation in the PDC?**

In order to address this research question teachers' responses that were obtained through the assessment tasks of the modeling ability tests (Test A and Test B) were analyzed using phenomenography (Marton & Booth, 1997). To illustrate how this method of analysis was undertaken, I present below the process of analysis for the assessment tasks that pertain to the identification of model components skill, as a typical example of the analysis that was followed for all the assessment tasks of the modeling ability tests.

To begin with, all responses that were collected from the first assessment task that evaluates teachers' identification of model components skill were transcribed and grouped into a word processing document to de-contextualize them, followed by printing the group

of responses as an unsorted list. The researcher subsequently read through the entire list of responses three times and began to create emergent categories while reading the list a fourth time. In doing so, the researcher examined and re-examined teachers' ideas illuminated within their responses, searching for similarities, consistencies and differences, while simultaneously attempting to categorize the ideas that appeared to be grounded on a common conceptual pattern, in distinct "qualitatively different" categories. These categories, as asserted by Eklund-Myrskog (1998) and Tsai (2004), correspond to the different ways that individuals conceive of the same phenomenon (here the identification of model components skill), and reflect on the different perspectives in which this particular phenomenon was conceptualized or experienced. It is also important to emphasize that in a phenomenographic analysis, similarities and differences are considered across categories, rather than within individuals' responses (Marton and Booth 1997).

As soon as the first round of categorizing teachers' responses into a cluster of qualitatively different categories was completed, the researcher reviewed the second list of teachers' responses that emerged from the second assessment task through which the same modeling component skill was evaluated, and expanded the initial cluster of categories by informing it with new categories that were revealed from the second list of responses. The researcher then evaluated the representativeness of each category while incorporating new category names and discarding those no longer deemed representative, and adhered on this continuous and iterative process until a parsimonious listing of conceptions representing the diversity of data set emerged.

The aforementioned procedure was followed for each set of the assessment tasks that evaluate the same component of the modeling ability framework, and eight different lists of hierarchically ordered categories of responses were formulated based on the components of the modeling ability framework (e.g. five modeling skills, two types of meta-modeling knowledge, and metacognitive knowledge about the modeling process). The hierarchy of the resulting categories for each of the modeling ability component increased from top to bottom, indicating that each subsequent category was superior to the preceding categories. In addition, the prevalence for each one of the resulting categories for each modeling ability component was calculated. The purpose of the latter was to compare if the prevalence of each category of participants' ideas differed prior to and after the study.

To assess the reliability of the defined categories, two coders independently were given the lists of the categories for each of the components of the modeling ability framework, and were asked to classify the responses provided by  $\frac{1}{4}$  of the participants into the defined categories of the lists. The two coders initially agreed on 83% of the codings, while a total of 10% of the responses on different items were not found to be coded to any of the defined categories. The disagreements between the two coders were resolved through discussion with the researcher, while the ungrouped responses enabled either the revision of the description of the concerned categories or the formulation of new categories. After these inter-rater disagreement issues were resolved, the two coders went through a new sample of assessment items provided by another  $\frac{1}{4}$  of the participants, and the final agreement based on the revised catalogues was 96%. Finally, the frequency of the teachers that were classified in each of the categories of the eight lists was calculated both for the pre- and post-test tasks, and therefore comparable pre- and post- results were obtained.

Quantitative analyses were followed after the phenomenographic analysis of teachers' responses in all assessment tasks in an attempt to answer the following questions: (i) *How does teachers' modeling ability prior to and after the PDC compare?* and (ii) *How does teachers' performance between the assessment tasks that evaluated the same aspect of the modeling ability framework prior to and after the PDC compare?* The analysis of the data followed non-parametric quantitative analyses due to the small sample. Specifically, it involved two Wilcoxon tests for the comparison of the pre-test scores to their corresponding post-test scores, one for Modeling Ability Test A and one for Modeling Ability Test B. These tests were used to compare if the differences that might have yielded from comparing the scores of the pre- and post- Modeling Ability Test A and pre- and post- Modeling Ability Test B were significant. Wilcoxon tests were also used for the comparison of the pre-test scores between Modeling Ability Test A and Modeling Ability Test B, and the comparison of the post-test scores between Modeling Ability Test A and Modeling Ability Test B. The latter tests were used to compare if teachers' performance between the assessment tasks that evaluated the same aspect of the modeling ability framework prior to and after the PDC was equal or not.

### 3.4.2. Research question 2: How do teachers' CK about models and modeling and CuK for MCSI change as a result of their participation in the PDC?

For the second research question ‘*How do teachers' CK about models and modeling and CuK for MCSI change as a result of their participation in the PDC?*’ data were collected through the use of various means. All data collection instruments related to teachers CK about models and modeling, and CuK for MCSI, in conjunction with the rationale behind their design and administration during the course, are provided in Table 6. The continuum of the administration of all data collection instruments along the two phases of the PDC is presented in Figure 8.

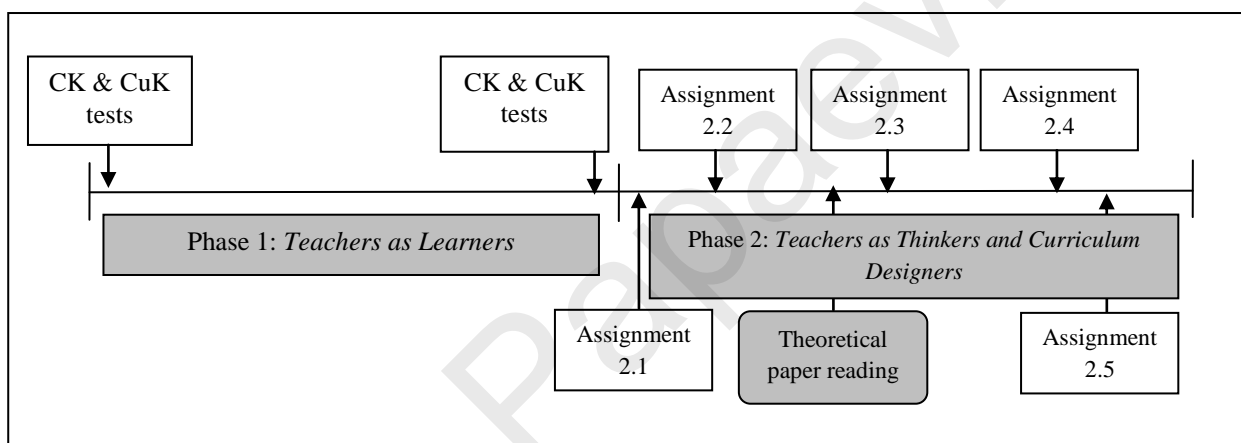


Figure 8. Continuum of the administration of the data collection instruments along the two phases of the PDC

The rationale for collecting multiple sources of data for evaluating teachers' CK about models and modeling, and CuK for MCSI is in line with the stance made by Magnusson et al. (1999) that the use of multiple data sources enables a very powerful way for better analyzing and monitoring the teachers' knowledge changes. In addition, the use of multiple data sources during different phases of the present research ensure its interval validity. The data that were obtained from the abovementioned data sources were analyzed using “grounded theory” methods (Glaser, 1978; Glaser and Strauss, 1967; Strauss, 1987; Strauss & Corbin, 1990; Creswell, 1998). Grounded theory methods involved focusing on a specific area of study, collecting many types of data from a variety of sources, and



systematically analyzing that data using coding and other types of analysis which results is the emergence of a theory. *Grounded theory coding*, according to Charmaz (2006),

*“...requires us to stop and ask analytic questions of the data we have gathered. These questions not only further our understanding of studied life but also help us direct subsequent data-gathering toward the analytic issues we are defining. Grounded theory coding consists of at least two phases: initial and focused coding. During initial coding we study fragments of data – words, lines, segments, and incidents – closely for their analytic import. From time to time, we may adopt our participants’ telling terms as in vivo codes. While engaging in focused coding, we select what seem to be the most useful initial coded and test them against extensive data. Throughout the process, we compare data with data and then data with codes. We may follow special procedures to elaborate our codes or move to extant theoretical codes but only if indicated by our emerging analysis. Signposts and guides make our sojourn with coding accessible and ease our way around obstacles” (p. 42)*

Table 6. Data collection instruments for assessing teachers' CK and CuK throughout the PDC

Type of knowledge	Data collection instrument	Description	Rationale
Content Knowledge (CK)	CK test	<i>Content Knowledge</i> about models and modeling	To evaluate teachers' development of content knowledge about the <ul style="list-style-type: none"> <li>• nature of models</li> <li>• models' relation with absolute reality</li> <li>• possible existence of candidate models to represent the same phenomenon</li> <li>• criteria for evaluating scientific models</li> </ul>
	Reflective diaries	Reflection on the modeling and other learning experiences throughout the course (completed after every session)	To complement the evaluation of teachers' CK with respect to the <ul style="list-style-type: none"> <li>• nature of models</li> <li>• models' relation with absolute reality</li> <li>• possible existence of candidate models to represent the same phenomenon</li> <li>• criteria for evaluating scientific models</li> </ul>
	Peer evaluation of models	Individual evaluation of a model created by a pair of teachers	To complement the evaluation of teachers' CK with respect to the <ul style="list-style-type: none"> <li>• nature of models</li> <li>• models' relation with absolute reality</li> <li>• possible existence of candidate models to represent the same phenomenon</li> <li>• criteria for evaluating scientific models</li> </ul>
	Asynchronous discussions in BeEP	Asynchronous discussions in BeEP on issues revealed from the reflective journals or classroom discussions/observations	To complement the evaluation of teachers' CK with respect to the <ul style="list-style-type: none"> <li>• nature of models</li> <li>• models' relation with absolute reality</li> <li>• possible existence of candidate models to represent the same phenomenon</li> <li>• criteria for evaluating scientific models</li> </ul>
Curricular knowledge (CuK)	CuK test	<i>Curricular knowledge</i> about the activities that are used within a MSCI curriculum that aim to help learners develop their modeling ability and the objectives of assessment tasks that are used for this purpose.	To evaluate teachers' development of Curricular knowledge about the activities that are used within a MSCI curriculum that aim to help learners develop their modeling ability and the objectives of assessment tasks that are used for this purpose.
	Assignments	2.1. Identification of the objectives of each of the modeling ability assessment tasks that were completed during Phase 1  2.2. Identification of the elements of the MCSI approach and the aspects of the modeling ability framework that were used	To investigate if teachers, after completing the modeling ability post-assessment tasks, are able to identify the objectives behind each assessment task.  To investigate if teachers' engagement with the curriculum during Phase 1 of the PDC enabled them to identify the elements of the MCSI approach and

for the design of the “Modeling 1-D Elastic Collisions” Curriculum

2.3. Identification of the modeling ability components in the Modeling Marine Ecosystems Curriculum and evaluation of the Modeling Marine Ecosystems Curriculum according to the level of promotion of the modeling ability components

2.4. Identification of the objectives of new modeling ability assessment tasks

2.5. Selection of a teaching unit from the national curriculum and explain the rationale behind the selection

the aspects of the modeling ability framework without receiving explicit instruction on these issues.

To evaluate teachers’ ability to transfer the theoretical underpinnings of the modeling ability framework they came up with from a theoretical paper they read for the identification of the modeling ability components in a new MCSI curriculum and the evaluation of this curriculum according to the level of promotion of the modeling ability components.

To evaluate teachers’ ability to transfer the theoretical underpinnings of the modeling ability framework they came up with from a theoretical paper they read for the identification of the objectives of new modeling ability assessment tasks.

To get insight into the criteria that teachers use and apply when selecting a teaching unit from the national curriculum that they would later reconstruct using MCSI as an instructional approach.

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In the present thesis, all data sources that were collected for the study of teachers' CK and CuK were in the form of *elicited* texts (Charmaz, 2006). Elicited texts, according to Charmaz, "involve research participants in producing written data in response to researcher's request and thus offer a means of generating data" (p. 35). Consequently, *open coding* was used to analyze teachers' responses in the CK and CuK tests respectively (both as a pre- and a post- test), as this was supposed to be the primary data sources for directly characterizing teachers' CK about models and modeling and CuK for MCSI. In doing so, the written responses of teachers in the CK and CuK tests were reviewed, one by one, to characterize each participant's CK and CuK, as opposed to looking across the data from other data sources for similar themes. In addition, specific themes were identified and constantly compared (Glaser & Strauss, 1967), and questions were asked on these emerging themes that led to *tentative* conceptualization of the data. In the next stage, that is the *axial coding*, the emerging conceptualizations were reconsidered together in an attempt to construct central categories based on the subcategories. It was at this stage that an attempt was made to determine how the subcategories identified in open categories fit together. As soon as central categories were determined, the process of selective coding began. In this stage, the central categories were integrated to form a description of the central phenomenon identified in the study (that is teachers' CK about models and modeling and CuK for MCSI and how teachers' CK and CuK changed or not as a result of their participation in the PDC). Finally, the issue of trustworthiness was addressed by means of triangulation and peer review. Specifically, 30% of the artifacts (e.g., teachers' responses in the CK and CuK tests, reflective diaries, peer evaluations of models, asynchronous discussions in the BeEP) were coded by another researcher, with an initial agreement of 81% that reached 98% after discussing the coding categories with the second researcher.

### **3.4.3. Research question 3: What are the characteristics of teachers' modeling-centered curriculum designs?**

To answer the third research question that pertains on the exploration of the characteristics of teachers' modeling-centered curriculum designs, the modeling curriculum designs that teachers prepared by the end of Phase 2 were used, and grounded theory methods (Glaser, 1978; Glaser and Strauss, 1967; Strauss, 1987; Strauss and Corbin, 1990; Creswell, 1998; Charmaz, 2006) were followed for their analysis. Specifically, my main focus during the analysis was on the content and the structure of the activities that teachers encompassed within their curriculum designs, while at the same time I attempted to identify possible

links between these activities and the modeling ability framework that the teachers were already familiar with during Phase 2. During the analysis, I tried to be “critical” by asking *myself* questions about my data. These questions, according to Charmaz (2006), are essential during open coding, as they help the researcher to “see actions and to identify significant processes (p. 51). Some *a priori* questions that guided the analysis were as follows:

- What types of learning objectives do teachers define and are willing to promote through their activities?
- How consistent are their learning objectives with their activities?
- What types of modeling activities do teachers incorporate in their curriculum design?
- What are the type and nature of the models that would be created by the learners who will receive teachers’ curriculum materials?
- What types of assessment tasks do teachers design to assess their learning objectives and how are these consistent with the activities that they incorporated in their curriculum designs?

Although codes were developed *in vivo*, using the participants own language within their curriculum materials, other codes were developed with insight from previous literature. For example, Magnusson et al.’s (1999) teaching orientations and Schwarz’s and Gwekwerere’s (2006) modifications on Magnusson et al.’s teaching orientations that pertain to several teaching approaches like didactic, activity-driven, academic rigor, project- based, conceptual change, inquiry, guided inquiry and model-centered guided inquiry were used during the data analysis. Teachers’ curriculum design orientations, as defined by Miller and Seller (1990) were also used. In addition, Schwarz’s and Gwekwerere’s (2006) classification of models (e.g., (1) causal or explanatory models, (2) models that embody patterns in data, and (3) models that embody typical examples of objects or phenomena) also aided the analysis of data.

Interrater reliability data were collected for this analysis as well. Specifically, two independent coders assessed 40% of the data (e.g., the curriculum materials of 8 teachers) and the proportion of agreement was calculated. The two coders initially agreed on 90% of the codings. The disagreements between the two coders were resolved through discussion with the researcher.

## CHAPTER 4: FINDINGS

### 4.2. Research question 1: How does teachers' modeling ability compare prior to and after their participation in a strategically designed PDC?

For answering this question, both qualitative (phenomenography) and quantitative (Wilcoxon test) analyses were followed. Firstly, the findings that were revealed from the phenomenographic analysis of the data collected for answering the research question are presented in three sub-sections, according to the three constituent components of the modeling ability framework (modeling skills, metacognitive knowledge about the modeling process, and meta-modeling knowledge). Each sub-section includes the levels that emerged from the phenomenographic analysis of teachers' responses to the sixteen modeling assessment tasks administered prior to and after Phase 1 of the PDC, and teachers' distribution across the emerged levels prior to and after to the PDC. To facilitate the presentation of the findings in each sub-section, a brief description of the corresponding assessment tasks (see Table 3 for further details) is provided. The actual assessment tasks appear in Appendices II and III respectively. Where appropriate, the evaluation criteria that were defined for the analysis of students' responses are also presented.

Secondly, the findings from the quantitative analysis that made use of the Wilcoxon test procedure are provided at the end of the qualitative findings. These findings are organized into two subsections. The first subsection focuses on the comparisons between teachers' modeling ability prior to and after the PDC for each aspect of the modeling ability framework. These findings will demonstrate if the PDC impacted on the development of teachers' modeling ability. The second subsection presents the comparisons of teachers' performance between the assessment tasks that evaluated the same aspect of their modeling ability both prior to and after the PDC. These comparisons will reveal if the aspects of the modeling ability framework are context dependent or not.

#### 4.2.1. Qualitative findings of teachers' development of modeling ability

##### 4.2.1.1. Modeling skills

The five modeling skills that were assessed through 10 assessment tasks (two isomorphic tasks per modeling skill) were as follows: (i) *model formulation skill*; (ii) *identification of*

*model components skill; (iii) comparing and contrasting models of the same phenomenon skill; (iv) model evaluation and formulating ideas for improvement skill; and (v) model validation through comparison with phenomena of the same class skill.* The presentation of the levels that emerged from the phenomenographic analysis of teachers' responses to the tasks that were used to assess each modeling skill, in conjunction with the prevalence of teachers' responses to the levels that emerged, are presented in the following subsections.

#### *4.2.1.1.1. Model formulation skill*

Teachers' model formulation skill was assessed through Assessment Tasks A1 and A2 (see Appendices II and III respectively). Both tasks had the same format and were designed in the context of physics; Assessment Task A1 was based on the context of kinematics (projectile motion), whereas Assessment Task A2 was based on the context of thermodynamics (thermal expansion). To begin with, when administering each task, the teachers had to watch a videotaped experiment. Then they were asked to make a drawing/model to represent the experiment they watched and try to explain how the experiment (or the phenomenon reproduced through the experiment) functions. They were also prompted to use verbal statements to accompany their drawings/models, if they were willing to do so, and they were also asked to identify and name the major components of their model and provide at least two specific examples for each of the identified model components.

In Assessment Task A1, the videotaped experiment referred to the case of a device that dropped two metallic balls simultaneously. One was given a horizontal velocity, while the other simply fell. As only the vertical component determined the fall time, both balls fell with the same acceleration and simultaneously impacted the table.

In Assessment Task A2, the videotaped experiment illustrated a man holding a rod with an attached metallic sphere at the end that could slip through a metallic ring at normal room temperature. Next, the man heated the sphere separately for a few minutes and when attempted to insert the sphere through the ring again, the sphere got stuck, because the sphere expanded in the radial direction.

Apart from creating paper-and-pencil models when the abovementioned assessment tasks were administered after the PDC, the teachers were also asked to develop their models in SC. The purpose behind asking teachers to perform this additional task was to enable them

to create a more dynamic model with the use of SC, since they were constrained for doing this during creating their models in paper. Prior to the PDC, the teachers were not asked to use SC for creating their models, because their knowledge and skills in terms of using SC as a modeling tool were very limited.

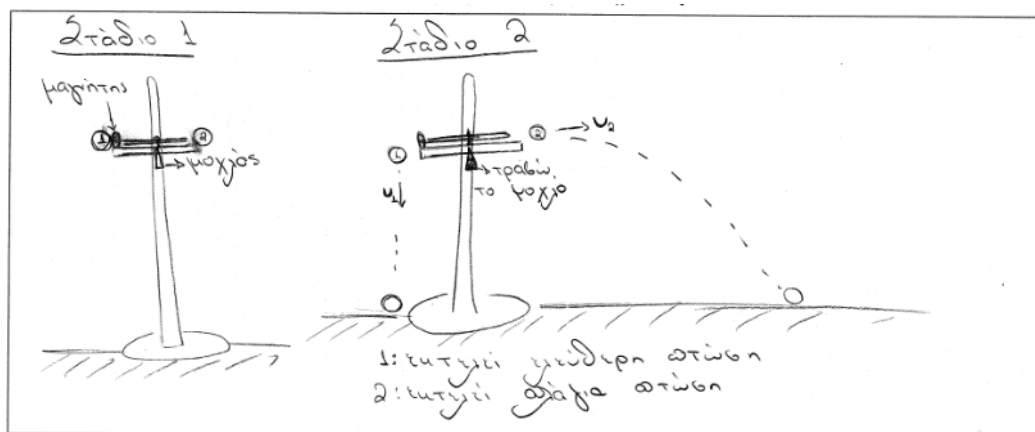
Six hierarchical levels with increased sophistication that illuminate the degree of teachers' development of the model formulation skill were revealed from the analysis of the teachers' models in pre- and post- Assessment Tasks A1 and A2. These levels are presented in Table 7 and are elaborated in detail henceforward.

Table 7. Model Formulation Skill: Emerged Levels' Description

Levels of model formulation skill	Level description
Level 1	The model provides a <i>superficial representation</i> of the phenomenon (e.g., most of the components of the phenomenon are missing) and lacks <i>interpretive potential</i> and <i>predictive power</i>
Level 2	The model provides a <i>moderate representation</i> of the phenomenon (e.g., only a few examples of the components of the phenomenon are represented) and lacks <i>interpretive potential</i> and <i>predictive power</i>
Level 3	The model (i) provides a <i>moderate representation</i> of the phenomenon (e.g., only a few examples of the components of the phenomenon are represented), (ii) encompasses a <i>mechanistic interpretation</i> for how the phenomenon functions, and (iii) lacks <i>predictive power</i>
Level 4	The model (i) provides a <i>moderate representation</i> of the phenomenon (e.g., only a few examples of the components of the phenomenon are represented), (ii) encompasses both a <i>mechanistic interpretation</i> for how the phenomenon functions and a <i>causal interpretation</i> that explains why the phenomenon functions the way it does, (ii) lacks <i>predictive power</i>
Level 5	The model (i) provides a <i>comprehensive representation</i> of the phenomenon (e.g., all types of the components of the phenomenon are represented); (ii) encompasses both a <i>mechanistic interpretation</i> for how the phenomenon functions and a <i>causal interpretation</i> that explains why the phenomenon functions the way it does; (iii) has a <i>limited predictive power</i>
Level 6	The model (i) provides a <i>comprehensive representation</i> of the phenomenon (e.g., all types of the components of the phenomenon are represented), (ii) encompasses both a <i>mechanistic interpretation</i> for how the phenomenon functions and a <i>causal interpretation</i> that explains why the phenomenon functions the way it does; (iii) has a <i>strong predictive power</i>

Level 1, which is the most inferior level that emerged, pertains to the case of models that encompass a superficial representation of the phenomenon being modeled (e.g., most of the components of the phenomenon are missing) and lack interpretive potential and predictive power. A representative example of a teacher's model is provided in Figure 9.





Να εντοπίσετε και να ονομάσετε τα βασικά συστατικά στοιχεία του μοντέλου που δημιουργήσατε στο σχέδιό σας. Για κάθε διαφορετικό στοιχείο να αναφέρετε τουλάχιστον δύο παραδείγματα από το σχέδιό σας.

Βασικά στοιχεία → ο τράβος ρίξης των σφαιρών - μαγνήτης - ελατήριο  
\* ραβδος σφίγγει

η τροχιά σου αντιστοιχεί η κάθε σφαίρα - κατακόρυφη κίνηση (σφαίρα 1)  
\* οριζωια (σφαίρα 2)

Figure 9. Level 1 of *Model Formulation Skill*: a teacher's model to represent the projectile motion of the two spheres that were presented in the videotaped experiment [Teacher #15, Prior to the PDC]

The model provided in Figure 9 shows the two stages of the experiment; stage 1 represents the initial state of the experiment, whereas stage 2 represents the trajectory that each sphere followed after released from the device. This model was classified in Level 1, because it represents only *objects* (e.g., the spheres, the device, and the table) and two of the *variables* (e.g., the velocity and the trajectory of each sphere) of the experiment. The model, as it has been represented, provides a superficial representation of the phenomenon, because it does not encompass (i) all other variables that relate with the phenomenon (e.g., time of flight of each sphere, the distance of each sphere from the table, etc), (ii) the *processes* that take place during the function of the phenomenon (e.g., processes that control the type of projectile motion of each sphere), and (iii) the interactions between model components (e.g., what are the interactions between the spheres' velocity and their time of flight?). Additionally, the model neither indicates if and how the velocity of each sphere changes after they are released from the device, nor it provides a *mechanism* to explain *how* and *why* each sphere follows the trajectory that was represented in the model. In the verbal statements that accompany the model, the teacher designates the two types of motion that the spheres follow (e.g., free fall and horizontal projectile). It also illustrates that the sphere to the right follows a parabolic trajectory and the sphere to the left follows a vertical trajectory, without identifying the factors that affect each type of motion. Finally, the model also falls short in enabling the formulation and testing of predictions (e.g., what would happen if the sphere in the right is released with half of the original velocity?)

Level 2 is superior to Level 1 in that the models which are clustered in this level embody a *moderate* representation of the phenomenon being modeled compared to the models of Level 1. For instance, the model in Figure 10 (see below) encompasses more examples of the components of the phenomenon, e.g., *objects* (the device, the two spheres, the table), *variables* (time of flight, position of each sphere during their motion, the velocity of each sphere), and *interactions* (relation of sphere's time of flight and its current position, relation of time of flight of sphere 1 and time of flight of sphere 2). Although the models in Level 2 revealed an improved representational complexity, they lacked interpretive potential and predictive power.

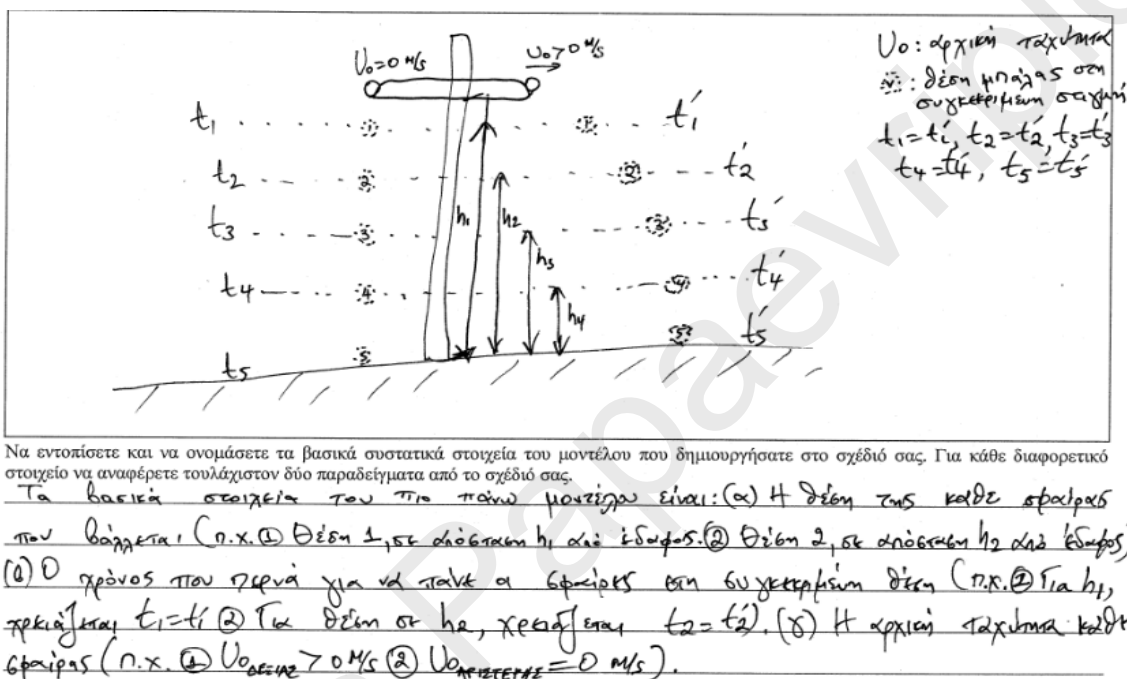
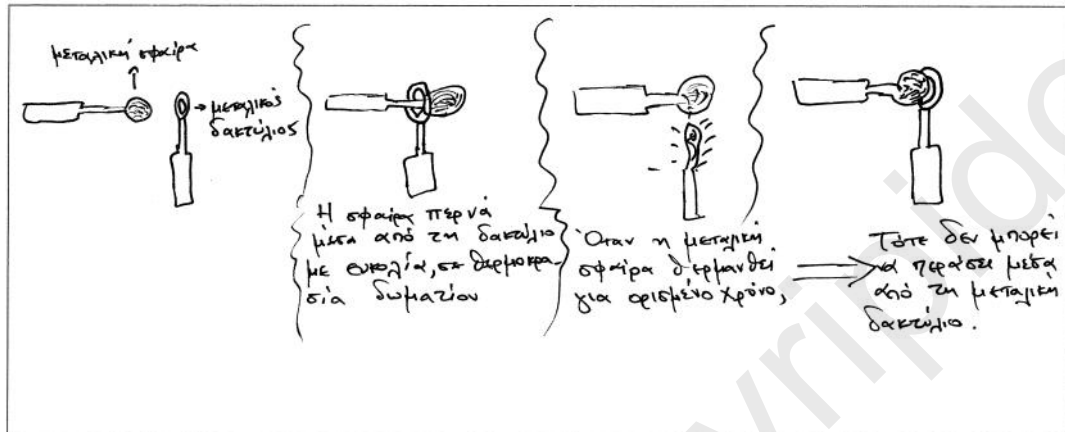


Figure 10. Level 2 of *Model Formulation Skill*: a teacher's model to represent the projectile motion of the two spheres that were illustrated in the videotaped experiment [Teacher #8, Prior to the PDC]

Level 3 entails the case of models whose representational complexity is considered as moderate (similar to those of Level 2), lack predictive power, but encompass a *mechanistic interpretation* for how the phenomenon functions. The *mechanistic interpretation* for how the phenomenon functions pertains to the description of the overall behavior of a mechanism that controls the function of the phenomenon, without providing evidence that accounts to *why* the phenomenon functions the way it does. Put differently, the mechanistic interpretation has a “phenomenological” attribute since it aims to provide only information of what a mechanism is doing and not to explain the way it produces it. In Figure 11, for example, the model that refers to the volumetric expansion of the metallic sphere entails a mechanistic interpretation that accounts for the expansion of the volume of the sphere,

since it merely describes the sequence of the events taking place during the phenomenon (e.g., the sphere is able to slip through the ring at room temperature, then it absorbs heat and expands, and thus it cannot slip again through the ring). Hence, this particular model fails to provide a causal interpretation to explain why the “internal workings” of the mechanism interact and control the behavior of the model the way they do.



Να εντοπίσετε και να ονομάσετε τα βασικά συστατικά στοιχεία του μοντέλου που δημιουργήσατε στο σχέδιό σας. Για κάθε διαφορετική πτυχή να αναφέρετε τουλάχιστον δύο παραδείγματα από το σχέδιό σας.

Τα συστατικά που γράφονται μέσα στο μοντέλο είναι η μεταλλική σφαίρα, η μεταλλική δακτύλιος και ο παροχιάς θερμότητας. Ο βασικός νόμος είναι:  $K = \rho \cdot V \cdot \Delta T$  Η θέρμανση της σφαίρας (π.χ. 1) Παράγεται θερμότητα (2) Αλλαγή θερμοκρασίας. (3) Το πάχος της σφαίρας μέσα από το δακτύλιο (π.χ. 1) Περνά (2) Δεν περνά σε θερμοκρασία δωματίου (3) Το πάχος της σφαίρας μέσα από δακτύλιο όταν κρύα θέρμανθεί (π.χ. 1) Περνά (2) Δεν περνά.

Figure 11. Level 3 of *Model Formulation Skill*: a teacher’s model to represent the volumetric expansion of a metallic sphere that was illustrated in the videotaped experiment [Teacher #8, Prior to the PDC]

Level 4 shares the same characteristics with Level 3, but is superior to Level 3 because its interpretive potential is more comprehensive. Specifically, the models of teachers that are classified in this level encompass both a *mechanistic interpretation* for *how* the phenomenon functions and a *causal interpretation* that explains *why* the phenomenon functions the way it does. To illustrate this new addition to the interpretive potential of the models of Level 4, a model from the context of thermal expansion was selected and presented in Figure 12.

The way the model in Figure 12 was represented along with the verbal statements that were provided entails a description of the overall external behavior of a mechanism that accounts to *how* the phenomenon functions (that is the mechanistic interpretation), and a causal explanation that illustrates *why* the phenomenon function the way it does (that is the causal interpretation). For instance, the mechanistic interpretation of this specific model

designates that the temperature of the sphere increases when the sphere absorbs heat from the burner and this results in the increase of its volume, whereas the causal interpretation moves beyond the external behavior of the mechanism that is evidenced during observing the phenomenon under study. It specifies the following sequence of events; when the sphere absorbs heat, its temperature increases, then the kinetic energy of its particles increases and thus particles' oscillation amplitude increases, and this results in making the volume of the sphere to expand. Although the interpretation of the thermal expansion phenomenon that derives from this model is not fully consistent with the scientific explanation from classical mechanics, it fulfills the two-part characterization of a mechanism, both from a mechanistic and a causal perspective.

Levels 5 and 6 are similar, in that they both provide a comprehensive representation of the phenomenon (e.g., all types of the components of the phenomenon are represented) and encompass both a mechanistic and a causal interpretation for the phenomenon. The difference between Level 5 and Level 6 lies on the degree of their predictive power; the models which are clustered in Level 5 have a limited predictive power, whereas the models in Level 6 present strong predictive power. Two representative models from Level 5 and Level 6 in the context of projectile motion are presented in Figure 13 and Figure 14 respectively and are discussed henceforward.

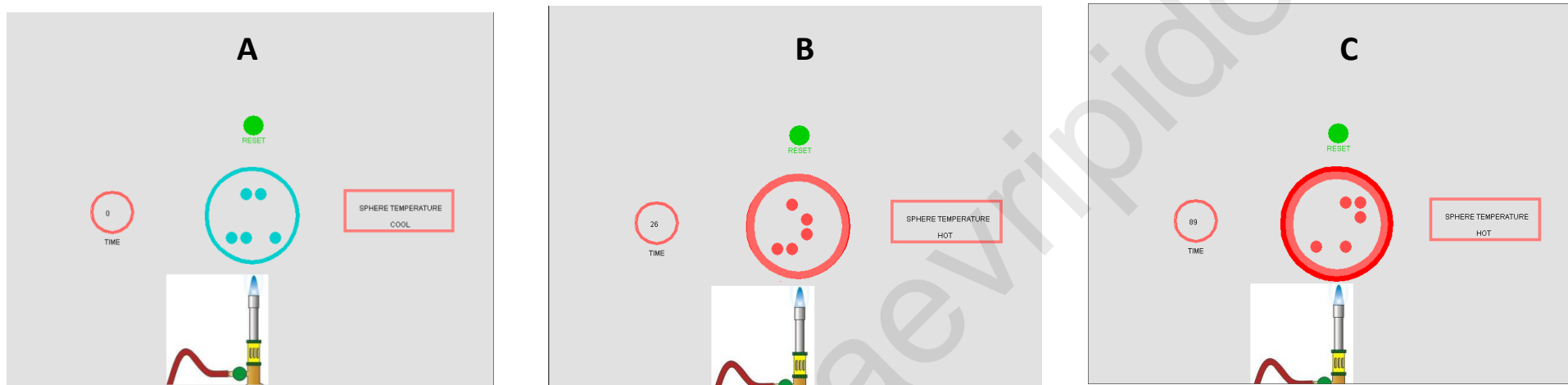


Figure 12. Level 4 of *Model Formulation Skill*: a teacher’s model in SC to represent the volumetric expansion of a metallic sphere that was illustrated in the videotaped experiment [Teacher #5, after the PDC]

Note: Figure 12 entails three screenshots that were taken from a model created in SC by a participating teacher. Screenshot A refers to the initial state of the experiment (the burner is switched off and the time is zero). Screenshot B pertains to the state which the sphere temperature goes from “cool” to “hot” because of heat transfer from the burner to the sphere and shows a small expansion of the volume of the sphere (the sphere turns from blue to red and changes size after 26 seconds). Screenshot C represents the sphere at the 89<sup>th</sup> second whose volume has expanded more than in screenshot B (the red outline of the sphere doubles in size). The dots inside the sphere designate a representative sample of the particles of the solid material of the sphere that move constantly in random directions while the model is running on the screen.

The creator of this model in SC provided some verbal statements to explain the underlying mechanism on which his model was built. These statements are as follows: *“Because the temperature of the sphere has increased, the kinetic energy of the particles has also increased and as a result, more space is needed for their motion. This is the reason why solids expand their volume when are heated, but their nature does not change. When heat is transferred to a solid material, its particles oscillate in greater amplitude and the macroscopic effect of this change results in volume expansion.”*

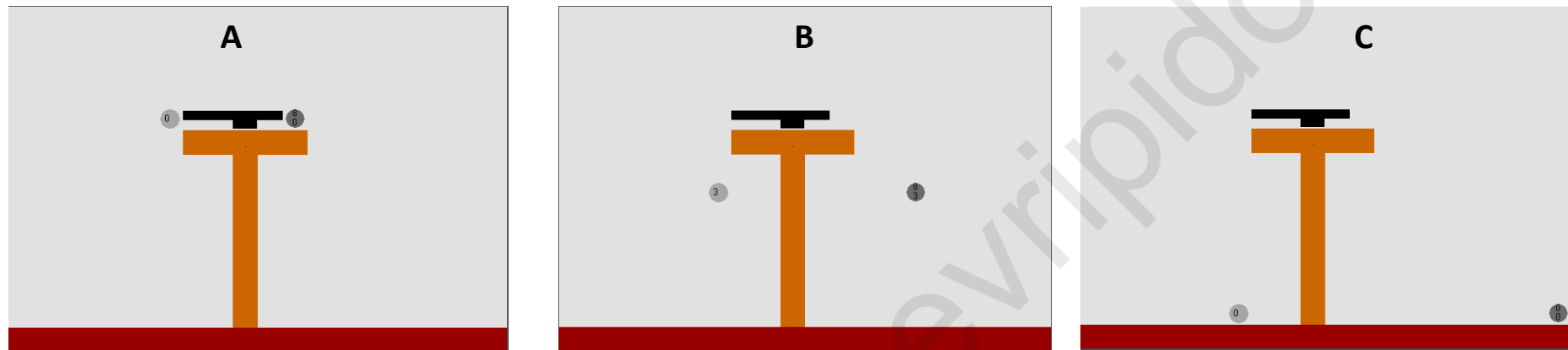


Figure 13. Level 5 of *Model Formulation Skill*: a teacher's model in SC to represent the projectile motion of two metallic spheres that was illustrated in the videotaped experiment [Teacher #12, after the PDC]

Note: Figure 13 encompasses three screenshots that were taken from a model created in SC by a participating teacher. Screenshot A refers to the initial state of the experiment (the sphere on the left is released with zero vertical velocity, whereas the sphere on the right is projected to the right with a velocity of 6 m/s). In screenshot B the two spheres appear to be on equal height above the table at the same time and both have equal vertical velocity (3 m/s). The right sphere has also a constant horizontal velocity. While the model runs, the left sphere follows a vertical direction, indicating that it is performing a free fall motion, whereas the right sphere follows a parabolic trajectory that is consistent with the projectile motion. Screenshot C relates to the end of the experiment showing the two spheres hitting the table at the same time, their vertical velocities are equal and are set to zero at the instance of the collision. The horizontal velocity of the right sphere also becomes zero at the event of the collision with the table.

The teacher who created this model accompanied his model with the following statement in order to explain the idea that he created his model around: *“The left sphere follows a free fall motion because the only force that is acting upon it is its weight because of the gravity. The free fall is an accelerated motion and thus the vertical velocity of the sphere is continually increasing until it reaches the ground. The right sphere experiences a horizontal force from the spring at the beginning of the experiment and on the vertical axis the gravity exerts a vertical force equal to the one of the left sphere. The resultant force of these two forces makes the sphere to follow a parabolic trajectory during its motion. The time of flight for each sphere is equal and both spheres' height from the ground is equal at every instant that the experiment runs. For making my model simpler, I chose to focus on the velocities that each sphere acquires and not on the forces that cause these velocities.”*

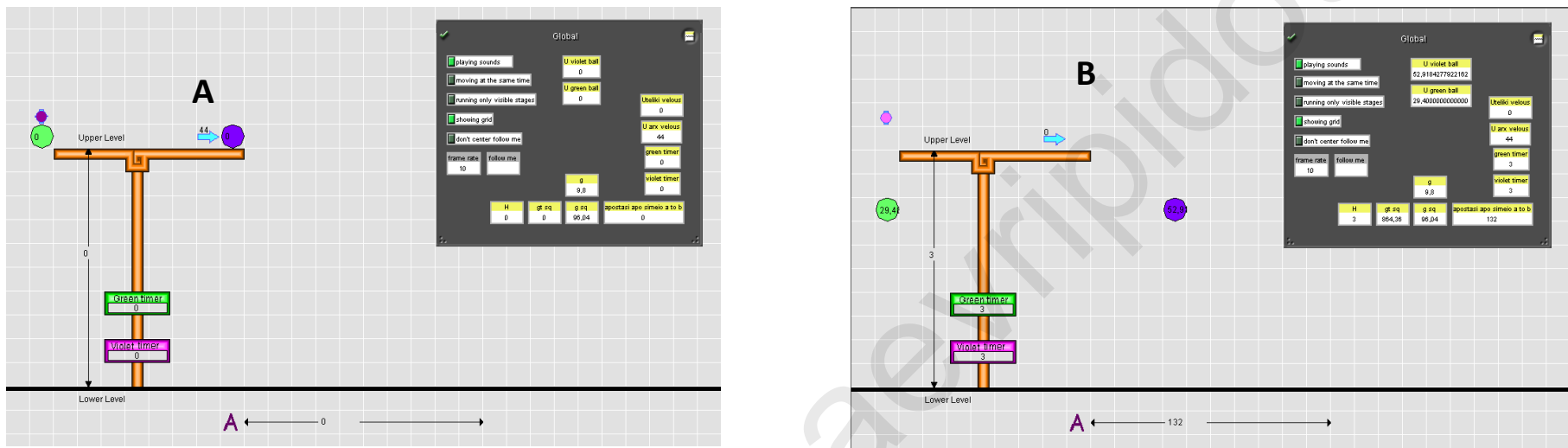


Figure 14. Level 6 of *Model Formulation Skill*: a teacher’s model in SC to represent the projectile motion of two metallic spheres that was illustrated in the videotaped experiment [Teacher #6, after the PDC]

Note: The model in Figure 14 represents in a comprehensive manner the videotaped experiment that the teachers watched. It encompasses (i) the device that holds both spheres at the beginning of the experiment; (ii) the force that is exerted at the right sphere at the beginning of the experiment; (iii) the time of flight for each sphere (see green and violet timer attached on the vertical rod of the device) that is calculated during executing the model; (iv) the resultant velocity of each sphere (see the number inside each sphere) is calculated and represented simultaneously for every second; (v) the horizontal distance that the right sphere travels (see marked area A on the right side of the device) is calculated during the time of flight of the sphere; (vi) the vertical position of each sphere (see the marked area on the left of the device) is calculated during the time of flight for both spheres (the model presents their relative vertical position which is the same during running the model). The grey box with the several rectangular boxes inside includes all variables of the model that the teacher created and used during formulating the rules for controlling the behavior of the objects of the model.

The two screenshots that appear in Figure 14 were chosen to show the model at 2 phases. Screenshot A refers to the initial state of the experiment; the green sphere is released with zero vertical velocity, whereas the purple sphere is projected to the right because a force is exerted on it (see the blue arrow at the left side of the purple sphere). In screenshot B the two spheres appear to be on equal height above the table at the same time and the number inside each sphere indicates their instantaneous velocity (the value for the instantaneous velocity for each sphere is calculated according to a formula that has been set by the teacher). While the model runs, the left sphere follows a vertical direction, indicating that it is performing a free fall motion, whereas the right sphere follows a parabolic trajectory that is consistent with the projectile motion.

The teacher also provided verbal statements similar to those used for the model in the previous level (Figure 14) that explain the mechanisms that control the behavior of each sphere.

Models like the one illustrated in Figure 13 were classified in Level 5, because they portray in an advanced way two of the three anticipated criteria that a scientific model needs to satisfy. These two criteria in conjunction with examples from the model presented in Figure 13 are discussed below.

A. *Model's representational complexity.* A model needs to represent the aspect of the phenomenon or the phenomenon itself that is of interest in way that illustrates the constituent components of the phenomenon and their relation. The model in Figure 13 encompasses:

- a. *Objects.* These are: (i) the device that holds the spheres at the beginning of the experiment; (ii) the spheres; (iii) the table
- b. *Variables.* These are (i) the velocity of each sphere (the number(s) inside each sphere); (ii) the trajectory of each sphere (it appears in a visual way while the model is running); (iii) the position of each sphere at every instant of the experiment; (iv) the horizontal displacement of each sphere (the sphere on the right moves away from the device, whereas the sphere on the left remains on the same point in the horizontal axis); and (v) the gravity force acting on each sphere and the horizontal force acting only on the right sphere.
- c. *Processes.* These are: (i) the sphere on the left is released to free fall, whereas the sphere on the right is projected with a horizontal velocity; (ii) the sphere on the left moves vertically, whereas the sphere on the right moves in a parabolic trajectory; (iii) the resultant velocity of each sphere is increasing with time and becomes zero when each sphere impacts on the table.
- d. *Interactions.* These are: (i) interactions between objects (e.g., the device with the spheres, the spheres with the table; (ii) interactions between variables (e.g., sphere's velocity with its position, sphere's velocity with the time of flight, sphere's velocity with its horizontal displacement); (iii) interactions between objects and variables (e.g., the table interacts with the velocity of each sphere at the event of their collision on it, the sphere interacts with its position, the sphere interacts with its velocity); (iv) interactions between processes (e.g., the free fall motion enables the sphere to move vertically during the time of flight, whereas the projectile motion enables the sphere to move in a parabolic trajectory during the time of flight).

B. *Model's interpretive potential.* A model needs to encompass a mechanism that helps in interpreting (or explaining) the way the phenomenon functions. Although this mechanism might not always be consistent with the up to date scientifically acceptable



conceptualization for how a phenomenon functions, it is considered essential to be embodied within a model that an individual builds, because it underlines his/her own interpretation of how a phenomenon under study functions. In addition, a model's interpretive potential is robust only if it entails both a *mechanistic* and a *causal interpretation* that account for *how* and *why* the phenomenon functions the way it is represented within the model. The model in Figure 13 encompasses both the abovementioned types of interpretations in the following ways:

- a. *Causal interpretation.* The structure of the model created in SC (e.g., the objects and variables that have been created, as well as the rules that have been formulated to control the functions and behaviors of the model) and the associated verbal statements, that provide clarification to the rationale the development of this model was grounded on, reveal that the model was built around (i) the idea of free fall that is an accelerated motion and is performed when an object is freely released from a certain height above the ground; and (ii) the idea of horizontal projectile that is a combination of a motion with constant acceleration on the vertical axis and a motion with constant velocity on the horizontal axis. Hence, by looking at the model while it is running and keeping in mind the associated verbal statements, we gain insight on the causal interpretation on which the model was built. For instance, since the sphere exhibits a free fall motion, it stays in the same horizontal position while it falls downwards towards the ground, and its velocity is continually increasing until it becomes zero at the event of its collision with the table, because the free fall is an accelerated motion. Likewise, the sphere that exhibits the horizontal projectile motion appears to move in a parabola-like trajectory, while the model is running, and this is justified by the resultant velocity that derives from the synthesis of the horizontal and the vertical velocities of the sphere.
- b. *Mechanistic interpretation.* While the causal interpretation informed us *why the phenomenon functions the way it does*, the *mechanistic interpretation* tells us *how the phenomenon functions*. In order to get insight on the mechanistic interpretation of the model, one needs to go beyond the visual representation of the phenomenon being modeled and unpack its internal workings (e.g., the variables, the rules), one needs to study how the various parts of the phenomenon (e.g., the spheres, the forces that are exerted on each of them, the table that stops the spheres, etc.) cause the spheres to move in the way characterized by the behavioral description. For instance, if we look at the

variables and the rules that have been created for each sphere in the model presented in Figure 13, we will uncover the following:

- i. *Left Sphere.* For this sphere the teacher created two variables; the *gravity force* variable and the *vertical velocity* variable. The rules that he created for the sphere are as follows:
  1. *If the gravity force is greater than zero, add 1 in the value of vertical velocity and move the sphere one square below.*
  2. *If there is a brown colored square under the sphere, put 0 in the value of the vertical velocity of the sphere.*
- ii. *Right sphere.* For this sphere, the teacher created four variables; the *gravity force* variable, the *vertical velocity* variable, the *horizontal force variable* and the *horizontal velocity* variable. The rules that he created for the sphere are as follows:
  1. *If the gravity force is greater than zero AND the horizontal force is 5, add 1 in the value of vertical velocity AND put 8 in the horizontal velocity AND move the sphere one square diagonally.*
  2. *If there is a brown colored square diagonally of the sphere, put 0 in the value of the vertical velocity of the sphere AND zero in the value of the horizontal velocity of the sphere.*

Although the model presented in Figure 13 satisfies the criteria of representational complexity and interpretive potential as described above, it falls short in its *predictive power*. This is the third criterion that a model needs to satisfy in order to be considered as “scientific”. Models similar to those in Figure 13 were found that their predictive power was limited, because the way they were created does not allow the formulation and testing of predictions. The reasons behind this assertion are as follows:

- A. The value of the horizontal velocity that the right sphere acquires (because of the horizontal force that acts on it at the beginning of the experiment) is set arbitrarily. Specifically, the sphere will always acquire the same initial horizontal velocity no matter what the value of the horizontal force is. Hence, because the model entails a fixed value for the horizontal force that is exerted on the right sphere cannot be used to predict the value of the horizontal velocity for any other value of the horizontal force.
- B. The model does not calculate the resultant force of the sphere to the right and thus we cannot predict, and then test, the value of the resultant velocity of the right

sphere. The model only calculates in an arbitrary fashion the horizontal and vertical velocity of the right sphere and the vertical velocity of the left sphere.

- C. The time of flight for each sphere is not calculated during running the model and thus we cannot predict and then test what would be the velocity for each sphere at a specific instant of time.

On the contrary, models like the one that appears in Figure 14 and clustered in Level 6 entail, apart from advanced representational complexity and interpretive potential, strong predictive power, because the rules that were created to control the behavior and functions of the model allow users to use the model for testing predictions about the phenomenon being modeled through the model. In doing this, the users can set any value in the variables of the model and the model will calculate the value for each of the other related variables. The variables that were created and implemented within the rules that control the function and the behavior of the model are as follows:

- a. Gravitational acceleration ( $g$ )
- b. Horizontal force exerted in the right sphere ( $F_{\text{purple}X}$ )
- c. Horizontal velocity of the right sphere ( $U_{\text{purple}X}$ )
- d. Vertical velocity of the right sphere ( $U_{\text{purple}Y}$ )
- e. Resultant velocity of the right sphere ( $U_{\text{purple}} = \sqrt{U_{\text{purple}X}^2 + U_{\text{purple}Y}^2}$ )
- f. Vertical velocity of the left sphere ( $U_{\text{green}Y}$ )
- g. Spheres' released height ( $H$ )
- h. Time of flight for each sphere ( $t_{\text{green}}, t_{\text{purple}}$ )
- i. Horizontal distance of the projectile ( $A$ )

Consequently, the models which belong to Level 6 move beyond the representation and explanation of the single case of the experiment that the teachers observed through the videotaped file, since they can be applied in various other cases related to the phenomenon. For instance, the model can be used to test whether the two spheres will impact the ground at the same time if the horizontal force that is exerted on the right sphere is doubled, or if the time of flight for the right sphere is independent to the horizontal velocity that acquires because of the horizontal force that is exerted on it at the beginning of the experiment, or what would be the horizontal distance of the projectile if the horizontal velocity is doubled, and so on.

Teachers' models that were created within Assessment Tasks A1 and A2 in relation to their classification to the emerged levels for the model formulation skill are presented in Table 8.

Table 8. Model Formulation Skill: Teachers' Model Distribution in Tasks A1 and A2 Across the Emerged Levels Prior to and After the PDC

Levels	Pre-Assessment Task A1 (projectiles)	Pre-Assessment Task A2 (volumetric expansion)	Post-Assessment Task A1 (projectiles)	Post-Assessment Task A2 (volumetric expansion)
Level 1	9	8	0	0
Level 2	6	3	0	0
Level 3	3	6	5	10
Level 4	2	3	3	3
Level 5	0	0	4	3
Level 6	0	0	8	4

The findings of Table 8 reveal that teachers' model formulation skill was enhanced after the PDC, since for both assessment tasks the teachers progressed from the lowest levels (e.g., Level 1 and Level 2) to the upper levels that emerged. However, teachers' performance in relation to this skill appeared to be different between Assessment Tasks A1 and A2 both prior to and after the PDC. Specifically, prior to the PDC,  $\frac{3}{4}$  of the teachers were clustered in Levels 1 and 2 in Assessment Task A1 (in both levels the models lacked interpretive potential and predictive power, and they differed only on the degree of the model's representational complexity). The remaining teachers were classified in Levels 3 and 4 (these levels are similar in that the models in these levels encompass moderate representational complexity and lack predictive power and differ in the degree of their interpretive potential; Level 4 is superior to Level 3 in that its interpretive potential embodies both a behavioral description of the underlying mechanism of the model and a mechanical description that accounts to the way the mechanism functions, whereas Level 3 encompass only the first type of description). On the contrary, teachers' performance appeared to be better in Assessment Task A2, as they were somehow split in Levels 1 and 2 (11 out of the 20 teachers) and Levels 3 and 4 (9 out of the 20 teachers).

Teachers' performance discrepancy in Assessment Tasks A1 and A2 was also maintained after the PDC, but this time their distribution across the levels that emerged was in favor of Assessment Task A1. According to their distribution in the levels presented in Table 8, the majority of teachers were classified in Level 3 in Assessment Task A2, and if combined with those who were grouped in Level 4 the percentage of teachers who scored in the intermediate emerged levels is raised to the 65%. On the contrary, the majority of teachers

in Assessment Task A1 were clustered in the highest levels that emerged (4 teachers in Level 5 and 8 teachers in Level 6), whereas the remaining teachers were clustered in Levels 3 and 4 (5 and 3 teachers respectively).

#### 4.2.1.1.2. Identification of model components skill

To assess teachers' *identification of model components skill*, the following two tasks were designed and administered to the participating teachers; in Assessment Task B1 (see Appendix II) the teachers were presented with a model that represented the image formation in the eye (e.g., light rays depart from a candle, pass through a concave lens and form the image of the candle on a screen). Likewise, in Assessment Task B2 (see Appendix III) the teachers were presented with a diagram that showed how soccer is played (e.g., arrows showed the several pathways through which the soccer ball was shoot from one player to another in order to succeed on shooting a goal). In both tasks the teachers were asked to carefully observe the models and identify the major components of each model according to the phenomenon it represents. They were also asked to provide (for every task) two examples for every component they identified.

The analysis of the data collected through the abovementioned assessment tasks, prior to and after the PDC, revealed 5 hierarchical levels that illuminate teachers' competency related to the identification of model components skill. The levels that emerged and representative teachers' responses for each level are presented in Table 9.

According to Table 9, there is a hierarchical classification of Levels 1 through 5 according to their complexity. Specifically, Level 1 is the less complex out of the five levels, since it pertains to an individual's capability to identify only examples of *objects* as the main components of a given model, whereas Level 2 pertains to individuals who can identify, in addition to objects, *variables*. Level 3 relates to those who are able to identify not only objects and variables, but also *interactions* among the model constituent components. Levels 1 through 3 pertain to teachers' capability to identify examples of *objects*, *variables*, and *interactions* from a given model without being able to indicate explicitly the type of the component that their identified examples fall into. On the contrary, Levels 4 and 5 differentiate from the previous levels because in both levels there is an explicit reference to the constituent components of the model (e.g., objects, variables, processes and interactions) in conjunction with the identification of examples from each component's classification. The only difference between Level 4 and Level 5 relates to the omission of

Table 9. Identification of Model Components Skill: Emerged Levels' Description, Typical Responses and Coding Scheme

Levels	Level description	Example of a participant response in Assessment Tasks B1 or B2	Coding scheme
Level 1	Identification only of examples of <i>objects</i> . No explicit reference on the names of the identified model components.	<i>"The components of the soccer model are: (i) the ball, (ii) the players, and (iii) the goal post."</i> [Participant #3, Task B2, prior to the PDC]	Objects: <i>(i) the ball, (ii) the players, and (iii) the goal post.</i>
Level 2	Identification of examples of <i>objects and variables</i> . No explicit reference on the names of the identified model components.	<i>"The components of this model are the candle, the distance between the candle and the lens, and the distance between the lens and the screen and the image that is formed on the screen."</i> [Participant #2, Task B1, prior to the PDC]	Objects: <i>the candle, the lens, the screen, the image</i> Variables: <i>the distance between the candle and the lens, the distance between the screen and the lens</i>
Level 3	Identification of examples of <i>objects, variables and interactions</i> . No explicit reference on the names of the identified model components.	<i>"This model components are: the candle, the lens, the screen, the rays, the distance between the candle and the lens and the distance between the lens and the screen, and the rays that change direction as they pass through the lens"</i> [Participant #14, Task B2, prior to the PDC]	Objects: <i>the candle, the lens, the screen, the rays</i> Variables: <i>the distance between the candle and the lens and the distance between the lens and the screen</i> Interactions: <i>Interaction of the rays and the lens, e.g., "the rays change direction as they pass through the lens"</i>
Level 4	Identification of examples of <i>objects, variables and interactions</i> and <i>explicit</i> reference on the names of the identified model components.	<i>"The soccer model encompasses:</i> 1. <i>Objects: the ball, the players, the goal post</i> 2. <i>Variables: the direction of the ball, the team of the players</i> 3. <i>Interactions: Two players of the same team interact when they exchange the ball or the ball interact with a player</i> [Participant #1, Task B1, after the PDC]	Objects: <i>the ball, the players, the goal post</i> Variables: <i>the direction of the ball, the team of the players</i> Interactions: <i>Two players of the same team interact when they exchange the ball or the ball interact with a player</i>
Level 5	Identification of examples of <i>objects, variables, interactions and processes</i> and <i>explicit</i> reference on the names of the identified model components.	<i>"The components of this model are:</i> 1. <i>Objects, e.g., the candle, the lens, the rays, the screen</i> 2. <i>Variables, e.g., the distance between the candle and the lens, the distance between the lens and the screen, the size of the image, the direction of the rays</i> 3. <i>Interactions, e.g., a light ray interacts with the lens, the light ray that interacts with the screen</i> 4. <i>Processes, e.g., a light ray departs from the candle, changes direction once it penetrates the lens, and leaves a light mark when hits the screen"</i> [Participant #17, Task B2, after the PDC]	Objects: <i>the candle, the lens, the rays, the screen</i> Variables: <i>the distance between the candle and the lens, the distance between the lens and the screen, the size of the image, the direction of the rays</i> Interactions: <i>a light ray interacts with the lens, the light ray that interacts with the screen</i> Processes: <i>a light ray departs from the candle, changes direction once it penetrates the lens, and leaves a light mark when hits the screen"</i>

examples of *processes* and the explicit reference on them as one of model components in Level 4, whereas in Level 5 there is a comprehensive identification and explicit reference on all four components of a model.

Prior to the PDC, the participants' responses in both Pre-Assessment Tasks were classified in Levels 1 through 3 and the majority of teachers were clustered in Level 2, as they appeared to be able to identify only objects and variables as the constituent components of a given model and did not make any explicit references on the terminology that relates to model components (see Table 9). After the PDC, all participants shifted from the lower to the upper emerged levels of the identification of model components skill, and specifically  $\frac{3}{4}$  and slightly more than  $\frac{3}{4}$  in Post-Assessment Tasks B1 and B2 respectively appeared to be able to explicitly define and at the same time to provide examples from each of the four model components. Levels 1 through 5 with their corresponding prevalence for both Pre-Assessment Tasks and Post-Assessment Tasks prior to and after the PDC are presented in Table 10.

Table 10. Identification of Model Components Skill: Teachers' Responses Distribution in Tasks B1 and B2 Across the Emerged Levels Prior to and After the PDC

Levels	Pre-Assessment Task B1 (eye function)	Pre-Assessment Task B2 (soccer)	Post-Assessment Task B1 (eye function)	Post-Assessment Task B2 (soccer)
Level 1	3	2	0	0
Level 2	12	14	0	0
Level 3	5	3	0	0
Level 4	0	0	5	4
Level 5	0	0	15	16

#### 4.2.1.1.3. Comparing and contrasting models of the same phenomenon skill

For evaluating this aspect of modeling ability, two assessment tasks were designed; one in the context of physics (simple electric circuits) and one in the context of chemistry (substance dilution). In Assessment Task C1 (see Appendix II), the teachers were presented with four different types of models of a simple electric circuit: (i) a drawing, (ii) a construction of ropes and pictures, (iii) a model in Stagecast Creator, and (iv) a verbal description. Similarly, in Assessment Task C2 (see Appendix III), the teachers were presented with four models that represented how a drop of coloring matter is diluted in water: (i) a drawing, (ii) a beaker containing white and red, (iii) a model in Stagecast Creator, and (iv) a verbal description. During the administration of both tasks, the instructor presented the teachers the context of each assessment task (e.g., in Assessment Task C1 he constructed the simple electric circuit and in Assessment Task C2 he poured a

drop of the coloring matter in the water), and then the teachers were given enough time to become acquainted with each of the representations (e.g., all different representations for both assessment tasks were accessed individually by the participants in their computers). Then, the teachers were asked to state (for each assessment task) which of the four models was the most appropriate and which was the least appropriate for describing and explaining the phenomenon they observed in each assessment task, and explain their reasoning.

The levels that emerged from the phenomenographic analysis of teachers' responses on these tasks are shown in Table 11.

Table 11. Comparing and Contrasting Models of the Same Phenomenon Skill: Emerged Levels' Description and Typical Responses

Levels	Level description	Example of a participant response in Assessment Tasks C1 or C2
Level 1	Detection of the best or worst model based on instructional appropriateness	<i>"The 3<sup>rd</sup> model is the best for describing and explaining the electric circuit, because this model can be used in a science class and the students will observe what happens when the switch is turned on. It is simple and easily understood by kids, especially the younger ones"</i> [Participant #13, Task C1, prior to the PDC]
Level 2	Detection of the best or worst model based on model's representational comprehensiveness	<i>"The drawing is the worst model to describe and explain the dilution of the coloring matter in water, because it neither shows the particles of the substance nor the particles of the water when the dilution occurs"</i> [Participant #15, Task C2, prior to the PDC]
Level 3	Detection of the best or worst model based on model's interpretive potential	<i>"The Stagecast Creator model is the worst model for describing and explaining what is happening in the electric circuit, because it doesn't explain how or why the light bulb is lit when the switch is on"</i> [Participant #16, Task C1, after the PDC]
Level 4	Detection of the best or worst model based on model's (i) representational comprehensiveness, and (ii) interpretive potential	<i>"The best model to show what is happening during the dilution of the color substance in the water is the Stagecast Creator model, because it shows the particles of both the water and the substance, they are represented in different colors and we can see how the particles of the substance are spread inside the water particles during their mixing and that's why the colorless water changes gradually to the color of the substance"</i> [Participant #1, Task C2, after the PDC]
Level 5	Detection of the best or worst model based on model's (i) representational comprehensiveness, (ii) interpretive potential, and (iii) predictive power	<i>"The best way to explain how the electric circuit functions is the verbal description because:</i> <ol style="list-style-type: none"> <li>(1) <i>it encompasses the basic components of the phenomenon, e.g., objects (light bulb, the wires, the battery), variables (type of circuit; open or closed, status of brightness; no brightness or normal brightness), processes (e.g., the connection of the light bulb to the battery with the use of wires), and interactions (e.g., the light bulb interacts with the battery in order to lit)</i></li> <li>(2) <i>it provides a mechanism that serves as an interpretation of the way the phenomenon occurs</i></li> <li>(3) <i>it enables the testing of predictions because there is a description of how the light bulb should be connected with the battery with the use of wires and thus we can formulate and then test a prediction if the several parts of the circuit are connected in a different way"</i></li> </ol> [Participant #5, Task C1, after the PDC]



According to Table 11, the levels that emerged from the phenomenographic analysis of teachers' responses prior to and after the PDC reflect the criteria that were used for selecting the best or the worst model during comparing and contrasting models of the same phenomenon. In Level 1 the criterion that was used in favor of or against the model that best interprets the phenomenon under study was the appropriateness of the model in relation to its exploitation in instructional practice. In Level 2 the selection of the best or worst model was based on model's representational comprehensiveness, whereas in Level 3 the interpretive potential of the model was used as the criterion for the selection of the best or worst model. Level 4 combines Levels 2 and 3 in that it encompasses both criteria that are used in the previous levels (e.g., representational comprehensiveness and interpretive potential), and Level 5 is an extension of Level 4 as there is a new criterion (e.g., the predictive power of the model) that is added to the previously defined criteria.

Teachers' responses to Assessment Tasks C1 and C2 in relation to their classification to the emerged levels for the comparing and contrasting models of the same phenomenon skill are presented in Table 12.

Table 12. Comparing and Contrasting Models of the Same Phenomenon Skill: Teachers' Responses Distribution in Tasks C1 and C2 Across the Emerged Levels Prior to and After the PDC

Levels	Pre-Assessment Task C1 (electric circuits)	Pre-Assessment Task C2 (dilution)	Post-Assessment Task C1 (electric circuits)	Post-Assessment Task C2 (dilution)
Level 1	4	1	0	0
Level 2	12	6	3	2
Level 3	3	1	1	0
Level 4	1	12	6	8
Level 5	0	0	10	10

The results of Table 4 indicate some similarities and some differences regarding teachers' performance in Assessment Tasks C1 and C2 prior to and after the PDC. Specifically, prior to the PDC the majority of teachers' responses in Assessment Task C1 were classified in Level 2 (detection of the best or worst model based on model's *representational comprehensiveness*), whereas the majority of teachers' responses in Assessment Task C2 were grouped in Level 4 (detection of the best or worst model based on model's *representational comprehensiveness* and *interpretive potential*). On the contrary, after their participation in the PDC the teachers shifted to the upper performance levels, since none of them used the criterion of model "fitness" to the instructional needs of the teacher or the student for selecting the best (or the worst) model among other candidates. Most importantly, half of teachers were classified to the highest performance level in both

assessment tasks, as they used the criterion of model's *predictive power* in conjunction to model's *representational comprehensiveness* and *interpretive potential* for selecting the best (or the worst) model to describe and explain a phenomenon under study. The majority of the remaining teachers provided responses that were classified to Level 4 and very few teachers were grouped in Levels 3 and 2. It is important to note that the big discrepancy that was revealed prior to the PDC concerning teachers' performance in the assessment tasks was eliminated after the PDC.

#### 4.2.1.1.4. Model evaluation and formulating ideas for improvement skill

Teachers' *model evaluation and formulating ideas for improvement skill* was examined through two assessment tasks; one in the context of biology (plant growth) and one in the context of physics (angular momentum). In Assessment Task D1 (see Appendix I), the teachers were provided with a model created in SC that represented the growth of a bean seed, whereas in Assessment Task D2 (see Appendix II) the teachers watched a videotaped experiment of a person standing on a revolving platform and holding a turning wheel which cause him to turn in order to conserve angular momentum (the wheel began vertically and the person rotated left or right depending on the tilt of the wheel). Next, a drawing that illustrated the phenomenon they watched was presented to them. For both assessment tasks, the teachers were asked to study carefully the model that was presented and state if the model was complete and explain their reasoning. In case of a negative response, they were asked to describe which aspects of the phenomenon were omitted.

The analysis of the data collected through the abovementioned assessment tasks, prior to and after the PDC, revealed 6 hierarchical levels that illuminate teachers' competency related to the model evaluation and formulating ideas for improvement skill. The levels that emerged and representative teachers' responses for each level are presented in Table 13.

Table 13. Model Evaluation and Formulating Ideas for Improvement Skill: Emerged Levels' Description and Typical Responses

Levels	Level description	Example of a participant response in Assessment Tasks D1 or D2
Level 1	Evaluation of a model based on (i) aesthetic criteria, and (ii) limitations of the representational completeness of the model, e.g., absence of objects or variables	<i>“The program that Niki created is incomplete, because some aspects of the plant growth are missing. There should be three separate plants because she planted three crops. The bean stalk is also a component that is missing from the program and the flowers that she created do not correspond to the real flowers that a bean plant grows. Hence, her program is not a representative of the phenomenon she tried to create. [Participant #15, Task D1, prior to the PDC]</i>
Level 2	Evaluation of a model based on the identification of limitations of (i) the representational completeness of the model, e.g., absence of variables (ii) the interpretive potential of the model (e.g, a mechanism that explains how the phenomenon functions is missing)	<i>“This program is incomplete, because major aspects of the plant growth are missing. For instance, the aspect that pertains to needs of plants for growth is omitted, e.g., the water and the sun light. Specifically, the plant, as it appears in this program, grows automatically without showing the contribution of the amount of water and sun light that are necessary for its growth”. [Participant #3, Task D1, prior to the PDC]</i>
Level 3	Evaluation of a model based on the identification of limitations of (i) the representational completeness of the model, e.g., a. absence of variables b. absence of processes (ii) the interpretive potential of the model (e.g, a mechanism that explains how and why the phenomenon functions is missing)	<i>“No, this program is incomplete. It shows only one case of the phenomenon (e.g., when the man holds the wheel vertical). It should represent two additional phases of the phenomenon, e.g., when the man holds the wheel horizontal and rotates clockwise and when it holds the wheel horizontally and rotates anticlockwise. The program should have also informed us that the man rotates in the opposite direction to the spinning wheel. [Participant #5, Task D2, prior to the PDC]</i>
Level 4	Evaluation of a model based on the identification of limitations of (i) the representational completeness of the model, e.g., a. absence of objects b. absence of variables c. absence of processes (ii) the interpretive potential of the model (e.g, a mechanism that explains how and why the phenomenon functions is missing)	<i>“This drawing is not complete, because it doesn’t represent in detail everything that occurs during the phenomenon. It should have been stated or shown that the man stands on a platform that can revolve, and that the wheel that he holds spins continually. When the tilt of the wheel becomes vertical, the man rotates. The direction of the tilt of the spinning wheel determines the direction of the rotation of the man”. [Participant #18, Task D2, prior to the PDC]</i>

Level 5	<p>Evaluation of a model based on the identification of limitations of</p> <p>(i) the representational completeness of the model, e.g.,</p> <ol style="list-style-type: none"> <li>a. absence of objects</li> <li>b. absence of variables</li> <li>c. absence of processes</li> <li>d. absence of interactions among the components of the model</li> </ol> <p>(ii) the interpretive potential of the model (e.g, a mechanism that explains how and why the phenomenon functions is missing)</p>	<p><i>“I consider Anna’s model as incomplete, because neither shows nor states explicitly how and when the man revolves in relation to the spinning wheel. Hence, some important components of the model are omitted, like: Objects: the revolving base that the man stands on Variables: Direction of rotation of the spinning wheel, direction of the rotation of the man, spinning wheel orientation (e.g., vertical or perpendicular) Processes: how the change of the spinning wheel orientation affects the direction of the rotation of the man Interactions: relationship between the orientation of the spinning wheel and the direction of the rotation of the man, interaction between the revolving base that the man stands on and the direction of the rotation of the spinning wheel”.</i> [Participant #4, Task D2, after to the PDC]</p>
Level 6	<p>Evaluation of a model based on the identification of limitations of</p> <p>(i) the representational completeness of the model, e.g.,</p> <ol style="list-style-type: none"> <li>a. absence of objects</li> <li>b. absence of variables</li> <li>c. absence of processes</li> <li>d. absence of interactions among the components of the model</li> </ol> <p>(ii) the interpretive potential of the model (e.g, a mechanism that explains how and why the phenomenon functions is missing)</p> <p>(iii) the predictive power of the model</p>	<p><i>“The program that Niki created is incomplete. I think that she tried to represent the development of growth of the bean seeds and failed to incorporate the factors that intervene during their development (e.g., sun light, water, etc). Niki did not include major components that relate to the growth of the bean seeds. For instance, she did not include the soil and the sun or the time span within which the seeds start to grow and develop. Her program fails in providing a sufficient interpretation of the phenomenon and does not allow for making predictions and hypotheses testing. For instance, what is the time that is needed for the part of bean to bloom? A comprehensive model should also incorporate the variables that affect the bean plant growth (e.g., sun light, water, oxygen, soil, etc) and designate how these variables affect the phenomenon of plant growth. The omission of such basic components from the model weakens its explanatory power and predictability. Comparing and contrasting this model with the real phenomenon one can easily identify all the missing components that relate to the development of the bean seeds to plants. Hence, improvements that are necessary to be made should be the addition of objects (e.g, soil, sun, water), variables (e.g., the amount of water and sun light that is required), processes (e.g., how and by which parts of the plant water and light absorbent are made) and interactions (e.g., the variable of water interacts with the plant vitality, for instance in case of water shortage the plant should wither).</i> [Participant #12, Task D1, after to the PDC]</p>

According to Table 13, there is a hierarchical classification of Levels 1 through 6 according to their complexity. Specifically, Level 1 pertains to the case of teachers whose evaluation of the given models was based on aesthetic and representational criteria that were omitted from the given model. Levels 2 through 5 are similar in that they involve two fundamental criteria for evaluating a model (e.g., model’s representational complexity and its interpretive potential) but differ in the identified types of model components that were omitted from the given model. For instance, Level 2 encompasses only the identification of *variables* as the component that was omitted from the representation of the phenomenon, Level 3 encompasses the identification of *both variables* and *processes*, Level 4 includes the identification of *variables* and *processes* and also the identification of *objects*, and finally Level 5 encompasses all previous model components and also *interactions* among model constituent components. Level 6, which is the highest hierarchical level, pertains to the case of teachers who used the two abovementioned evaluation criteria (e.g., model’s representational complexity and interpretive potential) and also made references on model’s *predictive power* as an additional evaluation criterion.

Teachers’ response distribution in Tasks D1 and D2 across the levels that emerged and described above prior to and after the PDC are presented in Table 14.

Table 14. Model Evaluation and Formulating Ideas for Improvement Skill: Teachers’ Responses Distribution in Tasks D1 and D2 Across the Emerged Levels Prior to and After the PDC

Levels	Pre-Assessment Task D1 (spinning wheel)	Pre-Assessment Task D2 (plant growth)	Post-Assessment Task D1 (spinning wheel)	Post-Assessment Task D2 (plant growth)
Level 1	0	6	0	0
Level 2	0	8	0	0
Level 3	10	5	6	4
Level 4	2	1	2	2
Level 5	8	0	8	8
Level 6	0	0	4	6

As Table 14 indicates, there is a discrepancy in the distribution of teachers’ responses in Tasks D1 and D2 prior to the PDC. In Task D2, the majority of teachers provided responses that were classified in Levels 1 and 2, whereas in Task D1 none of teachers’ responses were classified in these lower levels. Instead, half of the teachers provided responses in Level 3 and almost the rest of the teachers provided responses in which they identified examples of the four major components of a model that were missing from the given model, and also judged model’s weakness in relation to its interpretive power. After the PDC, this discrepancy seemed to have been eliminated, since the distribution of

teachers' responses across the emerged levels of the *model evaluation and formulating ideas for improvement skill* appeared to be almost similar for both assessment tasks, and also, it appears that the participants made a significant move to the upper levels in both assessment tasks after the PDC. Nevertheless, the number of teachers who were able to use all three judgmental criteria for evaluating the models of the assessment tasks (e.g., model's representational complexity, interpretive potential and predictive power) was relatively low.

#### 4.2.1.1.5. Model validation through comparison with phenomena of the same class skill

The evaluation of the fifth modeling skill that pertains to the validation of a model through comparing phenomena of the same class was accomplished through Assessment Tasks E1 and E2 (see Appendices II and III respectively). In both assessment tasks the teachers were provided with the description of a context within which a student studied a phenomenon (e.g., *buoyancy* in Assessment Task E1 and *light refraction* in Assessment Task E2), collected data from the phenomenon under study, and the model he created based on the data collected. Then the teachers were asked to describe the steps that needed be followed for validating the proposed model.

Four hierarchical levels were revealed after the phenomenographic analysis of teachers' responses to the abovementioned assessment tasks and are presented in Table 15.

Table 15. Model Validation through Comparison with Phenomena of the Same Class Skill: Emerged Levels' Description and Typical Responses

Levels	Level description	Example of a participant response in Assessment Tasks E1 or E2
Level 1	Validation of a model through evaluating if all aspects of the phenomenon are represented within the model	<i>"He needs to check if his model encompasses all aspects of the phenomenon it represents"</i> . [Participant #3, Task E2, prior to the PDC]
Level 2	Validation of a model through studying if the relationships among the variables of the model have been correctly introduced to the model	<i>"The student needs to check if the model he created is true for each set of data he collected. For instance, he needs to check if the refraction ray's angle is always smaller than the angle of the incident ray for each case of the data he collected"</i> . [Participant #5, Task E2, prior to the PDC]
Level 3	Validation of a model through altering the value of specific variables of the model and study the fitness of the model in each new case	<i>"He needs to repeat his experiment by choosing an object with a mass equal to the mass of the water and test if his model fits in this new case. He might also need to choose a new liquid, measure its mass and then test if an object with a certain mass would behave as his model"</i> . [Participant #5, Task E2, after the PDC]

Level 4	Validation of a model through applying it in a total new case of a phenomenon (e.g., a phenomenon of the same class) and study if the model fits in this new case	<i>“Antonis needs to try his experiment again with light rays of different wave length in order to test if his “theory” applies to all light rays across the wave length spectrum. If he wants to expand his model and his theory to a larger extent (e.g., a model to account for light rays of several wave lengths and all different kinds of liquids), he needs to repeat his experiment using a different liquid. Also, he needs to make some more trials by altering the means that the light ray propagates through (e.g., instead of air he might perform his experiment with a light beam traveling through another substance (e.g., ether) before entering the liquid). Through these steps, he will be able to check his model validation through applying it in all these classes of the same phenomenon”.</i> [Participant #18, Task E2, after the PDC]
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As Table 15 indicates, the teachers who were clustered in Level 1 and Level 2 conceived the model validation task as a model evaluation task and thus they stated the procedure they would follow to test model’s fitness with the phenomenon it represented. Level 1 is inferior to Level 2 in that it describes in a general fashion that for model validation purposes one should check if all aspects of the phenomenon are represented within the model under study. On the contrary, Level 2 is superior to Level 1, because even though it refers to a model evaluation procedure for model validation purposes, it focuses on a specific type of test; one should study if the relationships between the variables of the model have been represented within the model in a correct manner.

Level 3 attests a progression from the previous levels in that it moves beyond the evaluation of the specific model per se. More specifically, it implies that model validation process should focus on whether the model is robust enough to provide valid results when giving a new value in one of the model’s variables and the outcome that the model produces is correct. Put differently, Level 3 conceives model validation as an “extrapolation” technique through which a model’s predictive power is assessed.

Lastly, Level 4 which is the most superior level that emerged from the phenomenographic analysis of teachers’ responses encompasses the correct procedure that should be followed when one is willing to validate a model s/he has previously built. Specifically, Level 4 suggests that in order to validate a model one should apply the model in a phenomenon of the same class and test if the phenomenon fits well in this new case. For instance, in the

context of 1-D collisions, in order to validate the “velocity swap model” that accounts to the event of two equal mass carts that move in opposite directions with different velocities and was built on the idea that the two carts “swap their velocities” during their collision, one should apply this model in a phenomenon of the same class (e.g., two unequal mass carts move in opposite directions with equal or unequal velocities) and test if the model “fits” in this totally new case of phenomenon.

Teachers’ responses to Assessment Tasks E1 and E2 in relation to their classification to the emerged levels for model validation through comparison with phenomena of the same class skill are presented in Table 16.

Table 16. Model Validation through Comparison with Phenomena of the Same Class Skill: Teachers’ Responses Distribution in Tasks E1 and E2 Across the Emerged Levels Prior to and After the PDC

Levels	Pre-Assessment Task E1 (sinking and floating)	Pre-Assessment Task E2 (refraction)	Post-Assessment Task E1 (sinking and floating)	Post-Assessment Task E2 (refraction)
Level 1	3	1	0	0
Level 2	9	15	0	0
Level 3	3	2	7	9
Level 4	5	2	13	11

Table 16 reveals that both prior to the PDC and after the PDC the distribution of teachers’ responses in Tasks E1 and E2 was different and particularly, the differences were stronger in the case of teachers’ responses prior to the PDC, although the majority of teachers were grouped in Level 2 prior to the PDC for both assessment tasks. After the PDC, it was found that the participants made a significant shift to the upper levels in both assessment tasks, since none of the teachers’ responses was clustered in either Level 1 or Level 2. However, the teachers seemed to perform slightly better in assessment task E1, given that the majority of them provided responses that were classified to the most superior level, whereas in the case of assessment E2 the majority of teachers remained in Level 4, after the PDC.

#### **4.2.1.2. Metacognitive knowledge about the modeling process**

Teachers’ metacognitive knowledge about the modeling process was evaluated through Assessment Tasks F1 and F2 (see Appendices II and III respectively) which were isomorphic in their format but each of them was based on a different context. The context



of Assessment Task F1 derived from observational astronomy (moon phases formation), whereas the context of Assessment Task F2 was based on states of matter (water cycle). Both assessment tasks entailed a scenario about an individual who was willing to create a model about a phenomenon of interest and was not aware of the steps necessary to follow for creating the model. The teachers were asked to describe in detail the steps that should be followed helping the individual in each scenario to build the model.

The levels that emerged from the phenomenographic analysis of teachers' responses to the aforementioned assessment tasks are presented in Table 17.

According to the emerged levels presented in Table 17, teachers' metacognitive knowledge about the modeling process appeared to follow a progressive pattern of increased sophistication. Specifically, Level 1, which is the most inferior of the emerged levels, reveals that the modeling process is conceived as a "self-study" approach through which one aims to improve his/her understanding about a particular phenomenon through the study of multiple sources (e.g., direct observations, studying from a video or a book, studying an analogical model that represents the phenomenon under study, etc). Thus, the teachers who were grouped in this level might have mistakenly associated the process that one should follow for creating an artifact to represent how he/she understands the function of the phenomenon with the internal mental processing that takes place during the development of mental models about phenomena we approach through our senses.

Level 2 entails in a minimalistic way two of the steps that are essential to be followed during the modeling process, and also the steps the way they are described, suggest that the modeling process is linear. Likewise, Level 3 reveals that the steps during the modeling process also follow a linear mode, but is superior to Level 2 because it includes additional modeling related steps than Level 2. For instance, apart from performing observations and then building a model with the use of the data collected during the observation stage, Level 3 involves comparing the model with the phenomenon it represents or with other candidate models and then improving the model according to the inconsistencies or the gaps identified during the previous stage.

Table 17. Metacognitive knowledge about the modeling process: Emerged Levels' Description and Typical Responses

Levels of Metacognitive Knowledge about the modeling process	Level description	Example of a participant response in Assessment Tasks F1 or F2
Level 1	The process of modeling involves the study of the phenomenon from multiple sources (e.g., direct observations, studying from a video or a book, studying an analogical model that represents the phenomenon under study)	<p><i>“Some of the steps that Costas needs to follow for creating his model are as follows:</i></p> <p><i>Firstly, he needs to perform observations about the moon phases throughout a month. In addition, he could watch a video that illustrates the motion of the moon around the earth and in relation to the sun. Also, he could study an apparatus that the earth and the moon are represented with balls and the sun is represented with a light source and he will be able to observe how the different positions of the moon in relation to the sun and the earth contribute to each moon phase”</i> [Participant #6, Task F1, prior to the PDC]</p>
Level 2	The process of modeling involves (i) collecting information about the phenomenon (e.g., discussing about the phenomenon with an expert, study from a book, performing observations, etc), and (ii) building a model based on the data collected	<p><i>“After completing the theoretical background for the natural phenomenon she investigates, a first step is to make a diagram to show all the stages of the water cycle. Each stage should entail a picture of the location of the water and its phase. All stages will be linked with arrows on which she needs to write down the requirements that are needed to progress to the next stage. Later, she might find it useful to transfer her model in a modeling software in which she will add the pictures and combine them with the variables that affect the water cycle. Depending on the value of the variable that she will manually add, the related stage of the water cycle will appear and the values of the other related variables might possibly change”.</i> [Participant #1, Task F2, prior to the PDC]</p>
Level 3	The process of modeling involves (i) collecting information about the phenomenon (e.g., discussing about the phenomenon with an expert, study from a book, performing observations, etc), (ii) building a model based on the data collected, (iii) comparing the model and the real phenomenon or the model with other models, (iv) improving the model.	<p><i>“Initially, she needs to perform observations about the phenomenon of the water cycle she is studying. Based on her observations, she needs to proceed on deciding of how to represent her observations in a model and then create her model. After finishing with the creation of the water cycle model, she has to compare her model with the real phenomenon in an attempt to identify consistencies and inconsistencies between the two. In case her model does not represent the phenomenon in a satisfactory way, she needs to make improvements.”</i> [Participant #14, Task F1, prior to the PDC]</p>
Level 4	The process of modeling involves (i) collecting information about the phenomenon (e.g., discussing about the phenomenon with an expert, study from a book, performing observations, etc), (ii) building a model based on the data collected, (iii) comparing the model and the real phenomenon or	<p><i>“Firstly, Costas should make careful observations of the phenomenon he is interested to build a model (e.g., the moon phases formation) and collect all necessary information he thinks is important to incorporate in his model. Afterwards, by making use of the data, he should build a model that</i></p>

the model with other models, (iv) improving the model, (v) use the model for testing predictions, (vi) repetition of the steps (iii) through (v).

Level 5

The process of modeling involves (i) collecting information about the phenomenon (e.g., performing observations, identification of the objects, variables, processes and interactions of the phenomenon), (ii) selection of the best appropriate means for building the model, (iii) building a model based on the data collected, (iv) comparing the model and the real phenomenon or the model with other models, (v) evaluation of the model according to its representational completeness, interpretive potential and predictive power, (vi) improving the model, (vii) testing the validity of the model, (viii) repetition of the steps (iv) through (vii).

*represents the phenomenon he observed with the use of the data he collected. When finished with this step, he should contrast his model with the real phenomenon in order to evaluate it. At this point, he should revise his model on the basis of new data that he did not collect during his initial observations. He should repeat these steps in an iterative manner in order to be able to end with a model that is accurate and consistent with the phenomenon. Hence, he will be able to use his model for formulating hypotheses and testing of predictions. In case the model fails in providing accurate results during prediction testing, Costas should go back to the phenomenon again, collect additional data that might have omitted from the previous data collection and improve the model accordingly.” [Participant #11, Task F1, after to the PDC]*

*“Katerina should begin her work by making observations of the phenomenon she wants to model (water cycle). This could be done either through experiments or through videos of simulated experiments. Then, she needs to decide the best appropriate means for representing her model. In this case I think a computer modeling tool would be more preferable. Additionally, she needs to specify the basic components that her model should entail (e.g., objects, variables, processes, and interactions). Once she finished with the previous step, she should start developing her model. When she creates her model, she should test it to see if it could explain the phenomenon under study and if the model permits the formulation and testing of predictions. In addition, it would be important to compare her model with other candidate models that represent the same phenomenon. Hence, if the model needs improvements, she needs to make the necessary changes in her model. As soon as the model improvement phase ends, she should follow again the abovementioned cyclical and iterative procedure and evaluate again her model at the end. Finally, she needs to check if her model can be applied in a new phenomenon of the same class and thus she needs to follow the model validation steps (e.g., follow again the model improvement procedure in order to validate her model).” [Participant #8, Task F2, after to the PDC]*

The new step, that is added in Level 4 and makes it superior to Level 3, is the step that refers to the evaluation of the model according to its predictive power. This step appears to be critical within the modeling process, because it signals the beginning of a “loop” between this step and the previous ones. Based on the outcomes that will result after the formulation and testing of predictions, the model creator (or the “modeler”) will receive feedback about the capability of the model to produce valid results and in case this criterion is not met, the modeler will revisit the phenomenon, obtain new data that might have been omitted during the initial observation stage, improve the model by implementing these data to the model and follow the remaining steps until the stage of prediction testing. Hence, Level 4 appears to be superior to Level 3 not only because it entails the stage of evaluating the modeling according to its predictive power, but because it reveals for the first time the cyclical and iterative nature of the modeling process.

The cyclical and iterative modes that characterize the modeling process are maintained also in Level 5, but Level 5 is the most superior among the levels that emerged, because it entails in a comprehensive and detailed manner all the steps that are necessary to be followed during the modeling process. Specifically, two important improvements in the modeling steps that were identified within the previous steps concern the stage during which the modeler access the phenomenon of interest for data collection purposes, and the stage that refers to the process of model evaluation. Within the first step, it has been added that the modeler needs to identify the objects, the variables, the processes, and the interactions among the constituent components of the phenomenon that they will be embodied in the model during the model formulation stage. As far as the second improvement is concerned, it has been added that the model evaluation stage should focus not only on the evaluation of model’s representational complexity that the previous levels entailed, but also on model’s interpretive potential and predictive power. Although the later was included in Level 4 as a final stage, it was not thought of as a criterion that should be used during model evaluation and therefore is considered as an improvement of this step.

Teachers’ responses distribution related to metacognitive knowledge about the modeling process in Assessment Tasks F1 and F2 both prior to and after the PDC are provided in Table 18.

Table 18. Metacognitive Knowledge About the Modeling Process: Teachers' Responses Distribution in Tasks E1 and E2 Across the Emerged Levels Prior to and After the PDC

Levels of metacognitive knowledge about the modeling process	Pre-Assessment Task F1 (moon phases)	Pre-Assessment Task F2 (water cycle)	Post-Assessment Task F1 (moon phases)	Post-Assessment Task F2 (water cycle)
Level 1	3	2	0	0
Level 2	10	11	0	0
Level 3	6	6	0	0
Level 4	1	1	4	5
Level 5	0	0	16	15

The findings in Table 18 designate that teachers' performance in the two assessment tasks both prior to and after the PDC was almost equivalent. Prior to the PDC, the majority of teachers were clustered in Level 2, whereas after the PDC the majority of them shifted to the most superior level that emerged. The transition from the lower to the upper emerged levels indicates that teachers' metacognitive knowledge about the modeling process has been enhanced after the PDC.

#### **4.2.1.3. Meta-modeling knowledge**

According to the modeling ability framework presented in Figure 3 in Chapter 2, meta-modeling knowledge refers to learners' epistemic awareness about (i) the nature of models and (ii) the purpose or utility of models. The levels that emerged from the phenomenographic analysis of the responses provided in the assessment tasks that were designed and administered during the PDC to evaluate these two aspects of teachers' meta-modeling knowledge are provided in the sections that follow.

##### *4.2.1.3.1. Nature of models*

In order to evaluate teachers' meta-modeling knowledge in relation to the nature of models, Assessment Tasks G1 and G2 (see Appendices II and III respectively) were designed and administered both prior to and after the PDC. Assessment Task G1, which was based in the context of color light vision, entailed a computer-based simulation that represented how the mixing of the certain amounts of the three major color lights affects the resultant color of light and how this is perceived from human brain, e.g., what is the resulting light color when red and green light at the same amounts are mixed? Assessment Task G2 was designed in the context of cell biology and entailed a graphical representation that illustrated the cell cycle division in relation to the DNA division during the several phases of the cell cycle. The teachers were asked to study carefully the representation in

each of the assessment tasks and then explain if each representation could be considered as a case of a scientific model.

The analysis of teachers' responses to the abovementioned tasks prior to and after the PDC revealed four different levels that illuminate their epistemic awareness status in relation to the nature of models. These levels appear in Table 19 and are discussed in detail henceforward.

Table 19. Nature of Models: Emerged Levels' Description and Typical Responses

Levels	Level description	Example of a participant response in Assessment Tasks G1 or G2
Level 1	A model is a representation of a natural phenomenon	<i>"This program can be considered as a scientific model given that it presents the basic components of the phenomenon. More specifically, it presents the light source on the left side and the human brain on the other side. It also presents the variations in the amount of the light source and how this is perceived from the human brain. Of course, the model could be more accurate if it presented the information-image processing mechanism that takes place in the human brain, but this could be very difficult to be created, so I would say that it approaches the representation of the phenomenon in the best possible way"</i> [Participant #3, Task G1, prior to the PDC]
Level 2	A model is a representation that enables the formulation and testing of predictions for the phenomenon under study	<i>"This representation cannot be considered a scientific model, because it doesn't allow the formulation and testing of predictions."</i> [Participant #13, Task G2, after the PDC]
Level 3	A model is a representation that describes and explains how a phenomenon functions	<i>"I think it could be a scientific model given the fact that it represents and describes the way we perceive the color light, which emerged through scientific procedures, e.g., data collection and analysis. Additionally, the fact that the mechanism that the model encompasses is in line with the current scientifically conception of the way we conceptualize the color light is another reason that we can use to support the classification of this model among the scientific models"</i> [Participant #4, Task G1, after the PDC]
Level 4	A model describes, represents and explains a phenomenon under study (e.g., provides a possible mechanism of how the phenomenon functions) and can be used to test predictions about specific aspects of the phenomenon	<i>"A representation can be considered as a scientific model, if it fulfills three criteria: a scientific model should: (1) represent in an acceptable way the phenomenon; (2) provide strong explanatory power; and (3) enable the formulation of hypotheses and testing of predictions. This model satisfies these criteria in some way. Firstly, it represents in an adequate way the cell cycle because it shows all stages of the cell cycle (1<sup>st</sup> criterion). Secondly, one can explain the various phases of the cell cycle because the pictures that are provided entail the mechanism that controls the cell division (2<sup>nd</sup> criterion). Thirdly, by studying this model one is able to predict what is going to happen in any phase of the cell cycle (e.g., we can predict what is going to happen during the teloPhase. I then use the model to test if our prediction was correct) (3<sup>rd</sup> criterion)." [Participant #12, Task G2, after the PDC]</i>

According to the levels presented in Table 19, Levels 1 through 3 are subsets of Level 4, since they encompass one or two of the three major criteria that a representation, an artifact or a computer-based simulation should satisfy in order to be considered as a scientific model. Level 1 encompasses only the criterion of model's representational complexity (e.g., a model should represent in the best possible visual way the phenomenon or the aspect of the phenomenon under study), Level 2 entails the aforementioned criterion and also the criterion that refers to model's predictive power, and Level 3 also embodies the representational aspect criterion and model's interpretive potential. Level 3 is considered as superior to Level 2, because model's interpretive potential is an aspect that does not emerge directly by just looking at a specific model. Instead, in order to judge a model in relation to its interpretive potential, one should go beyond the visual representation of the model and examine the functions, the processes and the behaviors that constitute the underlying mechanism that the model entails. On the other hand, evaluating a model in terms of its predictive power is a less demanding cognitive task, because one should first formulate a prediction and then check if the model is capable to yield reliable results that confirm or refute the prediction being made.

Level 4 encompasses in unison all the aforementioned criteria that were provided in the previous levels. These criteria which underline the nature of scientific models pertain to model's representational complexity (e.g., a model should provide a comprehensive representation of the phenomenon it relates with), interpretive potential (e.g., a model should provide an interpretation to account for why and how the phenomenon functions the way it does), and predictive power (e.g., the structure and the format of the model should enable the formulation and testing of predictions for aspects or conditions of the phenomenon that were not directly observed during collecting data at the formulation stage of the model).

Prior to the PDC, the participants' responses in both Pre-Assessment Tasks were distributed across all emerged levels (see

Table 20 below); in Assessment Task G1, almost all teachers were equally split in Levels 1, 2, and 4, whereas in Assessment Task G2 their distribution followed a slightly different pattern. After the PDC, the majority of the teachers used all three criteria that define the nature of scientific models and thus they were clustered to the most superior level that emerged (see Table 19 for details).

Table 20. Nature of Models: Teachers' Responses Distribution in Tasks G1 and G2 Across the Emerged Levels Prior to and After the PDC

Levels of meta-modeling Knowledge: Nature of models	Pre-Assessment Task G1 (color light vision)	Pre- Assessment Task G2 (cell division)	Post- Assessment Task G1 (color light vision)	Post- Assessment Task G2 (cell division)
Level 1	6	7	0	1
Level 2	6	6	2	4
Level 3	2	3	3	1
Level 4	6	4	15	14

#### 4.2.1.3.2. Purpose or utility of models

The second aspect of meta-modeling knowledge, *purpose or utility of models*, was evaluated through the use of the context of the same assessment tasks that were administered for evaluating teachers' meta-modeling knowledge in relation to the nature of models. After the teachers responded to the question of Assessment Tasks G1 and G2 (e.g., "Is the representation you just saw a scientific model?"), the teachers were asked to study again the two types of models presented in each assessment task (e.g., a computer based model of the color light vision in Assessment Task G1 and a graphical representation of the cell division in Assessment Task G2) and answer the following question: "Is it important to build representations (or computer-based models) like the one you have studied? Explain your response by providing at least three reasons to highlight the importance of building such a representation (or a computer-based model)".

The analysis of teachers' responses in the abovementioned question in each of the assessment tasks (Assessment Task H1: color light vision, Assessment Task H2: cell division) revealed five levels that illuminate the development of their meta-modeling knowledge in respect with the purpose or utility of models. These levels are presented in Table 21 and are elaborated below.



Table 21. Purpose or Utility of Models: Emerged Levels' Description and Typical Responses

Levels	Level description	Example of a participant response in Assessment Tasks H1 or H2
Level 1	The models serve as (i) replicas of reality; and (ii) information delivery tools	<i>“(1) Such a representation helps in creating a realistic image about the cell and its real dimensions (we cannot observe them with our bare eyes). (2) The accompanied statements help in making things more clear. They help us get all important info about the cell division. (3) This representation presents each stage of cell division in detail. So it helps in avoiding getting confused of what is really happening during each stage.”</i> [Participant #9, Task H2, before the PDC]
Level 2	The models serve as (i) information delivery tools; and (ii) instructional aids	<i>“Representations like this one are very useful, because all information about such a complex process are organized and well embedded within the representation, in a way that facilitates better rote memorization than if the whole process was written in plain text. The use of images helps in reducing significantly the amount of information that is needed for describing an image in words, and this helps the student during learning about cell division.”</i> [Participant #1, Task H2, before the PDC]
Level 3	The models serve as (i) instructional aids; (ii) simulations; (iii) facilitators of our conceptual understanding about a phenomenon under study; and (iv) communication tools	<i>“Such a construction constitutes an attempt for interpreting our daily observations, they enable making new observations which we might have not performed before, and they allow the change of variables and watch the outcome. Also, engaging students with constructions like this, we help them develop procedural skills (e.g., control of variables skills), other scientific skills and positive attitudes towards science. Lastly, this artifact is important, because the person who created it aims to help people who did not think of how the phenomenon functions to get an understanding.”</i> [Participant #12, Task H1, before the PDC]
Level 4	The models serve as (i) instructional aids; (ii) simulations; (iii) facilitators of our conceptual understanding about a phenomenon under study; (iv) communication tools; and (v) external representations for a phenomenon under study	<i>“The reasons why such a representation is important are as follows: (1) Through this representation we make things “visible” that cannot be observed with bare eyes, thus it enables a representation of a phenomenon that is difficult to observe. (2) The representation enables the performance of additional observations for the phenomenon it represents, just like what simulations do. (3) By using such a representation within our instruction we save valuable time, because the observation through a microscope of the cell division process would be difficult and time consuming. We also give students the opportunity to investigate the properties of the models by changing the values of its variables and observing the impact of these changes. (4) By studying the representation we can interpret the phenomenon it represents in a better way.(5) Representations like this one serve as tools to communicate our ideas about how phenomena function to anyone who lacks knowledge about the phenomenon.”</i> [Participant #19, Task H2, after the PDC]
Level 5	The models serve as (i) instructional aids; (ii) simulations; (iii) facilitators of our conceptual understanding about a phenomenon under study; (iv) communication tools; (v) external representations for a phenomenon under study; and (vi) vehicles for formulating and testing of predictions	<i>“First of all, the development of a model benefits the creator of the model, because during developing the model he gives emphasis to the essential processes that take place during the phenomenon, and also to the relationships between objects and variables. Hence, he doesn't need to pay attention to details that pertain to the visual appearance of the phenomenon and thus he understands in a better way the phenomenon. Secondly, not only the creator of a model is benefited for engaging himself in modeling a phenomenon, but also those who use and study the model afterwards are also benefited, because it helps them in explaining how the phenomenon functions. Thus, a model can be used effectively for instructional purposes, especially when the direct observation of a phenomenon is difficult, or when a phenomenon is too short or long lasting, etc. Also, the model can be used by a wide range of audiences, because it serves as a tool for public communication between its creator and the people who are going to use it. Finally, a model can help us in formulating and testing of predictions, because we can vary the value of one of its variables and study what would be the effect. This is similar to what the simulations enable us to do so.”</i> [Participant #10, Task H1, after the PDC]

The levels presented in Table 21 demonstrate increasing sophistication in quantity and quality of teachers' epistemic awareness in relation to the purpose or utility of models. Starting from the least inferior level, the teachers, whose responses were classified in this level, considered the models as tools that help in mimicking *reality* and for *information delivery*. The first purpose reflects a naive conception for the purpose of models, as it implies a "1:1" association of the model and the phenomenon it represents. The latter purpose that pertains to models as vehicles for information delivery can be considered among the many purposes that models play in science teaching and learning, but it is not one of the primary purposes for developing models in science. Additionally, Level 2 also encompasses two purposes for model development (e.g., for instructional purposes and information delivery), but again these purposes cannot be thought as among the primary purposes for building models. Even though Level 2 and Level 1 share the information delivery related purpose in their definition, Level 2 is superior to Level 1, because it does not entail the naive conception of models as replicas of phenomena. Instead, it entails the purpose of models as *instructional aids*, a notion that is common among teachers who introduce ready-made models within their instruction to help their students gain insight to phenomena that are difficult to be approached through direct observations.

Level 3 entails the purpose of models as instructional aids that was identified in the previous level, but it also includes three other important purposes. The first relates to the use of *models as simulations*, and the second relates to the purpose of models as vehicles for enhancing our understanding about a phenomenon. To document the purpose of models as simulations, the teachers stated that *models can often substitute the setup of an experiment for investigating a phenomenon*, or *models facilitate the experimentation for the phenomenon being modeled*, or *models can be used for making additional observations or collecting data about a phenomenon that is not easily accessed*. Secondly, to support the claim that *models serve as tools that enhance our conceptual understanding* about a phenomenon under study, the teachers mentioned that models *help in understanding of how a phenomenon functions*, or *provide an explanation of a possible underlying mechanism of the phenomenon they represent*, or *help in interpreting a phenomenon*. The third purpose relates to *models as communication tools*. Statements that entailed a social contribution of models to enhance the communication between the creator and the users of the model (e.g., *a model serves as a communication tool through which its creator disseminates his ideas to the public*) were coded within the communicative role of models.

Level 4 entails all the purposes that are met in Level 3, and also the notion that models serve as *external representations* for a phenomenon under study. Statements from teachers' responses that were used to support this claim were as follows; *models enable the representation of a complex phenomenon, models make things "visible, and models help in decomposing a phenomenon into its constituent components.*

Lastly, Level 5, which is the most superior level that emerged, embodies all the purposes that constitute Level 4 and also the purpose of models in relation to the formulation and testing of predictions/hypotheses. This idea was more frequent in the case of Assessment Task H1 that made use of the computer-based model of the light color vision, since the teachers were able to alter the quantity of each of the mixing light colors and see the resultant color of light that the human brain perceived.

Both prior to the PDC and after the PDC the distribution of teachers across the levels that emerged was found to be almost equivalent, although a few more teachers were grouped in Level 5 in Task H1 after the PDC (see Table 22 below). Nevertheless, the comparison between teachers' performance prior to and after the PDC designates that teachers' meta-modeling knowledge with respect to the purpose or utility of models was enhanced, since all teachers moved to the upper levels that emerged from the analysis of their responses in the assessment tasks.

Table 22. Purpose or Utility of Models: Teachers' Responses Distribution in Tasks H1 and H2 Across the Emerged Levels Prior to and After the PDC

Levels of meta-modeling Knowledge: Purpose or utility of models	Pre-Assessment Task H1 (color light vision)	Pre-Assessment Task H2 (cell division)	Post-Assessment Task H1 (color light vision)	Post-Assessment Task H2 (cell division)
Level 1	5	5	0	0
Level 2	5	7	0	0
Level 3	8	7	0	0
Level 4	2	1	8	11
Level 5	0	0	12	9

#### 4.2.4. Quantitative findings of teachers' modeling ability

Quantitative analyses were followed after the phenomenographic analysis of teachers' responses in all assessment tasks in an attempt to answer the following questions: (i) *How does teachers' modeling ability prior to and after the PDC compare?* And (ii) *How does teachers' performance between the assessment tasks that evaluated the same aspect of the*

modeling ability framework prior to and after the PDC compare? The findings that were revealed in relation to these questions are provided in the sections that follow.

#### 4.2.4.1 How does teachers' modeling ability prior to and after the PDC compare?

The Wilcoxon test procedure revealed that the rank scores on each set of the post-assessment tasks that evaluated the same aspect of the modeling ability framework were statistically higher than the corresponding scores on the pre-assessment tasks. These findings indicate that the PDC had a great impact on the development of all aspects of teachers' modeling ability in unison. All comparisons for each aspect of the modeling ability framework and their statistical significance are presented in Table 23.

Table 23. Pre- and Post- Comparisons for Each Aspect of Teachers' Modeling ability

Modeling ability aspect	Assessment Task	Z score	P
<i>Model formulation skill</i>	Task A1	-3.943	<.0001
	Task A2	-3.471	.001
<i>Identification of models component skill</i>	Task B1	-3.976	< .0001
	Task B2	-3.977	<.0001
<i>Comparing and contrasting models of the same phenomenon skill</i>	Task C1	-2.194	.028
	Task C2	-3.968	<.0001
<i>Model evaluation and formulating ideas for improvement skill</i>	Task D1	-3.598	<.0001
	Task D2	-3.360	.001
<i>Model validation through comparison with phenomena of the same class skill</i>	Task E1	-3.314	.001
	Task E2	-2.714	.007
<i>Metacognitive knowledge about the modeling process</i>	Task F1	-4.008	<.0001
	Task F2	-4.008	<.0001
<i>Meta-modeling knowledge: Nature of models</i>	Task G1	-3.050	.002
	Task G2	-3.122	.002
<i>Meta-modeling knowledge: Purpose or utility of models</i>	Task H1	-4.018	<.0001
	Task H2	-4.018	<.0001

**4.2.4.2. How does teachers' performance between the assessment tasks that evaluated the same aspect of the modeling ability framework prior to and after the PDC compare?**

To evaluate how teachers' performance between each set of assessment tasks that evaluated the same aspect of the modeling ability framework compares, the Wilcoxon test procedure was used. The procedure was followed to compare teachers' performance prior to and after the PDC for each set of the assessment tasks. The findings that yielded from this analysis are presented in Table 24 and are discussed henceforward.

Table 24. Teachers' Performance between Assessment Tasks of the same aspect of the modeling ability framework (Pre-Assessment and Post-Assessment Comparisons)

Modeling ability aspect	Assessment Tasks	Z score	P
<i>Model formulation skill</i>	Pre-Task A1 vs Pre-Task A2	-1.200	.230
	Post-Task A1 vs Post-Task A2	-2.648	.008
<i>Identification of models component skill</i>	Pre-Task B1 vs Pre-Task B2	-1.000	.317
	Post-Task B1 vs Post-Task B2	-1.000	.317
<i>Comparing and contrasting models of the same phenomenon skill</i>	Pre-Task C1 vs Pre-Task C2	-3.428	.001
	Post-Task C1 vs Post-Task C2	-1.261	.207
<i>Model evaluation and formulating ideas for improvement skill</i>	Pre-Task D1 vs Pre-Task D2	-3.150	.002
	Post-Task D1 vs Post-Task D2	-1.807	.071
<i>Model validation through comparison with phenomena of the same class skill</i>	Pre-Task E1 vs Pre-Task E2	-0.649	.516
	Post-Task E1 vs Post-Task E2	-1.851	.074
<i>Metacognitive knowledge about the modeling process</i>	Pre-Task F1 vs Pre-Task F2	-0.447	.655
	Post-Task F1 vs Post-Task F2	-1.000	.317
<i>Meta-modeling knowledge: Nature of models</i>	Pre-Task G1 vs Pre-Task G2	-1.089	.276
	Post-Task G1 vs Post-Task G2	-1.394	.163
<i>Meta-modeling knowledge: Purpose or utility of models</i>	Pre-Task H1 vs Pre-Task H2	-1.732	.083
	Post-Task H1 vs Post-Task H2	-1.732	.083

The Wilcoxon test procedure revealed that the rank scores on all but three sets of the pre-assessment or post-assessment tasks, that evaluated the same aspect of the modeling ability framework, were not statistically higher than the corresponding scores on the pre-assessment or post-assessment tasks. This finding designates that the aspects of the modeling ability framework for which no statistically significant differences were found

are not content-specific. Statistically significant differences were found in the (i) pre-assessment tasks that evaluated teachers' *comparing and contrasting models of the same phenomenon skill*, and *model evaluating and formulating ideas for improvement skill*, and (ii) post-assessment tasks that evaluated teachers' *model formulation skill*.

Given the fact that no statistically significant differences were found in the post-assessment tasks that evaluated teachers' *comparing and contrasting models of the same phenomenon skill*, and *model evaluating and formulating ideas for improvement skill*, the differences that emerged prior to the PDC might be associated with either the *content* of the assessment task or teachers' *level of acquisition of these modeling skills* or *prior knowledge* prior to the PDC. The first assumption (i.e., the differences can be attributed to the content of the assessment tasks) can be safely rejected, because if this was true, the content of the assessment tasks would also affect teachers' performance on these assessment tasks, when administered after the PDC. Hence, the second and third assumptions (i.e., teachers' prior knowledge or level acquisition of these specific modeling skills prior to the PDC) can be used to explain these differences.

On the other hand, the statistically significant differences that were revealed between the post-assessment tasks for the *model formulation skill* might be attributed to either teachers' prior background knowledge and understandings of the phenomena they were asked to model, or to the degree of transfer of their model formulation skill in new contexts, or both. The credibility of these assumptions is discussed in the Discussion chapter.

### **4.3. Research question 2: How do teachers' CK about models and modeling and CuK for MCSI change as a result of their participation in the PDC?**

#### **4.3.1. Teachers' CK about models and modeling**

Teachers' CK about models and modeling was assessed through three data sources. The first data source concerns the CK test (see Data Collection section in Chapter 3) that was administered prior to and after Phase 1 ("Teachers as Learners") of the PDC, the second data source relates to teachers' reflective diaries that were completed after each class meeting during Phase 1 of the PDC, and the third data source entails teachers'

asynchronous discussions in BeEP on certain topics that took place during the Phase 1 of the PDC. All sources of data were analyzed with the use of open-coding techniques. The findings that emerged from the analysis of the abovementioned data sources are presented in three consecutive sections in relation to teachers' CK about models and modeling.

#### 4.3.1.1. Teachers' CK about models

Teachers' (i) definitions of scientific models, (ii) knowledge about the possible existence of two models to represent the same phenomenon, (iii) knowledge about models' feasibility to represent the "absolute reality", and (iv) knowledge about model evaluation criteria, constitute the four lenses through which teachers' CK about models was studied. To examine teachers' CK for each of these lenses, data from all data sources described above were used. Each of these lenses is elaborated below.

##### 4.3.1.1.1. Definitions of scientific models

Whenever teachers were prompted to reflect on the question "What is a scientific model in natural sciences?", they made statements that embodied their epistemic understandings about the *nature of models*, *purpose of models*, *entities of models*, and *means for developing models*. Of course, this does not imply that all teachers' definitions of scientific models always included references on all four epistemological domains mentioned above; instead, the *nature of models* was the central theme in all teachers' statements, followed by references that pointed to the *purpose of models*, and the rest of their statements either fell on the domain of *entities of models* or the *means for developing models*. The following three teachers' definitions of scientific models are used as representative examples to explain this assertion.

Table 25. Examples of teachers' definitions of scientific models in conjunction with their epistemological elements

	Definition	Epistemological elements within definitions
1.	"A model is a representation of a phenomenon that we use in science teaching".	Nature of models: A model is a representation of a phenomenon Purpose of models: We use in science teaching
2.	"A model is developed with a computer software through which we try to make a representation of a phenomenon we are interested in.	Means for developing models: A model is developed with a computer software Nature of models: a representation of a phenomenon we are interested in
3.	"The term 'model' relates to any representation we create with various means (e.g., concrete materials, modeling software, etc) through which we aim at interpreting a phenomenon	Nature of models: The term 'model' relates to any representation Means for developing models: concrete materials, modeling software, etc

*under study. In developing a model, we pay attention in integrating the variables and processes that we identified from the phenomenon”.*

Purpose of models: *we aim at interpreting a phenomenon under study*

Entities of a model: *variables and processes*

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Teachers varied dramatically in their initial attempts to define a scientific model (see Table 26 for the emerged themes and their prevalence). Although the majority of teachers made a reference about the nature of models that relates to models as *representations of phenomena* under study, they also made statements that point to models as: (i) *static forms* (see theme A2 in Table 26); (ii) *replicas of reality* (see theme A3 in Table 26); and (iii) *mental or analogical representations* (see themes A4 and A7 in Table 26 respectively). There was also a limited number of references on *models as not replicas of reality* (see theme A6 in Table 26), and also very few participants confused scientific models with the term “teaching models” used in instructional settings (see theme A5 in Table 26).

In terms of the *purposes of models*, the two most frequent themes that emerged relate to models as *means for enhancing our understanding* of a phenomenon under study (see theme B1 in Table 26), and models as *instructional aids* that facilitate students’ learning during science teaching (see theme B2 in Table 26). Other less frequent themes that pertain to the purpose of models concern the use of models for *interpreting our observations* (see theme B3 in Table 26), for *testing of predictions* for the phenomenon being modeled (see theme B4 in Table 26), and for *helping a less knowledgeable person in understanding a particular phenomenon* (see theme B5 in Table 26).

As far as the *entities of models* and the *means used for creating models* are concerned, the references within teachers’ definitions of models were scarce. For instance, there was only one reference on *processes* and one on *relationships* as the entities of models (see themes C1 and C2 in Table 26 respectively), and a few references on the use of modeling software or other means (e.g., mathematical formulas, drawings, etc) for creating models (see theme C1 in Table 26).



Table 26. Teachers' Definitions of Scientific Models Prior to Phase 1 of the PDC

Clusters of emerged themes	Emerged themes from teachers' definitions	<i>f</i>
A. Nature of models	1. a model is a representation of a phenomenon (e.g., a process, a system, a concept, an object) under study	13
	2. a model is a concrete object (e.g., an apparatus, an image, etc)	6
	3. a model is a copy or a replica of a prototype in a smaller scale or in a simplified manner	6
	4. a model is a mental representation of a phenomenon or a process	3
	5. a model refers to the context within which science teaching is implemented (e.g., a model of teaching)	3
	6. a model is not a replica of the phenomenon, thus it does not represent the absolute reality	2
	7. a model is an analogical representation of the physical world	2
B. Purpose of models	1. a model helps in understanding in a better way a phenomenon	9
	2. a model serves as an instructional medium that is used in science teaching	7
	3. a model helps in explaining our observations	3
	4. a model enables the testing of predictions based on the phenomenon being modeled	2
	5. a model is a way for a more knowledgeable individual to help a less knowledgeable person understand a particular phenomenon	1
C. Entities of a model	1. a model entails relationships between its elements	1
	2. a model entails processes from the phenomenon	1
D. Means for developing models	1. models are created with the use of computer-based software or other means (e.g., mathematical formulas, drawings, etc)	4

During the PDC, the teachers were systematically asked to provide their evolved definitions of scientific models (e.g., within their reflective diaries, asynchronous discussions in BeEP, and their completed activity sheets). Their definitions embodied several standpoints that illuminate their content knowledge about scientific models. To illustrate how teachers' initial attributes of scientific models were enriched, revised, changed or remained stable during Phase 1 of the PDC, emerged themes that were revealed from the analysis of teachers statements during Phase 1 of the PDC are provided in Table 27.

Table 27. Emerged Themes from Teachers' Definitions of Models During Phase 1 of the PDC

Clusters of emerged themes	Emerged themes	Extracts from teachers' definitions of scientific models
A. Nature of models	1.1 A model is defined by its (i) representational completeness, (ii) interpretive potential, and (iii) predictive power	<i>"I realized that the models are representations of the physical world, through which we seek to interpret the phenomena we are studying, and we can use them for formulating hypotheses about the phenomena or testing predictions about the phenomena"</i> [Participant #12, After Session 4 of Phase 1 of the PDC]
	1.2 A model is defined by its (i) representational completeness, (ii) interpretive potential, (iii) predictive power, and (iv) its validity (applicability to phenomena of the same class)	<i>"A major characteristic of scientific models is their validity; specifically the model should entail the basic aspects of the phenomenon it represents (e.g., objects, variables, process, and interactions), provide a mechanism for how the phenomenon functions, and enable the formulation and testing of predictions. In addition, it should apply to a number of phenomena of the same class. For instance, the model we created for the first experiment we observed applied only in a single case of 1-D elastic collisions, whereas the final model we created at the end of the sessions was characterized by its wide applicability, as it applied to a range of 1-D collision phenomena (e.g., any carts with any velocity and any mass that collide)"</i> [Participant #19, After Session 6 of Phase 1 of the PDC]
	2. Models are continually improved in light of new evidence	<i>"I learned that a model that we build is continually improved, because there isn't a model that cannot be improved. For instance, the first model that we created in paper was incomplete, because it didn't show the evolution of the phenomenon in a dynamic way (it was static). It also didn't show what was going on during the event of the collision. Hence, we improved our model by creating it from scratch in Stagecast Creator and we paid attention in adding the information that was missing from our previous model"</i> [Participant #6, After Session 1 of Phase 1 of the PDC]
	3.1 Elegance is important; simpler models may explain better than complex ones	<i>"I learned that for making a model more robust, you need to continually compare it with the real phenomenon it represents. Whenever you identify something new from the phenomenon (e.g., a variable, a process, etc) you need to go back to your model and improve it by adding these new elements"</i> [Participant #4, After Session 1 of Phase 1 of the PDC]
3.2 Elegance is important; simpler models would be understood better by learners	<i>"Because the model we are creating should be as simple as possible, then we need to create simple rules in Stagecast Creator for achieving this goal. There could be more than one models that are valid. The criterion for selecting the most appropriate one is model's elegance"</i> [Participant #12, After Session 2 of Phase 1 of the PDC]	
	3.2 Elegance is important; simpler models would be understood better by learners	<i>"I learned something new after this class session. This is the issue of model's elegance. Our models should be as simple as possible, because a simpler model might help the user of the model, whether the user is a young student or not, to understand in a better way the phenomenon the model represents"</i> [Participant #1, After Session 2 of Phase 1 of the PDC]

4. Models should provide an interpretation of how a phenomenon functions

*“The interpretation for the collision phenomenon we observed is given through our model and is based on the idea of “velocity transfer” from the moving cart to the stationary cart at the event of the collision. For example, the moving cart moves to the right with constant velocity prior to the collision. Next, it collides with the stationary cart and as a result the value of the velocity of the moving cart is “transferred” to the value of the variable of the stationary cart. As a result, the value of the velocity of the moving cart is set to zero and the stationary cart starts moving to the right with the value of the velocity that acquired from the moving cart.” [Participant #9, After Session 2 of Phase 1 of the PDC]*

*“In Stagecast Creator we ended up with a model through which our primary purpose was to interpret the phenomenon of the collision we observed. Although we are at an initial stage of our model, we are planning to create rules to illustrate what is happening during the moment of collision.” [Participant #10, After Session 2 of Phase 1 of the PDC]*

*“Additionally, the activity that asked us to propose a name for our model helped me to think of what is happening behind the phenomenon we modeled; was it the energy or the velocity or both that was transferred? [Participant #10, After Session 2 of Phase 1 of the PDC]*

5.1 A model should be consistent with the existing scientifically acceptable knowledge for the phenomenon it represents

*“Maybe we could replace the velocity variable with a new variable that we will create, the “kinetic energy” variable, in order to make our model more conceptually correct. Of course, this could be done in the next session after receiving the feedback from our peers” [Participant #5, After Session 2 of Phase 1 of the PDC]*

*“I need to declare that during the collision the two carts swap their kinetic energy and not their velocities. Even though we built our model around the idea of velocity swap, in improving our model we will make it more scientific by showing the kinetic energy swap. I’m a physicist and this is a fundamental knowledge that I already know and need to incorporate it in our model” [Participant #2, After Session 2 of Phase 1 of the PDC]*

5.2 A model might be created around an idea that even though is not consistent with the scientifically established knowledge, it interprets the phenomenon in a satisfactory level

*“What I learned in this session is that when creating a model, it is not necessary to formulate rules that exist in real. If the model produces the same behavior as the real phenomenon does, then our model is considered as satisfactory one. For instance, although the mechanism that exists for the real phenomenon relates to the transfer of energy from one cart to the other, in our model we applied the velocity swap mechanism, and noticed that the results of our model are congruent with the results obtained from the real phenomenon” [Participant #11, After Session 4 of Phase 1 of the PDC]*

B. Purpose of models

1. Models serve as tools that enhance our conceptual understanding about phenomena we are studying

*“Building a model helps in understanding the phenomenon. I think that it was better that we didn't interpret the phenomenon prior to constructing it. The rules that we created for the objects of our model, as well as the variables that we needed to create helped us in analyzing and explaining the phenomenon” [Participant #20, After Session 3 of Phase 1 of the PDC]*

2. Models serve as platforms for formulating and testing of predictions

*“One can use our model for testing a prediction for the phenomenon it represents. First, he needs to make a prediction; next he can alter the value of the variable, and then observe the changes that occur within the*

		<p><i>phenomenon. Hence, he can verify or reject his prediction and through this way he will increase his understanding about the phenomenon.” [Participant #13, After Session 3 of Phase 1 of the PDC]</i></p>
	<p>3. Models serves as means for a more knowledgeable person to explain to a less knowledgeable person how a phenomenon functions</p>	<p><i>“Following the activity sequence of the curriculum we were working with, we were asked to formulate a prediction and then check our prediction by using our model. Unfortunately our model didn’t satisfy the criterion of predictability, because we didn’t connect the velocities of the two carts. The user and not the model had to manually set the value for each of the cart velocity and “test” his predictions. As a result, the predictive power of the model was very limited. Consequently, we had to revise our model in a way that the formulation and testing of predictions was feasible. What we did was introduce in our model another velocity variable, the ‘velocity after the collision’, and then formulated a rule to connect the initial with the final velocities” [Participant #4, After Session 2 of Phase 1 of the PDC]</i></p>
<p>C. Entities of models</p>	<p>1. A model encompasses objects, variables, processes, and interactions among its constituent components</p>	<p><i>“Our model entails all necessary information that will help someone who look at it to get insight on how the collision phenomenon we observed functions. There is no need for the user to have a look at the real collision; instead she can study our model and see what is happening during the collision of the two carts (e.g., the carts swap their velocities during the event of the collision).” [Participant #16, After Session 5 of Phase 1 of the PDC]</i></p>
	<p>2. A model encompasses a mechanism that explains how the phenomenon functions</p>	<p><i>“In the previous session I learnt that the major components of a model are the objects (e.g., the carts, the air-track), the variables (e.g., the velocity of each cart, the mass of each cart), the processes (e.g., the motion of the carts, the swapping of their velocity during the collision), and the interactions (e.g., the velocity of each cart interacts during the event of the collision).” [Participant #6, After Session 3 of Phase 1 of the PDC]</i></p>
	<p>3. A model encompasses the aspects of the phenomenon that are needed for testing a theory</p>	<p><i>“Apart from the constituent components of the model (e.g., objects, variables, processes, and interactions), a model entails a mechanism that account for the behavior or the function of the phenomenon. For instance, in our second model the mechanism that we created to control the behavior of the carts after the collision was based on the idea of “velocity reflect” (e.g., the velocity of each cart changes from negative to positive and vice versa at the moment of collision) [Participant #17, After Session 3 of Phase 1 of the PDC]</i></p>
	<p>3. A model encompasses the aspects of the phenomenon that are needed for testing a theory</p>	<p><i>“I also came to understand that a necessary condition that needs to be satisfied is that the model should entail all aspects of the phenomenon that are useful for testing a theory” [Participant #7, After Session 5 of Phase 1 of the PDC]</i></p>

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According to Table 27, the themes that emerged from teachers' ongoing definitions of scientific models indicate that teachers' personal engagement with the modeling-based curriculum activities during Phase 1 of the PDC enabled them to enrich their content knowledge about models, and at the same time to surpass their naïve conceptions about the nature of models that were expressed at the beginning of the PDC. This claim is also supported from the findings that came out from the analysis of teachers' definitions of scientific models in the CK test that was administered after the end of Phase 1 of the PDC (Note: the same CK test was administered at the beginning of Phase 1 of the PDC and the findings from CK test are reported in Table 26). The emerged themes from teachers' definitions of scientific models and the clusters of these emerged themes after the PDC are presented in Table 28. Table 28 also entails the findings from the same CK test in relation to teachers' definitions of scientific models for comparative purposes.

Table 28. Comparisons of Teachers' Definitions of Scientific Models in the CK test Prior to and After Phase 1 of the PDC

Clusters of emerged themes	Emerg ed themes from teachers' definitions	Prior to Phase 1 of the PDC	After Phase 1 of the PDC
A. Nature of models	1. a model is a representation of a phenomenon (e.g., a process, a system, a concept, an object) under study	13	19
	2. a model is grounded on a personal theory of its creator that points to how the creator understands how the phenomenon functions	0	11
	3. a model is not a replica of the phenomenon, thus it does not represent the absolute reality	2	10
	4. a model should apply to a family of phenomena of the same class	0	6
	5. a model is a concrete object (e.g., an apparatus, an image, etc)	6	0
	6. a model is a copy or a replica of a prototype in a smaller scale or in a simplified manner	6	0
	7. a model is a mental representation of a phenomenon or a process	3	0
	8. a model is an analogical representation of the physical world	2	0
	9. a model refers to the context within which science teaching is implemented (e.g., a model of teaching)	3	0
B. Purpose of models	1. a model helps in representing, explaining or interpreting (e.g., provide a mechanism for how the phenomenon functions) the phenomenon, and enable the formulation and testing of predictions	0	12
	2. a model enables the testing of predictions based on the phenomenon being modeled	2	8
	3. a model helps in understanding in a better way a phenomenon	9	6
	4. a model serves as a means for a more knowledgeable person to help a less knowledgeable person in understanding a particular phenomenon	1	5
	5. a model helps in explaining our observations	3	2
	6. a model serves as an instructional medium that is used in science teaching	7	0
C. Entities of a model	1. a model encompasses objects, variables, processes and interactions among the components of the phenomenon	0	19
	2. a model encompasses only certain aspects of the phenomenon	0	12

	that we are interested in studying		
	3. a model contains relationships between its elements	1	0
	4. a model encompasses processes from the phenomenon	1	0
D. Means for developing models	1. models are created with the use of computer-based software or other means (e.g., mathematical formulas, drawings, etc)	4	15

The findings presented in Table 28 indicate that, after Phase 1 of the PDC, the prevalence of some themes that emerged prior to Phase 1 was either increased or eliminated, and also new themes emerged after the end of Phase 1. Specifically, as far as the nature of models is concerned, almost every teacher stressed that *a model is a representation of a process, a system, a concept, an object, etc* (see emerged theme A1), and half of them noted that *models do not represent the absolute reality*, and thus they do not serve as copies of the phenomenon they represent (see emerged theme A3). Two new themes, which appeared within teachers' responses after Phase 1 of the PDC, indicate that *a model is grounded on a personal theory of its creator that points to how the creator understands how the phenomenon functions* (see emerged theme A2), and *a model should apply to a family of phenomena of the same class* (see emerged theme A4). The first one, which was mentioned by slightly more than half of the participants, encompasses two important issues in relation to the nature of models. The first issue relates to the element of *subjectivity* that characterizes a model (e.g., a model is grounded on a *personal* theory of its creator, that illustrates how he/she thinks or understands the function of the phenomenon), and the second issue points to models as *human constructs* (e.g., a model is created by a someone...). The second new emerged theme (that models should apply to family of phenomena of the same class), albeit not frequently expressed, it also points to another aspect of the nature of models; models can be considered as valid, if they are applicable not only to the phenomenon they originated from, but if they apply on a family of phenomena of the same class (e.g., in the context of 1-D elastic collisions, the teachers came to understand that their model was considered as valid when it could be effectively applied to each different collision experiments they studied).

Additionally, the themes that point to uninformed views of the nature of models and were evidenced within teachers' definitions of scientific models were eliminated after Phase 1 of the PDC (see A5 through A9 emerged themes in Table 28).

As far as the purposes of models are concerned, the most frequent statement that was evident in more than half of the participants' definitions of models and appeared only in the post CK test, refers to the *use of models for representation and interpretation (or explaining) purposes*, and also for the formulation and testing of predictions (see emerged theme B1 in Table 28). The rest of the participants used only the part of the previous comprehensive statement that relates to the use of models for testing of predictions (see emerged theme B2 in Table 28) and a combination of other purposes of models like *a model serves as a means for a more knowledgeable person to help a less knowledgeable person in understanding a particular phenomenon* (see emerged theme B4 in Table 28), or *a model helps in understanding in a better way a phenomenon* (see emerged theme B3 in Table 28), or, *a model helps in explaining our observations* (see emerged theme B5 in Table 28). It is important to state, that the use of a model as an instructional medium, a theme that was revealed in the statements of seven teachers in the pre-CK test, was eliminated in their post CK test responses.

Significant changes were also evidenced in teachers' references on the entities of a model. As the findings in Table 28 indicate, prior to Phase 1 of the PDC, the teachers did not make any references on the entities of a model when they sought to provide a definition for a scientific model. On the contrary, after Phase 1 of the PDC, almost every teacher thought of important to state that a model encompasses *objects, variables, processes, and interactions among the components of the phenomenon*. Additionally, twelve teachers expressed the idea that a model should encompass *only* the aspects of the phenomenon that we are interested in.

Lastly, the number of teachers who made references on the means that are used for developing models was also increased by the end of Phase 1 of the PDC (see theme D1 in Table 28). This finding might be attributed to the fact that throughout Phase 1 of the PDC the teachers created models of two forms (e.g., paper-and-pencil models and computer-based models with the use of SC software), and they were also introduced to other forms of models for the same phenomenon like verbal models, mathematical formulas, and graphs.

#### *4.3.1.1.2. Knowledge about the possible existence of two models to represent the same phenomenon*

A second lens through which teachers' CK about models was studied pertains to teachers' standpoints on whether a phenomenon could be represented by two different models. Prior

to Phase 1 of the PDC, all but one teacher agreed that it is feasible two different models to represent the same phenomenon, but the arguments used to support this claim varied considerably. For instance, the most predominant argument they posed was that two models might differ in relation to the representational medium used for their creation (see emerged theme 1 in Table 29). Other less frequent arguments relate to the difference between the models with respect to: (i) the aspect of the phenomenon each model represents (see emerged theme 2 in Table 29) or (ii) the prior knowledge and the age level of the creator of each model (see emerged theme 3 in Table 29). The number of references that embodied scientifically informed arguments, e.g., there could be two different models that represent the same phenomenon depending on: (i) how the creator of each model understands or interprets the phenomenon (see emerged theme 4 in Table 29), and (ii) the interpretive power of each model and the degree of its complexity (see emerged theme 5 in Table 29), was very limited. A summary of the emerged themes that were revealed from the analysis of teachers' responses about the possible existence of two models that represent the same phenomenon are presented in Table 29.

Table 29. Teachers' CK about the possible existence of two models that represent the same phenomenon prior to Phase 1 of the PDC

Emerged themes	Prior to Phase 1 of the PDC
<i>There could be two different models that represent the same phenomenon, depending on ...</i>	
1. ...the modeling medium (e.g., computer-based modeling models, physical models, graphical models, mathematical models, etc) that was used for the development of the model	8
2. ...the aspect of the phenomenon that was chosen to be modeled	6
3. ...the prior knowledge and age level of the creator of each model	5
4. ...how the creator of each model understands or interprets the phenomenon (e.g., a phenomenon could be explained by more than one "personal" theories)	4
5. ...the interpretive power of each model (e.g., the underlying mechanism that each model was developed differs) and the degree of its complexity	3
6. I don't know if there could be two models that represent the same phenomenon	1

From the very first session of Phase 1 of the PDC, the participants were asked to create a paper-and-pencil model for the collision experiment they observed and then, after evaluating their model and identified its weakness to represent, interpret and be used for testing of predictions, they proceeded on developing an improved version of their model in SC. During creating their model in SC, the teachers encountered difficulties when they were trying to decide of a possible mechanism that could be used for interpreting the collision phenomenon they observed. Those who succeeded on creating a model that was



consistent with their observations, the model they created was based on a complex mechanism in terms of the rules they created in SC to control the motion of the two colliding carts, and its applicability to other similar collision phenomena was very limited (e.g., their model could run correct only with specific values in the velocities of the carts). They also struggled to think of alternative way of how the phenomenon they observed could be represented in SC. The following extract from a participant's reflective diary is particularly revealing:

*“I think there could be multiple models that represent the same phenomenon. However, I cannot think of an alternative way that we could have followed for creating our model in Stagecast Creator.”*

Once the teachers finished creating a model in SC, they were asked to compare it with the paper-and-pencil model they created right after they observed the event of an elastic collision, and reflect on the similarities and differences between the two models. The purpose behind this curriculum activity was to enable teachers to understand that the modeling medium used for developing a model might constrain its representational completeness, its interpretive potential, and also its predictive power. An extract from a pair of teachers' activity sheet is provided below to illustrate the criteria used during comparing the two models.

*“In our model in Stagecast Creator the velocities of the two carts are always visible, so one can observe that the carts move with constant velocities. You can also see what is happening during the collision; the two carts swap their velocities. These important features of our model are not met in the paper-and-pencil model; the model in paper shows the four major instances of the phenomenon, and the intermediate phases are left to the observer to infer what is going on. Hence, even though the two models represent the same collision experiment, the model in Stagecast Creator is more dynamic and more comprehensive.”*

From the abovementioned extract it is evident that the teachers identified that the paper-and-pencil model fell short in: (i) representation comprehensiveness (e.g., it did not show the velocity of each cart as the experiment was running or it is not dynamic compared to the SC model); and (ii) interpretive potential (e.g., it did not reveal a mechanism to explain what is happening with the velocities of the carts during collision).

As the sessions of the PDC continued, the teachers came to understand that one of the key features of scientific models is their “elegance”. This epistemic understanding was cultivated both during teachers' engagement in modeling the elastic collision phenomena

they studied, and during discussing about or evaluating their models with their peers. Accordingly, they used model elegance as an additional criterion for evaluating a scientific model. The rest of the model evaluation criteria that teachers developed during the PDC pertain to model: (i) representational comprehensiveness; (ii) interpretive potential; and (iii) predictive power. The following extract from a participant’s reflective diary is an exemplar of the criteria used for choosing the most appropriate model for representing and interpreting a phenomenon.

*“During the previous session, I confirmed something I already knew theoretically, but I’m not sure if I have ever been in the case to confirm it in practice. We discussed with my peer if it is feasible for more than one models to exist that can describe the same phenomenon, and how can we decide which one is better to choose to use or create. Basically, both models that we thought of could describe and interpret the collision experiment we observed, and both of them could be used for testing predictions. Hence, a second criterion that we decided to apply in choosing the best model was model elegance. Between two models that are equal in terms of validity, we tend to choose the simplest one. If one combines this criterion with the development of a theory (theories=families of models), she will find out that not only a theory has to be in line with our observations, or has strong predictive power, but it should also be simple and understandable by a wide audience.”*

To obtain comparable pre- and post- test results concerning teachers’ CK about the possible existence of two models that represent the same phenomenon, the same question that was used in the pre- CK test was administered again after the end of Phase 1 of the PDC. The findings that yielded from the analysis of teachers’ responses in the post-CK test, in conjunction with the findings from the pre- CK test, are presented in Table 30.

Table 30. Teachers’ CK about the possible existence of two models that represent the same phenomenon prior to and after Phase 1 of the PDC

Emerg ed themes	Prior to Phase 1 of the PDC	After Phase 1 of the PDC
<i>There could be two different models that represent the same phenomenon, depending on ...</i>		
1. ...how the creator of each model understands or interprets the phenomenon (e.g., a phenomenon could be explained by more than one “personal” theories)	4	15
2. ...the modeling medium (e.g., computer-based modeling models, physical models, graphical models, mathematical models, etc) that was used for the development of the model	8	13
3. ...the interpretive power of each model (e.g., the underlying mechanism that each model was developed differs) and the degree of its complexity	3	7
4. ...the aspect of the phenomenon that was chosen to be modeled	6	6
5. ...the prior knowledge and age level of the creator of each model	5	0
6. I don’t know if there could be two models that represent the same phenomenon	1	0

According to the findings of Table 30, the majority of teachers used scientifically informed arguments for supporting their statements about the possible existence of two models to represent the same phenomenon after Phase 1 of the PDC. Specifically,  $\frac{3}{4}$  of the participants reported that there could exist two different models that represent the same phenomenon, and the difference between these models lies on the “personal theory” the creator of each model used for their development (see emerged theme 1 in Table 30). The teachers who used this argument designated that given the creator of a model personal theory pertains to the way she/he understands or interprets the way the phenomenon functions, then two individuals who interpret a phenomenon in totally different ways might end up with two different models that interpret the phenomenon in totally different causal or explanatory mechanisms. Even though this argument is quite similar to the argument that two models might differ in terms of their interpretive power and their complexity (see emerged theme 3 in Table 30), the later argument does not explicitly entail the idea of models as social constructs, and hence it is considered as a different type of argument.

Additionally, the prevalence of the argument that pertains to the idea that two models might differ with respect to the modeling medium used for their development was also increased at the end of Phase 1 of the PDC (see emerged theme 2 in Table 30), whereas the prevalence of the argument that two models might differ with respect to the aspect of the phenomenon they represent remained the same (see emerged theme 4 in Table 30). The first argument (e.g., two models might differ with respect to the modeling medium used for their development) was frequently found within teachers’ reflective diaries, when they were prompted to compare and contrast their paper-and-pencil models with the models created in SC. Consequently, the increase of the prevalence of this argument might be attributed to teachers’ learning experiences gained during Phase 1 of the PDC.

#### *4.3.1.1.3. Knowledge about models’ feasibility to represent the “absolute reality”*

A third aspect of teachers’ CK about models concerned their understandings of whether models should represent the “absolute reality”. Prior to Phase 1 of the PDC, the teachers held several misconceptions about the nature, purpose or utility of models and these were revealed within their responses to the question “Do models represent the absolute reality?” (see Table 31 for details). Specifically, the statement that was most frequently found within teachers’ responses to the abovementioned question pertains to the scientifically incorrect idea that *models should represent the absolute reality, but this is not feasible because the*

*phenomena are too complex to be modeled in such a detailed way.* In addition, even though the rest of the themes that emerged from the analysis of teachers' responses entailed a disagreement about models' feasibility to represent the absolute reality, the explanations provided to support this statement in some cases further reinforce the notion that models serve as replicas of physical phenomena (see emerged themes 4 through 7).

Table 31. Teachers' CK about models' feasibility to represent the "absolute" reality

Emerged themes	Prior to Phase 1 of the PDC
1. A model should represent the absolute reality, but this is infeasible, because the phenomena are too complex (e.g., too many variables interact at the same time) to be modeled in such a detailed way	8
2. A model cannot represent the absolute reality, because since a lot of aspects within a phenomenon are "hidden" or not easily observable, the model entails only the creator's subjective interpretation (e.g., a suggested underlying mechanism) for how a phenomenon under study functions	4
3. A model cannot represent the absolute reality, because a model refers to specific aspects of a phenomenon and hence it does not represent a phenomenon as a whole	3
4. A model cannot represent the absolute reality, because a model is just a "tool" that is used for helping someone to understand a phenomenon in a better way	3
5. A model cannot represent the absolute reality, because there could be consistencies and inconsistencies between the model and the phenomenon it represents	3
6. A model cannot represent the absolute reality, because the creator of the model ignored major aspects of the phenomenon or decided to encompass within the model only a few aspects of the corresponding phenomenon (models are human constructs and thus may contain errors or omission of some of the phenomenon components)	2
7. A model cannot represent the absolute reality, because it is constrained by the modeling medium used for modeling the corresponding phenomenon	1

Evidence from teachers' reflective diaries that were completed during Phase 1 of the PDC revealed that teachers were split into three groups according to their views about models' feasibility to represent the absolute reality. The first group pertains to the teachers who expressed the notion that models *should* represent the absolute reality, the second group pertains to the teachers who claimed that models *cannot* represent the absolute reality because this is not feasible, and the third group pertains to the teachers who reported that models *should not* represent the absolute reality. Representative examples from teachers' statements of each group are presented in Table 32 and are elaborated henceforward.

Table 32. Examples of teachers' statements with respect to models' relation with absolute reality

A. Models should represent the absolute reality	B. Models cannot represent the absolute reality because this is not feasible	C. Models should not represent the absolute reality
<p>1. [Which aspects from the real phenomenon are missing from your model?] <i>I think the man who performs the experiment is missing from our model. We need to create a character to show his hand and then create a rule to show that he triggers the experiment (pushes the left cart with his hand and thus the cart moves on the air track). In addition, we need to show the surface in which the carts move on.</i></p>	<p>1. <i>"In my opinion, I agree with what our peers suggested; that for making a model functional, it does not necessarily mean that it must represent the reality, because we are not able to do such a thing. If our model represents the major components from the phenomenon in a way that someone who uses our model will be able to make predictions about the phenomenon, then our model is acceptable. Of course, as much as the absolute reality is represented within our model, this will make our model more robust."</i></p>	<p>1. <i>"In my opinion, a model should not represent the absolute reality because if this was the case, then the whole focus would be on the detailed design of the model and the fundamental objective of modeling, which is the interpretation and explanation of a phenomenon, would be ignored. Different individuals create different representations of the same phenomenon according to how each of them perceives the way the phenomenon functions, and this approach gives freedom to the creator of the model to present the phenomenon from his own perspective."</i></p>
<p>2. <i>"Then we created rules for the carts we observed. We were very careful during creating these rules in order to make the carts look like as close as possible to the real experiment."</i></p>	<p>2. <i>"A model should not substitute reality, because this is not feasible, but it should approximate it in the most accurate manner"</i></p>	<p>2. <i>"I don't agree with this stance, because a model should not represent the absolute reality. Instead, it represents some of the aspects of the phenomenon under study. The model entails similarities and inconsistencies with the reality. The elements that are incorporated within a model are those one is willing to study; and that's why he builds a model. For instance, in the context of the elastic collisions that we are currently studying, we chose to add in our model the aspects from the phenomenon that we want to study, e.g., the change of the velocity and the direction of the carts."</i></p>
<p>3. <i>"The closer the representation is to the reality, the more successful and valid the model we created is."</i></p>	<p>3. <i>"The absolute reality is so difficult, or even unattainable to be represented within a model. Besides, what is 'absolute reality'? Who knows it? May be only God! If we were able to know it and were equipped with the appropriate means, then a model that represented absolute reality would be fascinating!"</i></p>	<p>3. <i>"Our model might not express the absolute reality, because this is not our purpose, but only a part of it; the part that is useful to make our model valid. For instance, we are not concerned about what is happening long before the experiment or long after the collision of the carts. Instead, we are concerned about what is happening just before the collision, during the collision, and immediately after the collision of the two carts."</i></p>

According to the extracts presented in Table 32, the teachers who were in favor of the idea that models should represent the absolute reality indicated that a model should retain every single detail of the phenomenon it represents, even details that are either irrelevant to the underlying mechanism that controls the function of the phenomenon or details that are considered as secondary in relation to the function of the phenomenon per se. For instance, in extract A1 from Table 32, the teacher insisted on implementing the person who initiates the experiment in their model. Likewise, in the second extract, the teacher suggested that special attention should be taken during designing the carts in order to make them appear as close as possible to the real ones.

On the other hand, the group of teachers who were willing to represent the absolute reality in their models but stressed that this was not feasible, argued that they would compromise with the construction of a model that approaches reality as much as possible. This group of teachers differentiates from the previous one in that the first group would devote their effort in making a model identical to reality, whereas the second group acknowledges that reality is not feasible to be represented within a model and thus they would seek to create a model as close as possible to reality. The latter justification is clearly stated within teacher's extract B3 in Table 32.

On the contrary, the third group of teachers seemed to have developed a more sophisticated and epistemologically informed understanding about the nature or purpose of models. According to a teacher's own words (see extract C1 from Table 32), *“a model should not represent the absolute reality because if this was the case, then the whole focus would be on the detailed design of the model and the fundamental objective of modeling, which is the interpretation and explanation of a phenomenon, would be ignored”*. Consequently, the teachers who were clustered in this group were not concerned if their model fell short in retaining every single detail of the real phenomenon, as their main focus was to create a model to illustrate how they themselves interpret the phenomenon they were studying.

After these different standpoints have been evidenced in teachers' reflective diaries, the instructors of the PDC decided to create a topic for discussion around the issue of models relevance with absolute reality in the BeEP, to help teachers compare and contrast their views about this issue, and reach consensus on whether models should represent the absolute reality or not. The discussion topic that was created (see Figure 15) presented two different viewpoints; one that was in favor of models as exact replicas of absolute reality

and one against. The teachers were asked to provide their own opinion about the topic of discussion, and respond to at least two of their colleagues' responses.

It has been claimed by some of your colleagues that a model we create to represent a phenomenon we are studying should represent the "absolute reality", e.g., the model should look alike to the phenomenon we are studying.

*What is your opinion about this issue?*

Read the following opposing responses provided by two of your colleagues.

A. *"I personally disagree with the above statement. In my opinion, a model does not represent the real phenomenon in an exact way. The aim of the model is to interpret the function and the behavior of some aspects of the phenomenon. Even though a phenomenon is complex, we choose to focus on the aspects that we are interested in and our aim is to create a model for these aspects. We need represent these aspects in such a way that it will help us in developing a theory through which we will interpret the phenomenon under study. We focus our study in the function of the phenomenon and in the relationships among its variables, so in a later stage we will be able to make predictions about the phenomenon. Besides, a model and the theory that the model is based on are evaluated on their capability to predict behaviors of the phenomenon. This can be undertaken even if the model is not a replica of the phenomenon it represents. Suffice it to say that the relationships and interactions among model constituent components are based on a theory."*

B. *"I agree with this statement, since the purpose of modeling is the representation of reality. Model creation refers to the representation of a phenomenon in a technical way, but it should be in exact match with the real phenomenon. We need to create the model in a way that represents as best as possible the phenomenon, so someone who did not observe the real phenomenon could use our model to collect all information he wants. Hence, our model should be as close to reality as possible, but it should be simplified in order to be understood by everyone. Because it so difficult to create the 'perfect' model, we need to attempt to create a model that approaches the reality as best as possible."*

Figure 15. Discussion topic about models relevance with absolute reality used in the BeEP

Overall, the topic of discussion was proven a significant learning opportunity for teachers to share and contrast their views about models' relevance with absolute reality with their peers. It also served as a means through which those who were in favor of the idea that models are replicas of absolute reality to abandon their initial views and develop informed understandings about this issue. To document this claim a selection of representative extracts from teachers' discussions are provided below.

Teacher # 2 was one of those teachers who from the beginning of the PDC expressed the idea that models should look alike to real phenomenon (see Group A in Table 32). In her first post in the discussion topic, she wrote the following:

Teacher #2: *“Dear colleagues, I agree with the second statement. Our purpose should be the representation of the phenomenon in the best possible way, in order to be comprehensible by everyone who studies it afterwards. In order to succeed on this, our model should entail all necessary components of the real phenomenon and in a simplified manner, so as for someone who does not know ‘the physics’ behind collisions to understand the phenomenon. I believe that ‘modeling’ refers to the creation of a model that is identical with the real phenomenon. If this model is not as close to the real phenomenon, then what is the purpose behind modeling?”*

According to her statement, her view that models are considered as replicas of the real phenomenon departs from the notion that the purpose of modeling is to create models of real phenomena that will help someone who do not have access to the phenomenon or does not know “the physics” behind the phenomenon, to comprehend how the phenomenon functions. Hence, she does not view models as personal constructs that help their creator to externalize how she herself interpret the way the phenomenon functions.

Teacher #7 replied to the statement made by Teacher #2 and sought to help her understand that models represent only specific aspects of the phenomenon we are studying, and that models that unify a lot of aspects of the phenomenon are difficult to be manipulated by young learners in their effort to understand a specific aspect of the phenomenon. Teacher’s #7 statement was as follows:

Teacher # 7: *“Dear Doris, I will disagree with you. The purpose of modeling is to create a model that represents only the aspects of the phenomenon we are interested in studying. We also select those aspects of the phenomenon that help us in interpreting the phenomenon, and making predictions about the phenomenon. Suppose a child is given a complex but ‘perfect’ model that represents the process of photosynthesis, respiration, and transpiration – because all three processes are interconnected – and seeks to explain and understand the process of respiration. It would be extremely difficult for the child to understand this process through such a complicated model. Instead, a simpler model would be more appropriate in this case”.*

Several other interventions to Teacher’s #2 statement were made by other teachers, each of them sought to help her refute her original view by providing examples from the learning activities of the PDC that contradicted with the second statement of the discussion topic. A noteworthy intervention was made by Teacher #20, who mentioned that the discussion that was developed around Teacher’s #2 original statement helped her in changing her own



personal view about why models cannot represent the absolute reality. Her statement is provided below and discussed henceforward.

Teacher#20: *“Dear colleagues, after reading your posts, I can say that I revised my views about modeling. Prior to this, I thought that a model should entail all elements of a phenomenon (maybe my opinion was affected by the technology progress!). Of course, this view contradicted with what we have been doing so far during our modeling sessions; we have been studying only some aspects of the phenomenon of the elastic collisions, and this approach raised some questions about modeling and its purpose. However, your responses enabled me to answer my questions, and now I’m almost convinced that because it is so difficult or impossible for a model to represent in a perfect way a real phenomenon, then we merely try through the creation of the model to provide some explanations for a certain aspect of the phenomenon. Hence, I will agree with the first stance and reject the second one, since it is so difficult a model to be identical with the phenomenon it represents. As one of you put it very aptly, ‘If the purpose of models was to duplicate the real phenomenon, then wouldn’t it be better if we visit the phenomenon and observe it itself?’ Consequently, the model needs to represent the aspects from the phenomenon that we are interested in, and if it permits the formulation and testing of predictions, then it fulfills the objectives we set a priori for its development”*

Although Teacher’s #20 report was encouraging in that the statements made by her colleagues helped her in changing her views about the models and absolute reality, the arguments used to support her claim revealed mixed views about this issue. Specifically, Teacher #20 made use of the argument twice that models cannot represent absolute reality, because this is not feasible (e.g., *“because it is so difficult or impossible for a model to represent a real phenomenon in a perfect way”* or *“since it is so difficult a model to be identical with the phenomenon it represents”*). This argument was also evident within teachers’ responses in the CK test, as the group B of teachers in Table 32 indicates. On the other hand, Teacher #20 used some more scientifically informed arguments in her response that point to her appreciation of models as tools through which we interpret specific aspects of the phenomena we are studying (e.g., *“through the creation of the model we provide some explanations for a certain aspect of the phenomenon”*).

While teachers like Teacher #20 felt that the discussion performed helped them in resolving their understandings about the relation between models and absolute reality, Teacher #2 noted that she was still confused about this issue. Her report below is particularly revealing:

Teacher # 2: *“Dear colleagues, after reading your responses I’m confused and do not know with which of the statements of the topic of discussion should I agree or disagree. It sounds reasonable that some examples of phenomena you referred to might not easily be*

*represented within a model, so they cannot be exact copies of the real phenomenon. Since I'm a physicist and think somehow unilaterally, I will use the context of elastic collisions to pose the following question: Could the 1-D elastic collision model be used to explain to someone who does not know what a collision is, if only an aspect from the phenomenon is represented in the model and not the phenomenon as a whole? Would it be acceptable, for example, if the model showed merely a collision of the two carts, whereas the swap of velocities and the change of direction were absent? I'm waiting for your opinions about these issues!!!"*

In her abovementioned report, Teacher #2 appeared somehow convinced that sometimes models are difficult to represent the absolute reality, compared to her initial statement that models should definitely represent the absolute reality. The example used from her experiences with modeling elastic collisions revealed both the roots of her concern of why models should represent the real phenomenon in an exact way, and her confusion around to which elements are considered as important to be incorporated within the model. Specifically, Teacher #2 seemed to have difficulties in differentiating between *facts* and *interpretations*, since she believed that *velocity swap* is something that literally exists during the collision experiment she was referring to (e.g., she thought of this as a “fact”), and failed to consider “velocity swap” as an interpretive mechanism that one invents during seeking for an interpretation or explanation to account for her observations.

Three of her colleagues responded to her statement and tried to help her resolve her epistemic difficulties emerged in her previous statement. Teacher #4 elaborated on the models they created for each of the collision experiments they observed, and tried to clarify that even though a model might work well for a single aspect of the phenomenon under study, it might not fit well with other aspects of the phenomenon (Note: Teacher #4 uses the term “aspects” to refer to “classes” of the collision phenomena). She also mentioned that the creator of the model needs to explicitly state the constraints and limitations of her model, in order to help the user of the model to use it correctly for the aspect of the phenomenon it represents. Nevertheless, her last claim, that it is impossible for models to represent the absolute reality, uncover the similar view expressed by other teachers that models cannot represent the absolute reality, because it is not feasible. Teacher's #4 assertion in the discussion was as follows:

Teacher #4: *“Dear Doris, try to recall the two collision models we built in the previous sessions and also everything we did last Wednesday, and things will clear up. In each of the models we created, we aimed to represent only one aspect of the overall phenomenon of the elastic collisions. The first model enabled us to represent what was happening when a moving cart collided with a stationary cart of the same mass, and it also enabled to test if the same outcome could be revealed when altering the value of the velocity of the moving*

cart. Additionally, the second model we created enabled the representation of two moving carts of the same mass that approached each other with equal velocities and illustrated what was happening during the event of the collision. Through the curriculum we were working with, we were asked to test if both models could be applied in the third collision phenomenon we observed (e.g., the two moving carts with unequal velocities were approaching each other from opposite direction), and all of us concluded that none of the models could be applied in the third collision phenomenon because of the syntax of the rules that controlled the behavior of the carts in each model. Accordingly, even though both models were capable to represent one aspect of the elastic collisions phenomenon, they fell short in representing new aspects of the phenomenon. Hence, it is important to denote the constraints of each model, so as a user of the model who would not expect that all possible predictions about the phenomenon could be confirmed or rejected while using either of the models. For instance, a collision model could pertain to elastic and plastic collisions and represent velocities exchange, changes in the direction of the carts, etc. (all unified in a single model) in one hand, and on the other hand, the model might focus on a single aspect of the phenomenon (e.g., elastic collisions), depending on the aim we set for the model. Even in the case that a model has been created to unify all different cases of collisions, I think that again it is impossible to represent the absolute reality, because of there is a plethora of variables that affect the phenomenon”.

Teacher #15, on the contrary, added two important aspects of models that helped in resolving the abovementioned reservations of Teacher #2. The first one pertains to the nature of models with respect to their interpretive potential (e.g., “*help in interpreting our observations*”), whereas the second one relates to the tentative aspect that characterizes science, part of which are models and theories. Teacher’s #15 argument is provided below.

Teacher # 15: “*I will agree with Lucy, even though I do not consider unreasonable all what Doris has stated. Your questions and reservations are logical, but what we aim to do when creating a model is to represent what we observe and not to present the whole phenomenon. If the model we created represents our observations in a satisfactory level, then this is enough. On the other hand, science is so temporary sometimes. A theory might be valid today, and tomorrow it might be proved wrong and another theory might substitute it. By creating models that represent what we observe and help in interpreting our observations, it saves us from dealing with complicate relationships and formulas, and with theories that might not be truly correct or valid.*”

Likewise, Teacher #11 continued as Teacher #15, and extended the discussion around the epistemology of models by adding two important aspects of the nature of models; *instantiation* and *idealization*. In his response, he sought to help Teacher #2 to understand that quite often we choose to reduce the complexity of the phenomena we are studying by eliminating those variables that intervene in the phenomenon and add up to its complexity. His response, which was particularly revealing, is provided below.

Teacher # 11: “*Hello Doris. I would like to add a comment in the discussion. There are instances during teaching physics at school that the phenomena we teach are presented in*

*an idealized fashion. I will use the free fall as an example. While studying this phenomenon, the teacher quite often makes a diagram on the whiteboard (we could say that this is an attempt for modeling the phenomenon of free fall) and he underlines that air resistance is not taken into account when studying free fall. In addition, we always consider that the shape of the falling body is the same, regardless of its real shape. In this way, we are studying not the real phenomenon but an idealized case for which we set the constraints in order to study the aspect of the phenomenon we are interested in. Something similar applies during attempting to model a phenomenon, because this perspective (instantiation, idealization) is one of the greatest advantages of modeling.”*

Overall, the topic of discussion on whether models should represent the absolute reality or not, provided the opportunity for the participants to compare and contradict their knowledge about this issue with their peers, and at the same time it enabled those who held naive conceptions about this issue at the beginning of the PDC, to develop most sophisticated understandings. In order to compare teachers’ individual knowledge about this issue prior to and after Phase 1 of the PDC, since the discussions were carried out at a collective level, the same question of the CK test that was administered prior to Phase 1 of the PDC was administered again after the end of Phase 1. The themes that emerged from the analysis of teachers’ responses, in conjunction with the themes from the pre-CK test, are presented in Table 33.

Table 33. Teachers’ CK about models’ feasibility to represent the “absolute” reality prior to and after Phase 1 of the PDC

Emergед themes	Prior to Phase 1 of the PDC	After Phase 1 of the PDC
1. A model cannot represent the absolute reality, because since a lot of aspects within a phenomenon are “hidden” or not easily observable, the model entails only the creator's subjective interpretation (e.g., a suggested underlying mechanism) for how a phenomenon under study functions	4	10
2. A model cannot represent the absolute reality, because a model refers to specific aspects of a phenomenon and hence it does not represent a phenomenon as a whole	3	9
3. A model cannot represent the absolute reality, because the creator of the model ignored major aspects of the phenomenon or decided to encompass within the model only a few aspects of the corresponding phenomenon (models are human constructs and thus may contain errors or omission of some of the phenomenon components)	2	5
4. A model cannot represent the absolute reality, because there could be consistencies and inconsistencies between the model and the phenomenon it represents	3	4
5. A model cannot represent the absolute reality, because a model is just a "tool" that is used for helping someone to understand a phenomenon in a better way	3	0
6. A model cannot represent the absolute reality, because it is constrained by the modeling medium used for modeling the corresponding phenomenon	1	1
7. A model should represent the absolute reality, but this is infeasible, because the phenomena are too complex (e.g., too many variables interact at the same time) to be modeled in such a detailed way	8	1

According to Table 33, at the end of Phase 1 of the PDC the majority of teachers achieved a significant transition from the naive conception that *a model should represent the absolute reality, but this is not feasible because the phenomena are too complex to be modeled in such a detailed way* (see emerged theme 7 in Table 33) to the epistemologically informed notion that *a model cannot represent the absolute reality, because since a lot of aspects within a phenomenon are “hidden” or not easily observable, the model entails only the creator's subjective interpretation (e.g., a suggested underlying mechanism) for how a phenomenon under study functions* (see emerged theme 1 in Table 33). However, only half of the participants incorporated within their responses this type of understanding, whereas almost half of the participants used the argument that *models represent only specific aspects from a phenomenon under study* to refute the idea that models should represent the absolute reality. Other less frequent arguments in favor of models as not replicas of physical phenomena relate to models' infeasibility to represent the absolute reality because of errors or inconsistencies with the physical phenomenon that the creator of the model made during developing the model (see emerged themes 3 and 4 in Table 33).

#### *4.3.1.1.4. Knowledge about model evaluation criteria*

The fourth lens through which teachers' CK about models was evaluated relate to their understandings about the criteria used for evaluating a scientific model. Through the CK test, that was administered both at the beginning and at the end of Phase 1 of the PDC, the teachers were asked to state the criteria they thought that are used during evaluating a model. Prior to Phase 1 of the PDC, the analysis of their responses in relation to this issue revealed ten different evaluation criteria, and also the prevalence of each criterion was different. The criteria that emerged are presented in Table 34 and are discussed henceforth.

Table 34. Teachers' CK about the criteria used for evaluating a scientific model prior to Phase 1 of the PDC

Emergenced themes	Prior to Phase 1 of the PDC
1. Model's interpretive power (e.g., does the model entail a mechanism that explains how the phenomenon functions?)	7
2. Model's representational completeness	5
3. Model's capability in facilitating the conceptual understanding for the phenomenon it represents	5
4. Model's appropriateness to be used within science teaching	5
5. Model's consistency with observations derived from the phenomenon it represents	4
6. Model's proximity to the phenomenon it represents (e.g. how close is the model to the phenomenon?)	4
7. Model's predictive potential	3
8. Model's elegance (e.g., simpler models are more preferable than more complex ones)	3
9. Model's fitness with the scientifically acceptable knowledge for the phenomenon it represents	3
10. Model's usability	1

According to Table 34, the most frequent criterion that was present in less than half of the participants' responses was model's *interpretive power*. In defining this criterion, the teachers stated that a model is evaluated upon its capability to provide an explanation or an interpretation of how the phenomenon represented through the model functions. Other less frequent evaluation criteria that were revealed from ¼ of teachers' responses were model's *representational completeness* (e.g., evaluation of the model in relation to the representation of the major components of the phenomenon), model's *capability in facilitating the conceptual understanding for the phenomenon it represents* (e.g., evaluation of whether the model helps someone who is using it to develop conceptual understanding about the phenomenon it represents) and model's *appropriateness to be used within science teaching* (e.g., evaluation of whether a specific model fits with the purposes of science teaching and thus it could be used as an instructional aid). Two additional criteria that were proposed by 1/5 of the participants were model's *consistency with observations derived from the phenomenon in represents* (e.g., evaluation of whether the model is in line with the observations made by its creator), and model's *proximity to the phenomenon it represents* (e.g., evaluation of the degree of similarity between the model and its target). Furthermore, three less frequent criteria that were evident in only 3 participants' responses relate to model's *predictive potential* (e.g., evaluation of whether the model can be used to test if a prediction formulated by the user of the model is correct

or not), model's *elegance* (e.g., evaluation of whether the format and structure of the model is simple enough for someone to use it), and model's *fitness with the scientifically acceptable knowledge for the phenomenon it represents* (e.g., evaluation of whether the knowledge that derives from a model does not contradict with the scientifically established knowledge about the phenomenon it represents). Lastly, there was a single reference on model's *usability* (e.g., evaluation of whether the model can be used without any difficulty and from anyone to access the phenomenon it represents) as one of the criteria that could be used for evaluating a model.

During Phase 1 of the PDC, the teachers were systematically asked to upload their final models to the BeEP, evaluate their peers' models, and respond to the evaluation comments received from their peers. It is noteworthy to state that through the curriculum the teachers never received explicit information about the criteria used for evaluating scientific models. It was expected that their engagement with the modeling activities they had been working with during Phase 1 of the PDC would help them develop themselves the criteria that are used for evaluating their models.

In their first attempts for evaluating their peers' models uploaded in the BeEP, the teachers focused mostly on the aesthetics of their models, and also on technical issues related to the syntax of the rules of the SC models. The following discussion, that took place between two groups of teachers who exchanged their models, supports this finding.

*"Hello friends! I've just finished studying your model and I can say that I liked the graphics you used for making the carts. I also liked the two 'soldiers' that you placed at the beginning and the end of the air-track to act as barriers for the carts. The carts moved like the real ones. Your model shows that after the collision, the moving cart stops and the other cart begins to move to the right".*

*"Dear friend, thank you for the comments. While creating our model, we decided that it would be nice if we put something at the end of the air-track to make the cart stop when it collides with it. And we decided to put the 'soldiers' to make our model more attractive to the eye of the user".*

After creating their second model of the elastic collision experiment, the teachers were prompted to answer three important questions that pertained to the requirements that a scientific model should satisfy. These questions were as follows:

*1. Does your model represent all major components of the collision experiment you observed?*

2. *Does your model encompass an interpretation of how the specific collision experiment you observe functions?*
3. *Can you use your model for testing predictions about the collision experiment it represents?*

Although these questions were not explicitly introduced as the aspects one should look into when evaluating a scientific model, evidence from teachers' evaluations of their peers' models indicate that teachers shifted from the aesthetic criteria and technical-related judgments to models' *representational complexity, interpretive potential, and predictive power* when evaluating their peers' models. The following extracts from two teachers' posts are particularly revealing.

Teacher # 4: *“Dear colleagues, I’ve just reviewed your model and I can say that it represents in a very good manner the objects and the variables of the collision experiment we observed. The carts seem to move according to the real experiment. I also used your model to test if it works fine with other values to the velocities of the carts, and noticed that the results were correct. Hence, your model is robust enough to enable the formulation and testing of predictions. My only reservation is that in the description you provided for your model you mentioned that your model was created around the idea that the two carts exchange velocities during their collision, but when I went to the syntax of the rules you created, I noticed that this idea was not supported by the syntax of your rules. Instead, I noticed that the syntax of your rules related to the idea that the two carts alter the sign of their velocity at the event of their collision. Can you please clarify if this is a misunderstanding of mine?”*

Teacher #13: *“Dear friend, thank you for your nice comments. I think you are right about the relation between the syntax of the rules and the idea that we wanted to create our model around. Although we wanted to make the carts exchange their velocities during the collision, we did not succeed on creating rules to make this possible, so we found a simpler way to make this; at the event of the collision the two carts just alter the sign of their velocities, and as a result the two carts change direction.”*

Teacher # 4: *“Dear friend, thank you for the clarification. Our team succeeded on creating rules that make the carts exchange their velocities during the collision, and thus we named our model “velocity swap model”. Hence, your interpretation about how the collision experiment we observed functions contradicts with what your model is actually doing. I suggest either to change the description of the interpretation of the collision or change the syntax of the rules you created to better align with the interpretation as it is now. I can help you in the next class to do this, if you want your model to run under the velocity swap perspective.”*

Likewise, evidence from teachers' reflective diaries indicates that they developed more sophisticated evaluation criteria for assessing their models towards to the end of Phase 1 of the PDC. A representative example from a teacher's reflective diary that illustrates in a comprehensive fashion the criteria used for evaluating a scientific model, is provided below.



*“A model should be evaluated on the basis of three important criteria which are as follows:*

*1. A model should entail a description and an explanation of the mechanism that the phenomenon under study functions upon. It neither needs to be nor it could be an exact representation of the real phenomenon, but the mechanism that controls the function of the phenomenon should be transparent enough in order a user of the model to comprehend why specific behaviors and outcomes of the phenomenon occur.*

*2. A model should be used for predicting behaviors of the phenomenon that it represents. For instance, the user of the model should be allowed to set different values in a variable and then study the outcomes of the model in relation to the new value of the variable. It is important that the outcomes and behaviors that the model provides should be aligned with what the real phenomenon would reveal under the same conditions. Hence, there should be a relation between the model and the phenomenon in such a way that the outcomes that are produced when running the model are in line with the outcomes from the real phenomenon.*

*3. The model should apply in a family of phenomena of the same class. During modeling, we are creating a model that might represent the phenomenon as a whole or a specific aspect of the phenomenon. In case the model represents a single aspect of the phenomenon, then we should test if altering the value of its variables, the outcomes are consistent with the outcomes that relate to other phenomena of the same class (model validation).”*

To evaluate individual teachers’ CK in relation to the evaluation criteria that should be used for assessing scientific models, the question that was given in the pre-CK test to evaluate teachers’ CK about this aspect of models was also given in the post-CK test. The findings that emerged from the analysis of teachers’ responses in the post-CK test, in conjunction with the findings from the pre-CK test, are presented in Table 35 and are discussed henceforward.

Table 35. Teachers’ CK about model evaluation criteria prior to and after Phase 1 of the PDC

Emergед themes	Prior to Phase 1 of the PDC	After Phase 1 of the PDC
1. Model’s predictive potential	3	18
2. Model’s representational completeness	5	17
3. Model’s interpretive power (e.g., does the model entail a mechanism that explains how the phenomenon functions?)	7	15
4. Model’s validity in relation to its applicability to phenomena of the same class	0	10
5. Model’s elegance (e.g., simpler models are more preferable than more complex ones)	3	7
6. Model’s consistency with observations derived from the phenomenon it represents	4	5
7. Model’s usability	1	0
8. Model’s capability in facilitating the conceptual understanding for the phenomenon it represents	5	0

9. Model's appropriateness to be used within science teaching	5	0
10. Model's fitness with the scientifically acceptable knowledge for the phenomenon it represents	3	0
11. Model's proximity to the phenomenon it represents (e.g. how close is the model to the phenomenon?)	4	0

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According to the findings presented in Table 35, the majority of teachers seemed to have developed informed understandings about the criteria that are used for the evaluation of the scientific models. Specifically, the prevalence of the criteria that pertain to the evaluation of a model in relation to its *predictive power*, *representational comprehensiveness*, and *interpretive potential* was significantly increased by the end of Phase 1 of the PDC. In addition, a new criterion that was mentioned by half of the teachers in the post-CK test and relates to *model validity in relation to its applicability to phenomena of the same class* was revealed in teachers' responses after the PDC. Less frequent criteria whose prevalence was also increased after Phase 1 of the PDC were *model's elegance* and *model's consistency with observations from the phenomenon that the model represents*, whereas the prevalence of criteria that were reported prior to Phase 1 of the PDC and were associated with a teacher-oriented perspective or a naïve conception about models was decreased to zero.

#### **4.3.1.2. Teachers' CK about modeling**

Teachers' CK about modeling was evaluated through two data sources. The first data source concerns the CK test (see Data Collection section in Chapter 3) that was administered prior to and after Phase 1 of the PDC, and the second data source relates to teachers' reflective diaries that were completed after each class meeting during Phase 1 of the PDC. The CK test entailed a question through which the teachers were asked to provide their definitions of scientific modeling, and also a second question that prompted teachers to state whether *modeling is a scientific enterprise, a teaching approach, or an ability that is developed during learners engagement with modeling activities*, and explain the reasoning behind their response. As far as the reflective diaries are concerned, all reflective diaries that teachers' completed after every session of Phase 1 of the PDC encompassed a set of questions that sought to capture their evolved CK about modeling after each session. The format of these questions was as follows: "What did you learn during this session about modeling? Did you learn something new? Explain. What do you expect to learn about modeling in the next sessions?"

#### 4.3.1.2.1. Teachers' definitions of scientific modeling

The analysis of teachers' definitions for scientific modeling provided in the CK-test indicated that while attempting to provide a definition for scientific modeling, teachers made references on the format and the types of steps followed during modeling, and also on the perspectives through which modeling is approached. The emerged themes that were revealed from the analysis of teachers' definitions for scientific modeling prior to Phase 1 of the PDC are presented in Table 36 and are discussed henceforth.

Table 36. Teachers' CK about scientific modeling prior to Phase 1 of the PDC

Emerg ed themes	Prior to Phase 1 of the PDC
<u>A. Definition of modeling</u>	
1. Modeling is the representation of a phenomenon through the use of a computer or other means	8
2. Modeling is a process for creating a model that will help in studying the phenomenon	5
3. Modeling is the process that is followed for creating a model that helps in (i) representing a phenomenon, (ii) explaining or interpreting how the phenomenon functions, and (iii) formulating and testing of predictions/hypotheses	1
4. Modeling is a process that is followed for creating a model for a phenomenon that helps in understanding and interpreting the phenomenon under study	1
<u>B. Reflection on the steps followed during modeling</u>	
1. Modeling involves several stages; performing observations, data collection, formulating predictions or hypotheses, representation of the phenomenon, revision or improvement of the model	2
<u>C. Perspectives of modeling</u>	
1. Modeling is a process of learning (through building external representations)	2
2. Modeling is a teaching approach	2
<u>D. Naive conceptions about modeling</u>	
	5

As Table 36 indicates, prior to Phase 1 of the PDC, teachers' CK for scientific modeling was very limited, as their definitions for scientific modeling varied dramatically. Specifically, eight teachers reported that *modeling pertains to the representation of a phenomenon through a computer or other means* (see emerged theme A1 in Table 36), whereas five teachers referred to *modeling as the process for creating a model that helps in studying a phenomenon* (see emerged theme A2 in Table 36). Although the teachers who expressed the latter view referred to modeling as a *process*, they failed in uncovering the steps that are followed during the process of modeling. In addition, five teachers' definitions of scientific modeling could not be grouped in any of the emerged themes, because their statements encompassed naïve conceptions about modeling. For instance,

Teacher #2 stated that “*Modeling refers to the field that deals with ‘modeling’*” or Teacher #9 wrote that “*Modeling is a process for presenting several themes through images and concrete objects*”.

On the other hand, two teachers provided scientifically informed definitions for scientific modeling; one declared that “*Modeling is a process that is followed for creating a model for a phenomenon that helps in understanding and interpreting the phenomenon under study*” (see emerged theme A3 in Table 36), and the other one stated the same as the previous one, and also added the notion that *the model that is created during modeling can be used for the formulation and testing of predictions* (see emerged theme A4 in Table 36). These teachers also reported that modeling involves several stages (e.g., *performing observations, data collection, formulating predictions or hypotheses, representation of the phenomenon, revision or improvement of the model*, see emerged theme B2 in Table 36), and also acknowledged modeling as both a *process of learning* and a *teaching approach* (see emerged themes C1 and C2 in Table 36).

During the PDC, teachers’ reflections on scientific modeling revealed several themes that point to their ongoing understandings about the nature and purpose of modeling. These themes are presented and discussed below.

A. *The teachers appeared to have associated modeling with the software used for creating their models.* For some teachers, scientific modeling was conceived as the work undertaken during creating their model in SC. Specifically, when they were asked to reflect on what they have learned about modeling during their engaged with the modeling activities of the curriculum, they stated the following:

*“I learned how to use Stagecast Creator in a more advanced way and I found out how to create more complex rules (e.g., rules that entail variables or the command if...then...)”*  
(Teacher #2, after session 1)

*“I learned that modeling requires the formulation of simple commands in Stagecast Creator, and this helped me in making my work easier and saving time. I became more confident in using the Stagecast Creator and modeling became easier and fun for me!”*  
(Teacher #9, after session 1)

B. *Teachers' personal engagement with modeling activities enabled them to identify modeling as a complex procedure.* During creating their models in SC, a lot of teachers struggled to create a model that was consistent with their observations. They experienced difficulties in deciding the format and syntax of the rules that needed to create in making the carts' behavior similar (or alike) with the real carts, and also they devoted a significant amount of time for debugging their models, because of conflicts and other technical issues. In reflecting about their experiences from the first session, they reported that they learnt that modeling is not as easy as they thought at the beginning of the course, and made references from the lessons learned during the session. The following extract from a teacher's reflective diary highlights this argument.

*"During this session we learned a lot of things about modeling through an empirical way. We also found out that modeling is not as simple as it appeared at the beginning of the session. On the contrary, it requires a careful and thorough observation of the phenomenon under study in order to be able to create a model that won't lack important aspects of the phenomenon it represents. Our first attempt for modeling the collision experiment we observed was a disaster! The carts did not move the way we wanted them to do, and also after the collision both carts continued to move (only the stationary cart should move after the collision, and the previously moving cart should stop). Our first thought was to delete every single rule we created and start from scratch, but my colleague insisted on studying the syntax of each rule and find out what went wrong. After a lot of attempts, we managed to make our model functional and we were very happy when we run the model and saw that they moving cart was transferring its velocity to the stationary one and hence it stopped and the stationary cart began to move!"* (Teacher #3, after session 1)

C. *Engaging teachers in the act of scientific modeling helped them to acknowledge the various steps followed during modeling.* Throughout Phase 1 of the PDC, the teachers as learners were engaged in multiple cycles of model development and deployment of elastic collision phenomena they observed through videos. The various modeling activities that they followed within the curriculum enabled them to expand their CK knowledge about the various steps of modeling, and at the same time they appreciated the importance of each step for the development and validation of their models. The following extracts from teachers' reflective diaries are particularly revealing.

*"During this session I have clarified the stages of modeling, starting from the time of performing observations until the stage that the model you have created is robust enough to represent and interpret the phenomenon you were studying, and check predictions about the phenomenon using your own model."* (Teacher #1, after session 2)

*“I learned that in making a model you need to start from observing the phenomenon of interest, then write down your modeling plan, and then proceed with the creation of the model.”* (Teacher #20, after session 1)

*“I learned that in order for a model to be correct, you need to continually compare it with the real phenomenon and the feedback you receive from this comparison should be used as a guide for further improving your model. I also learned that it is very important to sketch a priori the steps that you plan to follow for creating your model, like when you are building a house, you need to follow a sequence of steps.”* (Teacher #19, after session 3)

*“What I haven’t resolved yet is how model gradual extension is made and at what point we can say that we have a completed and robust model. We have learned that we concentrate on a single aspect of the phenomenon during modeling, but what about the other aspects of the phenomenon? If they are absent from our model, wouldn’t this lead to misunderstandings about the phenomenon or this is just a step and then at a later stage all other aspects will be unified to form a completed model for the phenomenon we are studying? I hope my questions would be resolved in the next sessions.”* (Teacher #1, after session 1)

The last extract presented above relates to a teacher’s reflection on whether there was something that was not clear enough during the modeling session, and what he expected from the next sessions. This teacher was one of many teachers who posed a critical question about models and modeling that merits some elaboration. The teachers quite often were discussing with their peers or with the instructors the issue of their model representational completeness, as they were concerned if their model fell short in representing in a precise way the collision experiment they observed. This type of concern can be attributed to their naïve conception that models should be “replicas” of the real phenomenon, and as a result they tended to pay attention not on the interpretive power of their model. Although this idea relates to teachers’ CK about the nature of models, it definitely affected and constrained both their modeling mode during constructing their models and their evolved CK about scientific modeling.

D. *The teachers reported that working with modeling activities impacted on the development of their conceptual understanding about the phenomenon they were studying.* Teachers’ engagement with modeling several 1-D elastic collision phenomena enabled them to better monitor their evolved understandings about the physics content behind the context they were studying, and appreciated the impact of modeling on scaffolding the development of their conceptual understanding about 1-D elastic collisions. The following extracts from two teachers’ reflective journals portray this finding.

*“Furthermore, I realized that during creating a model you examine and comprehend the phenomenon more and more. You don't need to understand everything from the beginning, but the whole modeling procedure helps you to understand what you want to explain through your model.”* (Teacher #19, after session 1)

*“Approaching the elastic collisions through modeling enabled me to comprehend in depth what is happening during elastic collisions, because neither we were offered ready-made pieces of existing knowledge about this type of phenomena nor we were expected to apply our physics knowledge obtained from high school for building our models. Instead, we were systematically trying to interpret each collision phenomenon in a way that was meaningful to ourselves and tested if our interpretation was consistent with our observations. Hence, we gradually passed through several interpretations to reach at the “conservation of momentum” as the best interpretation that applied to all cases of the elastic collisions we observed. Consequently, the process of modeling helped me in understanding the physics behind elastic collisions in a better way than the traditional way we were taught during high school, and I'm now confident that my knowledge is more robust and permanent.”* (Teacher # 14, after session 5)

E. *The teachers felt ready to transfer and transform their learning experiences for the design of their own science modeling-based instruction.* Besides reflecting on their ongoing understandings about what scientific modeling entails, the teachers made references on their future teaching plans in relation to the integration of modeling within their science instruction. They stated that experiencing modeling from first hand enabled them to become more confident on how to design learning environments for scaffolding their students' modeling pathways during their modeling-based instruction. The extracts from three teachers' reflective journals that follow illustrate their plans for transforming their own learning experiences into instructional activities for their students.

*“The truth is that I was not aware of all these stages and if I tried to engage my students in modeling, I would have failed if I myself have not gone through all these stages. Now I'm more confident in that I know what I should expect from my students to do during each stage of modeling and I can evaluate in a better way myself and my students.”* (Teacher #1, after session 1)

*“I have never had the opportunity to work with modeling before, so everything for me is new. I must confess, though, that all these experiences are very fruitful and useful for me that I will try to implement similar activities with my students, because through modeling, science teaching becomes more challenging and fun for your students.”* (Teacher #11, after session 1)

*“What I expect to learn in the next sessions is how I will be able to help my students avoid relating the interpretation they provide for the phenomenon they are studying with the unique and ‘true’ explanation for the phenomenon. Specifically, I would like to learn how to help my students understand that a model should entail an interpretation of how the phenomenon that is represented through the model functions, and that this interpretation should be consistent with our observations. Also, I would like to know how to help my students understand that this interpretation should not be considered as the unique*

*interpretation of the phenomenon, and that different people might interpret the same phenomenon from different perspectives.” (Teacher #19, after session 3)*

The latter extract is particularly revealing, as it highlights a teacher’s anticipation on how to help her students understand that the interpretation of a phenomenon under study is a core component of a scientific model, and that it pertains to a subjective way of how an individual conceptualizes how a phenomenon under study functions. This teacher’s concern highlights her epistemic awareness in relation to the nature of models, and specifically her understanding that: (i) models are human constructs; (ii) a phenomenon could be interpreted from different perspectives; and (iii) any interpretation of how a phenomenon functions should be consistent with the observations derived from the phenomenon.

At the end of Phase 1 of the PDC, the analysis of teachers’ definitions for scientific modeling revealed that they developed sophisticated understandings about scientific modeling, since they provided more comprehensive definitions compared to those provided in the pre-CK test (see Table 37 for details). More specifically, almost  $\frac{3}{4}$  of the teachers defined *modeling as the process that is followed for creating a model that helps in (i) representing a phenomenon, (ii) explaining or interpreting how the phenomenon functions, and (iii) formulating and testing of predictions/hypotheses* (see emerged theme A1 in Table 37), whereas the remaining provided a similar definition but the notion about the formulation and testing of predictions was omitted from their definitions (see emerged theme A2 in Table 37). Moreover, the majority of the teachers referred on the several steps that are followed during the process of modeling (e.g., performing observations, model development, model improvement, model validation, model evaluation, continuous model improvement), and most importantly, they emphasized that these steps are followed not in a linear fashion, but in a *cyclical* and *iterative* manner (see emerged theme B1 in Table 37). Lastly, the findings also indicate that more teachers came to conceive modeling as both a *learning process* and a *teaching approach*, and also as a *scientific enterprise*. Even though the latter modeling perspective (e.g., modeling as a scientific enterprise) was mentioned only by eight of the participants, it is important to state that it has been evident only in teachers’ definitions for scientific modeling after Phase 1 of the PDC. More elaboration on the three different perspectives of scientific modeling is provided in the next section.



Table 37. Teachers' CK about scientific modeling prior to and after Phase 1 of the PDC

Emerg ed themes	Prior to Phase 1 of the PDC	After Phase 1 of the PDC
<b>A. <u>Definition of modeling</u></b>		
1. Modeling is the process that is followed for creating a model that helps in (i) representing a phenomenon, (ii) explaining or interpreting how the phenomenon functions, and (iii) formulating and testing of predictions/hypotheses	1	14
2. Modeling is a process that is followed for creating a model for a phenomenon that helps in understanding and interpreting the phenomenon under study	1	6
3. Modeling is a process for creating a model that will help in studying the phenomenon	5	0
4. Modeling is the representation of a phenomenon through the use of a computer or other means	8	0
<b>B. <u>Reflection on the steps followed during modeling</u></b>		
1. Modeling is a <i>cyclical</i> and <i>iterative</i> process that involves several stages; performing observations, model development, model improvement, model validation, model evaluation, continuous model improvement	0	15
2. Modeling involves several stages; performing observations, data collection, formulating predictions or hypotheses, representation of the phenomenon, revision or improvement of the model	2	5
<b>C. <u>Perspectives of modeling</u></b>		
1. Modeling is a process of learning (through building external representations)	2	11
2. Modeling is a teaching approach	2	8
3. Modeling is a scientific enterprise	0	8
<b>D. <u>Naive conceptions about modeling</u></b>		
	5	0

#### 4.3.1.2.2. Teachers' understandings of modeling as a scientific enterprise, as an instructional approach, and as an ability that is developed within MCSI settings

Along with teachers' evolved definitions for scientific modeling, another question was also used within the CK test to capture teachers' understandings of three different perspectives of scientific modeling. Specifically, the teachers were asked to state whether modeling is a *scientific enterprise*, a *teaching approach*, or an *ability that is developed by learners during their engagement in MCSI learning environments*, and explain the reasoning behind their response. The rationale for administering this type of question was to examine the origins of teachers' modeling knowledge prior to the PDC, and also to study if their engagement as learners with the modeling curriculum during Phase 1 of the PDC could impact on the development of informed understandings about the three "faces" of modeling.

The analysis of teachers' responses to the abovementioned question revealed that both prior to and after Phase 1 of the PDC all teachers suggested that modeling could be conceived as a scientific enterprise, an instructional approach, and an ability that is

developed. However, the arguments that they used for supporting each perspective of modeling differed dramatically from the pre-CK test to the post-CK test. The themes that emerged from the analysis of teachers' arguments in favor of each of the three perspectives of modeling are provided in Table 38 and are discussed in detail in Chapter 5.

Table 38. Teachers' arguments for each of the three different perspectives of modeling prior to and after Phase 1 of the PDC

Perspectives of modeling	Prior to Phase 1 of the PDC	After Phase 1 of the PDC
<i>A. Modeling as a scientific enterprise</i>		
1. Modeling is a major enterprise followed by scientists while trying to understand, interpret, and explain natural phenomena. Through modeling scientists build and revise models to test their theories or create new models after interpreting their data from new perspectives	3	10
2. Modeling is followed by scientists when they build or use models to test their theories	7	10
3. Modeling is a scientific enterprise, because it follows the stages of scientific method, e.g., observations, hypothesis formulation, data recording, data interpretation, formulation of conclusions	10	0
<i>B. Modeling as an instructional approach</i>		
1. Modeling is an instructional tool that is used by teachers when they seek to help their students understand and interpret natural phenomena through the development of models. It involves several activities like observation of a phenomenon, interpretation of the phenomenon, representation of the phenomenon through the use of various modeling means, comparison of the model with the physical phenomenon, model revision, comparing models of the same phenomenon, and model validation	0	20
2. Modeling is an instructional approach, when a teacher creates models or uses ready-made models and integrates them in her science instruction	10	0
3. Modeling is an instructional approach, when a teacher designs science instruction around the scientific method (e.g., observations, predictions, experiments, conclusions)	10	0
<i>C. Modeling as an ability</i>		
1. Modeling is an ability that is developed by learners when they are engaged in modeling-based activities (constructing models, improving models, comparing models with their target, revising models, validating models)	0	15
2. Modeling is an ability that is developed by learners when they construct a model about a natural phenomenon	7	5
3. Modeling is an ability that is developed by learners when they follow the scientific method	10	0
4. Modeling is an cognitive ability through which learners build mental models through information processing	3	0

#### 4.3.2. Teachers' CuK for MCSI

As it was stated in the data collection section, teachers' CuK for MCSI was evaluated through two main data sources; the CuK test (see Data Collection section in Chapter 3) that was administered both prior to and after Phase 1 of the PDC, and the several assignments

that were completed by the teachers at various instances during Phase 2 of the PDC. Consequently, the findings will be presented in two sections according to the two data sources.

#### **4.3.2.1. Capturing teachers' CuK through the CuK test**

At the beginning of the PDC, all teachers' responses to the PCK questionnaire revealed a limited understanding of how the MCSI approach should look like in science curriculum. Moreover, their knowledge about the objectives of the teaching activities and the assessment tasks that are involved within a unit that is fostered through a MCSI approach was found to be inadequate or incomplete. The following extracts from two participants' responses document this claim.

*“Modeling in a science class is the process through which a phenomenon is represented in a model, mostly with the use of computer software, which shows how the phenomenon evolves over time. This is a personal view, since I have never learned about modeling or engaged in modeling-based learning before.”* [Participant # 5, prior to Phase 1 of the PDC]

*“Teaching a science lesson through modeling entails a way through which the teacher uses different materials to show and explain a phenomenon to the students. In some cases, we can use computer software to illustrate a specific phenomenon. I'm not sure if what I said is correct because neither had the chance to teach through modeling so far nor attended a class at the university that focused on how modeling is followed for teaching a science topic”.* [Participant # 11, prior to Phase 1 of the PDC]

In both abovementioned responses it is clear that the teachers perceived modeling as an instructional tool that facilitates teachers' work for representing a phenomenon that would be used later for demonstration within their science teaching. This stance pertains to a rather “authoritarian” view of teaching science through modeling, as it reveals that modeling is an instructional aid for the needs of the teacher while planning a science lesson and not a student-centered approach that enables students to represent, explain and interpret a phenomenon under study.

After their engagement with the MCSI curriculum materials of Phase 1, the majority of teachers seemed to have developed comprehensive understandings of the design principles of MCSI approach. They also stated that their experiences with the course helped them to refine their view of MCSI, revealing that it was a more complex and dynamic process than they had originally presumed. The following extracts from Teacher#9 document this claim:

“Modeling in science curriculum is the process of model creation. During modeling, we begin by observing a phenomenon and then formulate a theory about how the phenomenon occurs. We need to identify the variables of the phenomenon and how these change during the occurrence of the phenomenon, and also the processes that take place. As soon as we create the model, it is important to compare the model with the real phenomenon and through continuous observations we need to evaluate how well the model fits to the phenomenon. New observations or new data enable a continuous model improvement. Part of the modeling process is the model validation process, e.g., test if a model can be applied in a new class of phenomena. This knowledge comes from the instruction I received during the course which was based on modeling.”[Participant # 11, after Phase 1 of the PDC]

With respect to teachers’ CuK about the types of modeling activities a teaching unit in science curriculum should entail, the analysis of teachers’ responses prior to and after Phase 1 of the PDC revealed fourteen different types of activities that are presented in Figure 16.

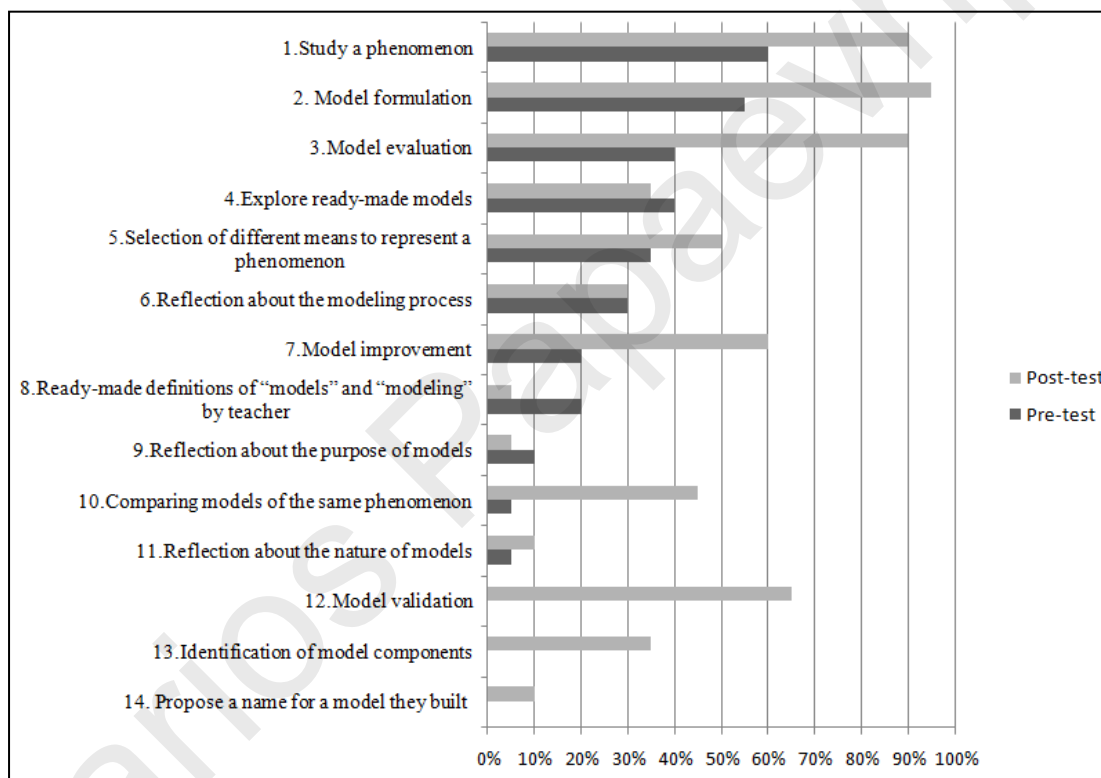


Figure 16. Teachers’ CuK related to the types of modeling activities a teaching unit in science curriculum should entail

The findings in Figure 16 indicate that at the beginning of the course the majority of the participating teachers’ knowledge about the types of activities a teaching unit in science curriculum should entail was very limited. Activities like *study of a phenomenon* and *model formulation* were identified by slightly more than half of the participants, whereas activities like the *exploration of ready-made models*, the *model evaluation*, and the

*selection of the appropriate means to represent a phenomenon* were identified by less than half of the participants. At the end of Phase 1 of the PDC, the prevalence for most of the activities that were identified prior to the PDC was increased and also, new types of activities were proposed, e.g., *model validation* (65%), *identification of the model components* (35%), and *propose a name for a model they built* (10%). The proposed activities that relate to the *nature of models* or the *purpose of models* were very limited after Phase 1 of the PDC, indicating that teachers did not consider activities related to the epistemic awareness about models and modeling as of great importance within a MCSI setting, although they themselves experienced such type of activities during their participation in the course.

As far as teachers' knowledge about the objectives of modeling assessment tasks is concerned, the findings from the analysis of teachers' responses are presented in Figure 17.

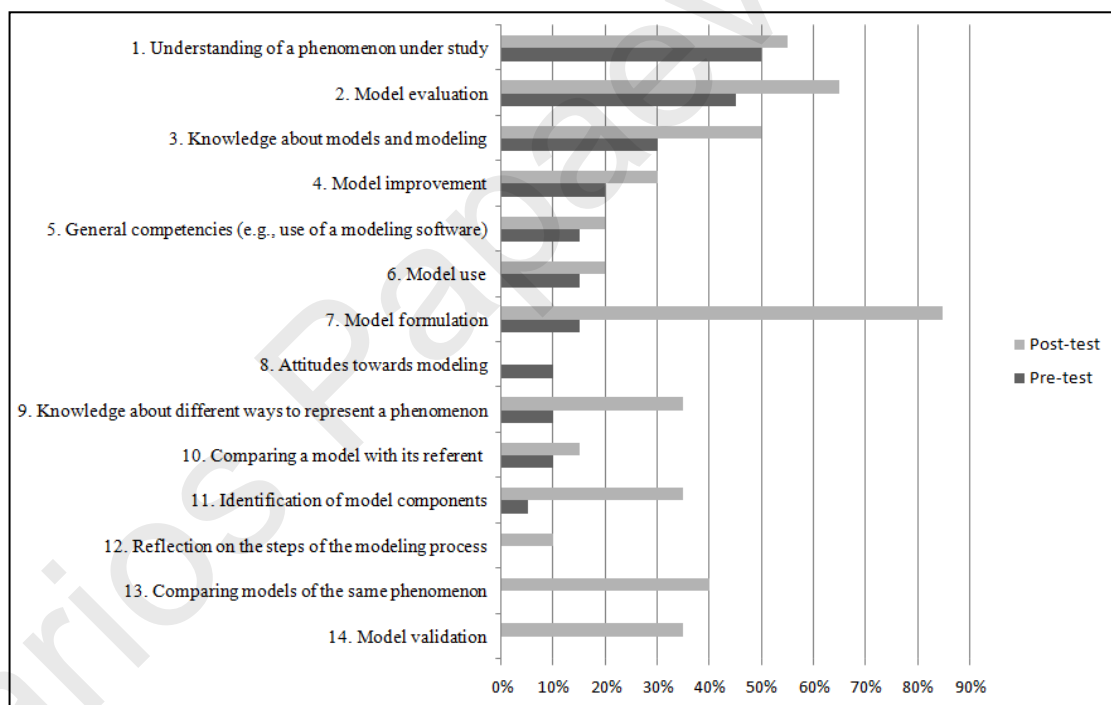


Figure 17. Teachers' CuK about the objectives of modeling assessment tasks

The findings in Figure 17 demonstrate teachers' limited prior knowledge concerning the objectives of assessment tasks that can be used to evaluate students' modeling ability. For instance, prior to the PDC about half of the teachers stated that for evaluating students' modeling ability the tasks should focus on *understanding a phenomenon under study* and *model evaluation*. Although the first type of objective (*understanding a phenomenon under study*) might not be considered as an indicator of students' modeling competence, the

teachers might referred to the case of studying a model for getting an insight of how the phenomenon functions. Additionally, the teachers made references on some other important objectives of modeling assessment tasks (e.g., *knowledge about models and modeling*, *model improvement*, etc, see Figure 17 for more details), but the prevalence of these assessment tasks within teachers' responses was very limited.

After Phase 1 of the PDC, the teachers' knowledge about the objectives of modeling assessment tasks that could be used within a MCSI setting seemed to have been enhanced to some extent, since the number of teachers who incorporated in their responses modeling-related assessment tasks was increased (see Type 2, 3, 5 in Figure 17 for examples), and also new objectives of modeling assessment tasks were proposed (see Type 12 and 14 in Figure 17 for examples). Nevertheless, modeling assessment tasks that focus on students' *model validation skill*, *identification of model components skill*, and *comparing models of the same phenomenon skill* were reported by less than half of the participants.

#### **4.3.2.2. Capturing teachers' CuK through a set of assignments**

The second data sources that I looked up for capturing teachers' CuK for MCSI was a set of assignments that were completed by the teachers at various instances during Phase 2 of the PDC (see Figure 8 in Data Collection in Chapter 3). The presentation of the findings begins with the findings that were revealed from the analysis of teachers' responses in Assignments 2.1 and 2.4 that pertained to the evaluation of teachers' CuK for the objectives of modeling assessment tasks. The subsequent section relates to the findings that came up from the analysis of teachers' responses in Assignments 2.2 and 2.3 through which teachers' CuK about the objectives of the activities within MCSI curriculum was assessed. The last section of findings pertains to the findings that were revealed from teachers' responses in Assignment 2.5 that focused on the criteria they used for selecting a unit from the national curriculum to reconstruct through incorporating the MCSI perspectives.

##### **4.3.2.2.1. Teachers' CuK about the objectives of modeling assessment tasks**

Assignment 2.1 was administered right after the teachers completed a set of assessment tasks through which the evaluation of the development of their modeling ability after Phase 1 of the PDC was performed. This assignment encompassed all the modeling ability tasks

that the teachers previously completed and they were asked to state this time, what was sought to be evaluated through each assessment task and explain the reasoning behind their response. The purpose for administering this assignment in the beginning of Phase 2 and, specifically after teachers' completion of the modeling assessment tasks, was to evaluate if teachers, after their participation in Phase 1 of the PDC as learners in a MCSI setting, developed informed understandings about the aspects of MCSI and the ways to assess them (e.g., what modeling capabilities are we expecting from students to have developed after their participation in MCSI settings?).

Assignment 2.4 was in the same format as Assignment 2.1, but differed in the assessment tasks that were used to evaluate teachers' knowledge about the objectives of modeling assessment tasks. Even though the set of assessment tasks were different, the objectives as well as their format were identical to those used in Assignment 2.1. The purpose for designing and administering Assignment 2.4 was to explore teacher's changes in terms of their CuK for MCSI, after reading a theoretical paper about MCSI and also to obtain data to compare teachers' CuK for MCSI prior to and after the reading of the theoretical paper.

The analysis of teachers' responses in Assignments 2.1 and 2.4 are presented in Table 39 and are discussed below. The percentages that appear in Table 39 refer to the degree of concurrence between what the assessment task pertains to, and teacher correct identification of the objective of the assessment task. For instance, in the model formulation assessment task 90% of the teachers identified correctly what the assessment task pertains to and 10% failed to do so.

Table 39. Identification of the objectives of modeling assessment tasks prior to and after the reading of the theoretical paper about MCSI

Objective of the modeling assessment task	Assignment 2.1	Assignment 2.4
1. Modeling skills		
1.1. Model formulation	95%	100%
1.2. Identification of model components	85%	100%
1.3. Comparing and contrasting models of the same phenomenon	85%	100%
1.4. Model evaluation and formulating ideas for improvement	65%	95%
1.5. Model validation through comparison with phenomena of the same class	30%	95%
2. Metacognitive knowledge about the modeling process	10%	90%
3. Meta-modeling knowledge		
3.1. Nature of models	30%	95%
3.2. Purpose or utility of models	75%	100%

According to the findings reported in Table 39, the majority of teachers appeared to be able to identify the objectives for most of the modeling ability assessment tasks prior to reading the theoretical paper. For instance, more than  $\frac{3}{4}$  of the teachers identified correctly the objective of the tasks that pertain to the evaluation of learners' *model formulation skill*, *identification of model components skill*, *comparing and contrasting models of the same phenomenon skill*, and *knowledge about the purpose or utility of models*, and more than half of the teachers were able to identify the objective of the task that related to *model evaluation and formulating ideas for improvement*.

The tasks that sought to evaluate learners' *model validation through comparison with phenomena of the same class skill*, *metacognitive knowledge about the modeling process* and *meta-modeling knowledge about the nature of models* appeared to be the most difficult for the majority of the teachers to identify them correctly. Specifically, the teachers appeared to conceive the task that referred to the evaluation of *model validation through comparison with phenomena of the same class skill* as a task that sought to evaluate learners' ability to judge a model's inconsistency with the phenomenon it represents and identify the ways of how the model could be improved. Put differently, the teachers identified this task as a task for the evaluation of a model and not as a task for validating a model. The following extract from a teacher's response is a representative example of this misunderstanding.

*“This task aims to evaluate if students are able to check if the model is correct (e.g., does the model represent the phenomenon or does it provide a mechanism to explain how the phenomenon through evaluating?) and suggest ideas for further improving the model.”*  
(Teacher # 12)

Likewise, the teachers failed to identify the purpose behind the task that sought to evaluate learners' meta-modeling knowledge about the nature of models. This task encompassed a representation about the cell division and the teachers were asked to study it and state if such representation could be considered as a scientific model. All but 3 teachers, prior to reading the theoretical paper about MCSI, considered this task as a task to be used for evaluating learners' skill to evaluate a model according to its fitness with the phenomenon it represents, and not as a means through which the learner is prompted to specify aspects of the nature of models within his/her response. Their responses were very similar to those they provided in the case of model validation task that was described above.



Teachers' knowledge about the objective of the task that pertained to the evaluation of a learner's *metacognitive knowledge about the modeling process* was assessed through a task that asked learners to suggest the steps that were needed to be followed in order to create a model about plant growth. Based on the analysis of their responses, all but 2 teachers, misinterpreted the objective of the task, as they appeared to have associated it with the technical steps that are followed for creating a model in Stagecast Creator and not as a task for evaluating learners' knowledge about the cyclical and iterative processes that are followed during modeling a physical phenomenon. The following extract from a teacher's response is particularly revealing:

*"This task refers to the evaluation of a learner's knowledge about the steps that are followed for building a model in Stagecast Creator. In order to build a model to represent the plant growth, we need to create the variables of the phenomenon in Stagecast Creator and then create rules for controlling the processes that take place during the plant growth."* (Teacher # 2)

The analysis of teachers' responses in Assignment 2.4, compared with the findings from Assignment 2.1 (see Table 39 for details), revealed that the teachers were able to identify correctly the objectives for all of the modeling assessment tasks. These findings indicate that the reading of the theoretical paper about MCI appeared to have a positive impact on the development of teachers' CuK about the objectives of modeling assessment tasks.

#### *4.3.2.2.2. Teachers' CuK about the objectives of the activities within MCSI curriculum*

Teachers' CuK in relation to the objectives of the activities a MCSI should entail was evaluated through Assignments 2.2 and 2.3. Both assignments had the same format but referred to a different MCSI curriculum. In both assignments, the teachers were asked to review the activities within a MCSI curriculum and identify the learning objectives of each activity or a set of activities that relate to MCSI. The "Modeling 1-D Elastic Collisions" curriculum that was used during Phase 1 of the PDC was the context of Assignment 2.2, whereas "Modeling Marine Ecosystems" curriculum was the context of Assignment 2.3. The latter MCSI curriculum was developed for the purposes of a previous study and the focus was the development of fifth grade students' modeling ability and understanding of concepts related to marine ecosystems.

The findings from the analysis of teachers' responses in Assignments 2.2 and 2.3 are presented in Table 40 and discussed hereafter.

Table 40. Identification of the objectives of the activities within the MCSI curricula prior to and after the reading of the theoretical paper about MCSI

Learning objectives of the activity (or a set of activities) within the MCSI curricula	Assignment 2.2 (Modeling 1D Collisions)	Assignment 2.3 (Modeling Marine Ecosystems)
1. Model formulation	80%	100%
2. Identification of model components	80%	100%
3. Comparing and contrasting models of the same phenomenon	75%	95%
4. Model evaluation and formulating ideas for improvement	60%	90%
5. Model validation	20%	95%
6. Meta-modeling knowledge with respect to the nature of models	30%	95%
7. Meta-modeling knowledge with respect to the purpose or utility of models	50%	100%
8. Metacognitive knowledge about the modeling process	10%	95%
9. Modeling ability scaffolds	15%	65%
10. Naming a model and justification of the given name	100%	100%
11. Description of the steps followed in Stagecast Creator for creating a specific model	70%	90%
12. Peer evaluation of models	60%	85%
13. Observation of a phenomenon or an experiment and data collection	100%	100%
14. Reflection on observations or provision of explanations	70%	90%
15. Investigation through experimentation and data collection	90%	100%
16. Inquiry scaffolds (e.g., data organization, identification of patterns or relationships between the phenomenon variables, etc)	30%	60%
17. Introduction of concepts	60%	80%
18. Conceptual understanding scaffolds	10%	70%

After their engagement as learners during Phase 1 of the PDC and prior to reading the theoretical paper about MCSI, the majority of teachers seemed to be able to identify correctly most of the objectives behind the design of specific modeling activities within the MCSI curriculum. For some of the activities (see Activities 4, 5, 7, 12, and 17 for example) the teachers showed a moderate performance, whereas for some other activities (see Activities 5, 6, 16, and 18 for example) the majority of the teachers failed to identify correctly the objectives behind the design these activities.

In contrast, the teachers seemed to performed better in identifying the learning of objectives of the curriculum titled “Modeling Marine Ecosystems” after the reading of the theoretical paper. Even though they did not experience this curriculum as learners during Phase 1 of the PDC like the one they have been engaged with during Phase 1, they were able to associate the activities of the curriculum with the MCSI objectives. Nevertheless, the activities that served as scaffolds during engaging learners in modeling or inquiry or

conceptual development activities (see activities 9, 16, and 18 for examples) were the least identifiable by the teachers. A possible explanation for this finding might relate to teachers' inadequacy to distinguish between the activities that focused on a specific learning objective (e.g., modeling, inquiry or conceptual) and their associated complementary activities that served as prompts for reflection, sense making and abstracting meaning.

#### 4.3.2.2.3. Teachers' criteria for selecting a unit from the national curriculum to incorporate the MCSI perspective

Teachers' CuK for MCSI was also assessed through an assignment they completed when they were asked to study the national curriculum and choose a unit to reconstruct by adopting MCSI as the instructional approach. Specifically, they were asked to provide the criteria they used for selecting their unit and explain their reasoning. The analysis of the reports they provided for the purposes of this assignment revealed 8 criteria that are presented in Table 41.

Table 41. Teachers' judgmental criteria when selecting a science teaching unit to reconstruct

Criterion	Representative extracts from teachers' reports	Frequency
1. Conceptual understanding limitations	<p><i>"The unit follows a content delivery approach that students won't be able to remember after they stop working with it". [Teacher # 12]</i></p> <p><i>"Surface approach of concepts; the students neither develop an understanding of the concept of density nor are guided to identify the variables that are associated with the density; they observe the sinking or floating of various materials in the water without being prompted afterwards to interpret the phenomenon of sinking/floating". [Teacher # 5]</i></p>	65%
2. Difficult concepts within the unit	<p><i>"The concepts that are anticipated to be grasped by the students are difficult and complex, so using a modeling-based approach will help my students to develop a comprehensive understanding about these concepts". [Teacher # 20]</i></p> <p><i>"Heat is an abstract concept that is difficult to be understood, especially by young students. Through modeling the students will be able to develop conceptual understanding about this concept, as they will be directed to create a representation of the heat and thus to make the "invisible" visible". [Teacher #15]</i></p>	60%
3. Students' misconceptions about concepts related to the unit	<p><i>"The students hold misconceptions about the concept of heat and they often cannot differentiate between temperature and heat". [Teacher # 15]</i></p> <p><i>"Student difficulties and misconceptions about concepts related to the unit were also a major criterion for selecting the teaching unit". [Teacher #20]</i></p>	45%
4. Students' familiarity with the concepts of the unit	<p><i>"I chose this unit because the unit should be as less complex as possible, meaning that the concepts that the unit entails should not be difficult to be developed by the students". [Teacher #2]</i></p> <p><i>"My students are already familiar with the concepts of the unit and thus they won't find it difficult to learn how to model a phenomenon". [Teacher # 8]</i></p>	10%

5. Procedural knowledge limitations	<p>“The structure of the unit does not allow students to investigate the variables that affect the sinking or floating of an object when placed inside a liquid and then to develop a model that integrates their findings. Hence, the students do not associate these findings with the concept of density”. [Teacher # 5]</p> <p>“The students are not engaged in investigations of how the type of lens affects the characteristics of the formed image or how the distance between the object and the lens affects the distance of the formed image. Since they do not design experiments to test a prediction or hypothesis, the students do not develop procedural skills that are necessary for learning science”. [Teacher #18]</p>	75%
6. Fitness of the unit with inquiry	<p>“The unit encompasses mainly experiments through which the students will observe the phenomenon under study and thus to identify the aspects of the phenomenon. This is the first step for modeling a phenomenon”. [Teacher #4]</p> <p>“Because the unit entails more processes than concepts (e.g., the propagation of light rays through a lens), the use of modeling as an instructional approach is more preferable”. [Teacher #1]</p>	60%
7. Affordances of Stagecast Creator	<p>“Stagecast Creator can be used effectively by the students for building their models to explain why an object will sink or float when placed inside a water tank”. [Teacher #5]</p> <p>“I chose this unit because the students at this age won’t find any difficulties in using Stagecast Creator to build their models in this context” . [Teacher #19]</p>	50%
8. Added value of modeling as an instructional approach	<p>“Through modeling students' conceptual understanding would be enhanced because they will build models to explain how the phenomenon functions and afterwards they will use their model for formulating and testing of predictions” .[Teacher #11]</p> <p>“I need to offer my students the opportunity to build various types of models (e.g., graphical, mathematical, verbal, computer-based models) to formulate and test hypotheses and thus to discover themselves the aspects of the phenomena they will be studying”.[Teacher #1]</p> <p>“Engaging students in modeling could be a challenging task for them, as it will stimulate their interest in learning and they will experience the science content like a game-play activity”. [Teacher #7]</p>	95%

According to Table 41, the teachers used a variety of criteria to document their selection of the teaching unit they would later reconstruct. These criteria, presented in Table 41, can be grouped into four distinct clusters that point to four different “lenses” through which they approached and evaluated the existing units from the national curriculum. The first lens that the teachers used during studying the unit they selected to reconstruct relates to the *conceptual understanding* dimension of the unit and the first four criteria in Table 41 are clustered within this dimension. The second lens through which teachers reviewed the units from the national curriculum concerns the unit’s relevance with *inquiry-based learning* and entails the identification of *procedural knowledge limitations* and the *fitness of the unit with inquiry* (see criteria 5 and 6 respectively in Table 41). The affordances of *Stagecast Creator as a modeling tool* that the teachers used during Phase 1 of the PDC was the third lens that teachers used to examine the unit they selected to reconstruct. Finally, the last but the most frequent lens that was reported in almost every teacher’s report

pertains to the *appreciation of modeling as an instructional approach* to be used for reconstructing their units. The four lenses that pertain to teachers' CuK with respect to the relevance of existing curriculum materials with the perspectives of MCSI approach are discussed in a more elaborated manner in Chapter 5.

#### **4.4. Research question 3: What are the characteristics of teachers' modeling-centered curriculum designs?**

For answering the third research question, the MCSI curriculum materials that teachers created by the end of Phase 2 of the PDC were used. These curriculum materials were rich in data sources, as they encompassed the following: (i) selection of a teaching unit and description of the rationale behind this selection; (ii) formulation of learning objectives; (iii) mapping the activity sequence; (iv) design and detailed description of the activities proposed in the activity sequence section; (v) design of activity sheets; (vi) design of assessment tasks; and (vii) computer-based models created by the teachers in SC. While redesigning the selected teaching unit from the national curriculum, it was expected that teachers would transform experiences, knowledge, and skills gained throughout the course and these transformations would be illuminated within their curriculum materials. Hence, teachers' modeling-based curriculum designs served as transparent prisms through which transformations of their evolved CK about models, modeling and the development of learners' modeling ability, and their CuK for MCSI were investigated.

Before proceeding to the presentation of the characteristics of teachers MCSI curriculum designs that emerged, the topics of the units that the teachers chose to reconstruct in conjunction to the names (pseudonyms) of the teachers are provided in Table 42.

Table 42. Teachers' topic selection used for the redesign of their MCSI curriculum materials

	Unit's topic	Name of teacher
1	Buoyancy	Dina, Alex
2	Electric circuits	Mary, Bill
3	Thermal interactions	Christina, Susan, George
4	Friction and motion	Bruce, Lucas, Martin
5	Geometrical optics	Lucy, Ann, Debra, Derek
6	Motion and Newton's laws	Doris, Debbie
7	Earthquakes	Jane
8	Oscillations	John
9	Substance dilution	Marlene
10	Expansion and contraction of solid materials	Molly

Teachers' MCSI curriculum materials were examined through the use of seven critical standpoints that enabled the identification of the characteristics of their curriculum materials. The characteristics that emerged for each standpoint were clustered along three levels of increased sophistication. The dimensions of analysis along with the levels of increased sophistication that illuminate teachers' MCSI curriculum characteristics are presented in Table 43 and are described in detail below.

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Table 43. Dimensions of analysis of teachers' MCSI curriculum materials; emerged characteristics and levels of sophistication

Dimensions of analysis of teachers' MCSI curriculum materials	Level 1	Level 2	Level 3
1. Overall curriculum design orientation	Transmissive	Transmissive AND Transactive	Transactive AND Transformative
2. Degree and type of reconstruction of the national curriculum unit	Replication of the national curriculum unit with few modeling activities as add-ons	Partial reconstruction of the national curriculum unit with a variety of modeling activities, although the role of modeling is not highly exemplified	Total reconstruction of the national curriculum unit with strong priority to modeling as the approach through which important learning goals could be achieved
3. Types of designed activities and role of modeling in the curriculum	Didactic activities - Modeling as a means for "mimicking" others' models	Fewer didactic and more hands on activities - Modeling as a vehicle for representing and interpreting phenomena in a superficial manner	Guided inquiry and Modeling-Centered Scientific Inquiry activities - Modeling as a vehicle for representing, interpreting and predicting phenomena
4. Integration of the modeling ability framework	Superficial cultivation of a limited number of the modeling ability framework components – the "lethal mutations" effect	Moderate cultivation of all components of the modeling ability framework – the "modeling for modeling's sake" effect	Efficient transformation of the modeling ability framework into pedagogically potent modeling activities
5. Models' progression	Development of various independent models to represent different but related phenomena	Development of various independent models to represent different aspects of a single phenomenon	Development of a sequence of interrelated models with a gradual complexity and applicability to represent various aspects of a phenomenon
6. Nature of suggested models	"Animation"- like models	"Simulation"- like models	Models consistent with the definition of scientific models
7. Evaluation of students' learning gains	Pre- and -post evaluation based only on students' conceptual understanding through true/false statements	Initial and final evaluation of students' development of modeling skills and conceptual understanding in the context of the curriculum	Initial, ongoing and final evaluation of students' development of modeling ability and conceptual understanding in new contexts

#### 4.4.1 Overall curriculum design orientation

Teachers' overall curriculum design orientation was evaluated after a thorough examination of the curriculum materials they developed. These were: (i) the rationale for the selection of their unit; (ii) the learning objectives; (iii) the activity sequence mapping; (iv) the description of the activities with the associated learning objectives; and (v) the curriculum itself. For the characterization of the curriculum design orientation that was extracted from the abovementioned artifacts, the Miller and Seller (1990) classification scheme was followed. This scheme classifies the curriculum design orientation into *transmissive*, *transactive* or *transformative* according to the role of the learner and the teacher in the overall teaching and learning environment. A *transmissive* curriculum design orientation assumes knowledge is content, controlled by the teacher, and transferred to students through demonstration and telling. A *transactive* curriculum design orientation, on the other hand, assumes knowledge is constructed by learners through the process of learning, and the role of the teacher is to facilitate learning and to create environments which stimulate learners' interests, recognizing that learning is social and at the same time individual. Finally, a *transformative* curriculum design orientation refers to the case of curricula that learning is developed through self-reflection, self-awareness, and self-learning; the learner is offered opportunities to "reassess new knowledge in relation to existing knowledge and reflect upon the underlying assumptions and biases that are the foundation of that existing knowledge" (Harris & Cullen, 2009, p. 57).

The analysis of teachers' curriculum materials in relation to their curriculum design orientation they chose to design around their curriculum revealed three hierarchical levels with increased sophistication (see Table 43). The three levels are described below in conjunction with extracts from teachers' curriculum designs that illuminate their curriculum design orientation.

*Level 1-Curriculum design orientation: Transmissive.* Level 1 entails the case of teachers' who designed their curriculum materials around an "authoritarian" and teacher-directed perspective. The activities they designed, as well as the description of the rationale behind the design of their activities, were permeated of strong *transmissive* pedagogies, since the teacher appeared to manage and control students' learning and the students acted as "followers" of the pieces of knowledge he/she diffuses throughout the lessons. Bill and Molly represent two teachers whose curriculum design orientation was classified as transmissive.



Bill, who chose the context of electric circuits as the context of his curriculum design, claimed that

*“...as it is difficult for my students to find all possible ways that a wire, a bulb, and a battery could be connected to form a closed electric circuit, I will let the students “play” with the materials at the beginning of the lesson, but later I will demonstrate the four different ways both through the crocodile physics simulation and through ready-made electric circuits that I would build from the previous day. Hence, I will make sure that my students will be informed about the possible ways to make a simple electric circuit and they won’t lose their interest when they experience difficulties of how to appropriately connect the materials to form simple electric circuits”.*

Additionally, while trying to justify his decision for the demonstration of the electric current in several types of circuits (e.g., simple circuit, two bulbs in a row circuit, and two parallel bulbs circuit), Bill stated the following:

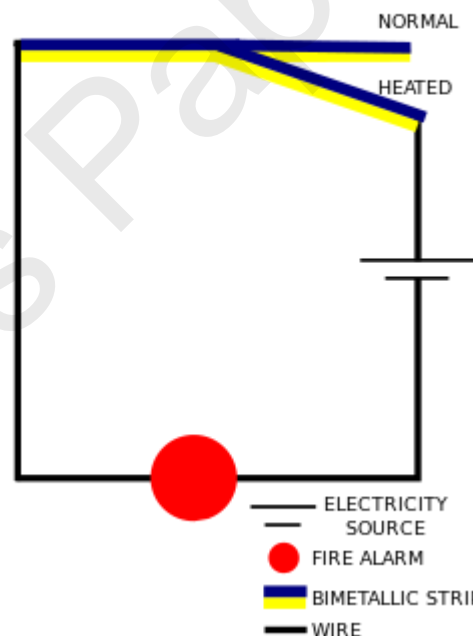
*“Since there isn’t a way to make any observations of the electric flow in a circuit with the use of any instrument, I decided to show my students the electric flow in the several circuits through simulations in Crocodile Physics, and I will explain them that the small dots that flow inside the wires are the electrons that move inside the circuit. Then, I will ask my students to create similar models of the ones they watched in Crocodile Physics in Stagecast Creator”.*

Bill’s abovementioned statement empowers the classification of the curriculum design orientation used to develop his curriculum materials into the transmissive pedagogy. Specifically, without prompting his students to think or interpret their observations, he decides to present a simulation through which ready-made knowledge is transferred to his students. Also, instead of asking his students to create their own models to represent their observations and also to provide an interpretation of how the several electric circuits function, he choose to present simulations that illustrate the electric flow and then asks his students to replicate what they observed for creating their models.

Likewise, Molly, who used the context of expansion and contraction of solid materials in her curriculum development, designed activities that illustrated the very limited role of students in the learning process and the dominant role of teacher during investigating,

modeling, and explain phenomena. Specifically, Molly explained that, because the experiments of expansion of solid materials require the use of burners, she herself will perform the experiments and the students will observe the changes that would happen during experiments' execution. She neither planned to ask her students to collect data from the experiments they were expected to observe, nor asked her students to provide explanations or interpretations for how a phenomenon functions after observing an experiment. Instead, she stated that during modeling the expansion of a piece of metal after heating it with a use of a burner, she would ask her students to create models in Stagecast Creator to represent the change of the shape of the metal strip, and she would be satisfied if her students would succeed on doing so. Additionally, even though she designed an extension activity to help her students understand the behavior of bimetallic strips and their use in fire alarms, the way she designed it also point to the dominant role of the teacher in students' learning. The following extract from her curriculum activities supports this claim.

*The following picture illustrates how a bimetallic strip is used in fire alarm systems. It shows that at the instance of fire, the metallic strip would bend and therefore it will make the circuit to close and thus the tocsin will begin to ring.*



*Use Stagecast Creator to create a model that illustrates how the alarm system functions. In your model try to show the changes that take place during the event of fire. You may add an alarm sound from the sounds library of Stagecast Creator to make your model more consistent with the real one.*

The abovementioned activity encompasses several characteristics that reveal the transmissive orientation Molly followed for the design of this activity. Firstly, instead of offering her students the opportunity to study the fire alarm system through direct observations of the real system and then to prompt them explain how the system functions (e.g., how does the bimetallic strip function and control the alarm system?), she presented a graphical representation of the inner parts of the fire alarm system and provided a ready-made explanation of how the bimetallic strip functions within the system, in the event of fire. Secondly, instead of asking her students to create a model that would: (i) represent the fire alarm system; (ii) provide an interpretation of the way it functions; and (iii) be used for predictions, she prompted her students to “mimic” the ready-made graphical representation provided through the curriculum for the creation of their model. Also, the fact that she asked her students to add a sound in their model designates that she used modeling as a tool for representation purposes, and not as a tool for interpreting phenomena.

*Level 2-Curriculum design orientation: Transmissive and Transactive.* This level pertains to the case of curriculum materials which were designed on the basis of a combination of transmissive and transactive curriculum design orientations. Specifically, the teachers whose curriculum designs were clustered in Level 2 switched between the two types of curriculum design orientations during engaging their students in modeling, inquiry-oriented and conceptual development activities. Mary and Dina are two teachers whose curriculum materials belong to Level 2.

Mary, who chose the context of electric circuits for her curriculum development, started her activity sequence with a driving question of how the lights in a Christmas tree function. She stated that she would let her students discuss in their groups their ideas and then present in class their explanations. Then, she planned to engage her students in inquiry-based activities through which they would try to explore the possible ways of how a wire, a light bulb, and a battery could be connected for making the light bulb lit, and afterwards she would challenge them to think of and develop a model for the electric current based on observing of what happens when a metallic clip is attached at the two poles of a battery. This activity was considered as a *transactive*-oriented activity, because knowledge would be constructed by learners through the process of learning, and the role of the teacher would be to facilitate their learning. On the other hand, when she proceeded to designing modeling-based activities through which her students were expected to create a model of a

two light bulbs in a row circuit, instead of prompting her students themselves to think and use the idea of electric current for interpreting why the brightness of the two light bulbs is equal, she wrote the following in her curriculum:

*“According to your observations, the brightness of the two light bulbs is the same. This means that the electric current that flows inside the first light bulb is the same that flows inside the second bulb. That’s why we call this a “serial circuit”. Don’t forget to use this idea when creating your “serial circuit” in Stagecast Creator.*

Similarly, Dina, whose curriculum design was based on the context of buoyancy, designed hands on activities through which the students would investigate the factors that affect the sinking and floating of solid materials into a liquid. For each of the factor they would investigate, she planned to ask her students to create models in Stagecast Creator to show how each factor affect the sinking or floating behavior of certain objects. Most importantly, the students would be prompted to improve their models after the investigation of each new variable in order to reach at a model that unifies all factors that affect or not an object’s buoyancy into a specific liquid. So far, Dina’s curriculum design orientation is considered as *transactive*, because she provides opportunities to her students to construct their own learning through investigation and modeling. However, at the point she planned to help her students understand that the “density” of an object is the variable that affects its sinking or floating in a specific liquid, she switched her curriculum design orientation to *transmissive*. Specifically, without guiding her students to understand the concept of density through important learning activities she could have designed, she introduced the concept of density through a technical and teacher-directed way (e.g., she asked her students to divide the mass value with the volume value of specific objects and informed them that the quotient is called the density of an object). As a result, her students would passively receive ready-made knowledge of an important concept that is central in the context of buoyancy, without conceptually orientating them to develop themselves an operational definition for this concept.

*Level 3-Curriculum design orientation: Transactive and Transformative.* The curriculum designs that were clustered in Level 3 were found to encompass a combination of *transactive* and *transformative* curriculum design orientations. Apart from the transactive activities through which the students would be supported in constructing their own learning and the instructor would act as a facilitator during students’ learning development, the

teachers designed several activities throughout their curriculum to indicate that students' learning would emerge through self-reflection, self-awareness, and self-learning. Specifically, these teachers systematically intended to prompt their students to elicit their existing knowledge about a topic under study, then they proceeded on helping students to confront their prior knowledge with knowledge that emerged through inquiry and modeling oriented activities, and at the end they engaged the students in self-reflecting activities for reassessing the new knowledge in relation to their existing knowledge.

Lucy is one of the teachers whose overall curriculum design orientation was clustered in Level 3. Her curriculum context was the geometrical optics and the driving question used at the beginning of her curriculum to trigger students' interest and to evaluate their prior knowledge was "What type of glasses a person with farsighted vision and a person with shortsighted vision should wear to improve their vision?" Through an authentic scenario she developed herself, she asked her students to become medicine students and keep individual reflective diaries in which they would record their initial ideas and solutions for the introductory problem, and then keep records of their evolved knowledge about geometrical optics throughout the course. She planned to help her students investigate how convex and concave lenses function in terms of the type of image that is formed with the use of each lens, and also to understand through hands on activities the mechanism of image formation with the use of different types of lenses. She also embodied within her curriculum several prompts for reflection, like "*What did you learn so far about models and modeling? Did you learn something you from the today's lesson? Explain*" or "*Is your initial solution for the type of glasses one with farsighted vision should wear consistent with your findings from the today's lesson? Explain*" or "*How does your model about the concave lens function relate with the problem that was initially introduced in the curriculum?*"

#### **4.4.2. Degree and type of reconstruction of the national curriculum unit**

The second dimension through which teachers' curriculum designs were studied concerns the type of reconstruction of the national curriculum unit they chose to follow for the design of their own curriculum. Specifically, each teacher's curriculum design was compared with the corresponding national curriculum unit in an attempt to examine the degree and the type of reconstruction the teachers had pursued for the development of their MSCI curriculum materials. Special attention was also given to the type, the format, and

the place of the modeling activities within the activity sequence the teachers incorporated within their curriculum. The three levels that emerged from the analysis of teachers' curriculum in relation to the degree and the type of reconstruction of the national curriculum unit are described below.

*Level 1- Degree and type of reconstruction: Replication of the national curriculum unit with few modeling activities as add-ons.* This level refers to the case of curriculum materials that showed little deviation from the existing activities of the national curriculum unit. Specifically, the examination of these curriculum materials revealed that the format, the structure, and the content of the activities of the national curriculum were maintained, while the few modeling activities that were designed were used as *add-ons* without truly being incorporated in the activity sequence. Martin's curriculum, which was developed in the context of "Friction and Motion", is a representative example of this type of curriculum development. To illustrate the degree and type of reconstruction Martin followed for his curriculum development, an extract of the activity sequence mapping from Martin's reconstructed unit is provided in Figure 18.

Scientific practices	Curriculum activities
Observe phenomenon	<ul style="list-style-type: none"> <li>•The teacher pushes the desk with difficulty</li> <li>•The students make observations</li> <li>•The teacher poses questions for reflection</li> </ul>
Explain phenomenon	<ul style="list-style-type: none"> <li>•The teacher introduces "friction" as the force that impede the motion of the desk</li> </ul>
Delivery of data	<ul style="list-style-type: none"> <li>•The teacher provides students with data about the friction and the force exerted on the desk</li> </ul>
<b>Model creation</b>	<ul style="list-style-type: none"> <li>•The students create graphical models and models in Stagecast Creator to represent the phenomenon</li> </ul>
Investigation	<ul style="list-style-type: none"> <li>•The teacher performs an experiment to test how the type of surface affects the motion of an object</li> <li>•The students keep records of the data collected and reported by the teacher</li> </ul>
Data interpretation	<ul style="list-style-type: none"> <li>•The students make inferences about the friction force in relation to the type of surface</li> </ul>
<b>Model creation</b>	<ul style="list-style-type: none"> <li>•The students create a model in Stagecast creator to represent the results from the investigation with the different surfaces</li> </ul>

Figure 18. Martin's activity sequence

(Note: The activities in gray colored boxes represent the new activities that Martin incorporated in his curriculum, whereas the activities in white colored boxes pertain to the activities that were transferred without any deviation from the national curriculum unit)

The extract from Martin's activity sequence presented above designates that Martin chose to keep the activities from the national curriculum unit intact, and the two modeling activities he designed were added as new "entries" in his curriculum reconstruction. He neither attempted to change the teacher-directed approach that was followed for the majority of the activities of the national curriculum unit (e.g., in explaining why it was difficult to move the desk while pushing it, the teacher, instead of asking the students to interpret the phenomenon, provided his own interpretation by introducing the concept of friction as the force that impedes the motion of the desk) nor actively engaged his students in the process of scientific inquiry (e.g., the teacher performs the experiments, collects the data, and asks his students to keep records of the data he reports). More importantly, the modeling activities he inserted as "add-ons" in the activity sequence not only were restricted to the mere representation of a phenomenon (e.g., pushing the desk with difficulty because of the friction force) or an experiment (e.g., representation of the distance that an object covers in four different types of surfaces), but the rationale behind the design of these activities was of meaningless scope. This is because the creation of a model for representation purposes, although a significant aspect of MCSI, might not promote important learning gains to students if it is used in isolation from the other purposes that the creation of models entails. In the case of Martin's curriculum reconstruction, the creation of a model to represent the outcomes of an experiment or the visual representation of an event does not help the students to extend what they have learned from the previous activities, because the place and the rationale of this activity in the activity sequence does not have an added value both from a modeling and a conceptual perspective. Hence, it seems Martin added these modeling activities to fulfill the requirements of the project he had to accomplish and not to facilitate the development of his students' epistemic awareness of the role of models as both representational and explanatory tools.

*Level 2 - Degree and type of reconstruction: Partial reconstruction of the national curriculum unit with a variety of modeling activities, although the role of modeling is not highly exemplified.* The curriculum designs that were clustered in Level 2 relate to those whose the format, the structure, and the content of the existing unit from the national curriculum were partially reconstructed, and the MCSI activities that were designed had

been interconnected with the rest of the activities of the curriculum in a meaningful manner. However, the potential of modeling was not highly exemplified through the modeling activities that have been designed, because only activities that aimed at developing students' modeling skills were incorporated in the activity sequence. Consequently, the omission of activities that pertain to students' development of both epistemic awareness of models (e.g., nature of models, purpose of models) and metacognitive awareness about the modeling process implies that the development of students' modeling ability throughout the curriculum would be fragmented.

Marlene's curriculum design, which was based on the context of substance dilution, is a representative example of curriculum designs that were classified in Level 2. According to Figure 19, Marlene managed to partially reconstruct the corresponding unit from the national curriculum when designing her own curriculum materials. Specifically, she transferred as intact the activities that pertain to the new concepts (or terminology) introduction, and the activity through which the students would investigate the impact of the temperature of the liquid in the substance dilution. Moreover, she reconstructed some of the existing activities by giving more authority to students to actively engage in hands-on experimentation, and thus to limit the dominant role of the teacher. She also planned to engage her students in the development of operational definitions for the concept of dilution, after the students classified their findings from the hands-on experimentation with the dilutions and the mixtures.

As far as the design of modeling activities is concerned, Marlene designed several modeling activities throughout her curriculum, through which the students were prompted to create and improve their models of a substance dilution in the water, compare their models with their peers' models, and evaluate their models according to their own criteria. Although the modeling activities that Marlene designed are considered as new entries in the national curriculum unit, they fell short in that they are not used as a means through which students' conceptual development about the phenomenon they explored is fostered. Instead of approaching the phenomenon of dilution from a microscopic perspective, and thus to prompt students to develop models through which they would provide an interpretation for how the phenomenon of a substance dilution in water occurs, Marlene's modeling activities were constrained to the macroscopic features of the phenomenon, since the students would be guided to develop models to show how the mass of the substance or the temperature of the water affect the dilution of the substance into the water. On the other



hand, because Marlene designed modeling activities that relate only with specific modeling skills (e.g., model formulation, evaluation of models, comparing and contrasting models of the same phenomenon), the students would not develop epistemic awareness of the nature or purpose of models, and thus they would not conceive models as tools for interpreting phenomena or tools through which the formulation and testing of predictions (or hypotheses) could be achieved.

Marios Papaevripidou

Marlene's activity sequence

National curriculum activity sequence

Marlene's activity sequence		National curriculum activity sequence	
Scientific practices	Curriculum activities	Scientific practices	Curriculum activities
Observe phenomenon	<ul style="list-style-type: none"> <li>The teacher asks students to create mixtures (or dilutions) with several liquids and substances that he provides.</li> <li>The teacher asks students to classify the resulting mixtures (or dilutions) according to three given criteria</li> </ul>	Observe phenomenon	<ul style="list-style-type: none"> <li>The teacher presents a glass with a colorless liquid (the glass contains water and an amount of salt that was previously diluted by the teacher)</li> </ul>
Introduce terminology	<ul style="list-style-type: none"> <li>The teacher introduces the terms "dilution" and "mixture"</li> </ul>	Formulate hypothesis	<ul style="list-style-type: none"> <li>The teacher asks students to make hypotheses about the nature of liquid in the glass</li> </ul>
Development of operational definitions	<ul style="list-style-type: none"> <li>The teacher asks to develop operational definitions for the dilution based on their experiences and the knowledge gained</li> </ul>	Introduce terminology	<ul style="list-style-type: none"> <li>The teacher asks a student to taste the liquid</li> <li>The teacher introduces new terminology: "dilution", "resolvent", "diluted substance"</li> </ul>
Observe phenomenon	<ul style="list-style-type: none"> <li>The teacher asks students to add certain amounts of salt, one each time, in a certain quantity of water and observe what is happening to the dilution of the salt</li> </ul>	Conceptual development	<ul style="list-style-type: none"> <li>The teacher introduces the characteristics of dilutions through questions and demonstration</li> </ul>
Model creation	<ul style="list-style-type: none"> <li>The teacher asks students to create a graphical representation (a model) to explain what happened to the dilution of the salt during the experiment they performed</li> </ul>	Investigation	<ul style="list-style-type: none"> <li>The students apply the characteristics of dilutions during investigation of new mixtures to decide if they are dilutions or not</li> </ul>
Model improvement	<ul style="list-style-type: none"> <li>The teacher asks students to compare their representation with its referent and improve it accordingly (e.g., add the amount of salt that has been dissolved, the volume of the water)</li> </ul>	Introduce terminology	<ul style="list-style-type: none"> <li>The teacher creates a dilution at saturation and introduces the term to students</li> </ul>
Introduce terminology	<ul style="list-style-type: none"> <li>The teacher introduces the term "dilution at saturation"</li> </ul>	Investigation	<ul style="list-style-type: none"> <li>The students design experiments to test if the temperature of the water affects the dilution of sugar</li> </ul>
Model improvement	<ul style="list-style-type: none"> <li>The teacher asks students to improve their models by creating and incorporating variables for the volume of the water and the mass of the diluted substance</li> </ul>		
Model comparison and model evaluation	<ul style="list-style-type: none"> <li>The students exchange their models and evaluate them according to their own criteria</li> </ul>		
Investigation	<ul style="list-style-type: none"> <li>The teacher asks students to design and perform experiments to test if the temperature of the resolvent affects the dilution of the substance</li> </ul>		
Model improvement	<ul style="list-style-type: none"> <li>The teacher asks students to improve their Stagecast models by incorporating the findings from their investigation (addition of the temperature variable of the resolvent to the rules that control the dilution of the substance)</li> </ul>		

Figure 19. Comparison of an extract from Marlene's activity sequence to the corresponding extract from the national curriculum unit.

(Note: Marlene's activities that appear in black colored boxes correspond to new activities, the activities in grey colored boxes represent activities that were partially reconstructed from the

national curriculum unit, whereas the activities in white color boxes relate to the activities that remained intact from the national curriculum unit.)

*Level 3 - Degree and type of reconstruction: Total reconstruction of the national curriculum unit with strong priority to modeling as the approach through which important learning goals could be achieved.* Level 3 encompasses the curriculum materials that their development was based on a total reconstruction of the national curriculum unit, and most importantly, the modeling activities that were interwoven within the curriculum revealed a strong priority to modeling as the approach through which students' conceptual scaffolding and enhancement could be achieved. The decision of whether the national curriculum unit had undergone a total reconstruction was determined through the comparison of the activities of the national curriculum unit with the teachers' designed activities, and through the study of the rationale that the teacher stated to support the selection of a specific unit for reconstruction. To illustrate how a teacher's curriculum that was classified in Level 3 looked like, Derek's curriculum is described below.

Derek chose to reconstruct a unit from the "geometrical optics" context, which aims to help students understand (i) the constructional differences between convex and concave lenses in relation to the image that is formed from each type of lens, (ii) how the distance between the object and the lens affects the size and nature of the image, and (iii) the use of lenses in everyday life. The structure and the content of the activities of the national curriculum unit are provided in Figure 20.

Scientific practices	Curriculum activities
Elicit students' ideas about the use of lenses	<ul style="list-style-type: none"> <li>• The teacher presents a lens and asks students to state where lenses are used</li> </ul>
Observe phenomenon	<ul style="list-style-type: none"> <li>• The teacher observe several lenses and identify their characteristics</li> </ul>
Investigation	<ul style="list-style-type: none"> <li>• The students investigate what happens to a parallel beam of light when penetrates a convex and a concave lens</li> <li>• The students report their findings in whole class discussions</li> </ul>
Introduce terminology	<ul style="list-style-type: none"> <li>• The teacher introduces the terms "convex" and "concave" lenses and asks students to identify these two types of lenses in their previous experiment</li> </ul>
Investigation	<ul style="list-style-type: none"> <li>• The students investigate how the size of the image of an object that is formed changes when a convex lens approaches the object from a distance</li> <li>• The students report their findings in whole class discussions</li> </ul>

Figure 20. "Geometrical Optics" in the national curriculum unit

When Derek decided to reconstruct the national curriculum unit, his first step was to identify the prerequisite concepts that students should have already developed before entering the study of lenses and geometrical optics, in general. In his statement about the rationale for selecting this particular unit, Derek noted that “...it would be futile to expect from students to understand how the images are formed with the use of lenses, if they had not already comprehended the linear propagation of light”. Consequently, he chose to start the design of the activity sequence with the context of shadow formation, as this context was considered as more suitable for the teaching of the idea of linear propagation of light (see Figure 21 for details). Additionally, Derek approached the shadow formation through interesting MCSI activities, and most importantly, he succeeded on designing modeling activities that were aligned with each of the three components of the modeling ability framework (e.g., modeling skills, meta-modeling knowledge about models, and metacognitive knowledge about the modeling process) he experienced during Phase 1 and Phase 2 of the PDC.

The next step that Derek followed for reconstructing his unit encompassed the design of activities that were grounded on the premises of the MCSI approach, through which the students would develop conceptual understanding about the mechanism that controls the image formation with the use of convex or concave lenses. This learning objective, which was a pivotal priority in Derek’s redesign attempts, was a new addition in the conceptually-oriented learning objectives of the national curriculum unit, since this unit aimed at merely offering experiences for students to investigate the image formation with the use of different types of lenses without prompting them to interpret the phenomena under study by “inventing” a possible mechanism that would account for their observations. Moreover, the attainment of this significant learning objective was accomplished through the interplay between carefully designed modeling-based and inquiry-based activities. For instance, after students investigated how the distance between the object and the lens affects the size, the nature, and the location of the image, they were prompted to create models to represent the phenomenon they observed, and most importantly, they were asked to provide their own interpretations for how and why this phenomenon occurs the way it had been observed, and integrate their interpretations in their Stagecast Creator models (see Figure 22 for more details).

Scientific practices	Curriculum activities
Observe phenomenon - Elicit students' prior ideas	<ul style="list-style-type: none"> <li>•The teacher presents a video of an artistic demonstration with shadows</li> <li>•The students are asked to express their ideas about the nature of shadows how they are formed</li> </ul>
Investigation	<ul style="list-style-type: none"> <li>•The students create shadows of an object with the use of a candle and a screen</li> </ul>
Model formulation	<ul style="list-style-type: none"> <li>•The students create graphical models to illustrate the mechanism of shadow formation</li> </ul>
Epistemic awareness with respect to the nature of models	<ul style="list-style-type: none"> <li>•The teacher informs students that the graphical representation of the shadow is called a "model" and that models help in representing and interpreting phenomena</li> </ul>
Compare models	<ul style="list-style-type: none"> <li>•The students compare their models with the models of their peers in an attempt to study the different interpretations of shadow formation</li> </ul>
Model improvement	<ul style="list-style-type: none"> <li>•The teacher asks students to improve their models by taking into account their peers' comments, and also by comparing their model with the real phenomenon</li> </ul>
Epistemic awareness with respect to the nature of models	<ul style="list-style-type: none"> <li>•The teacher prompts students to discuss within their groups if there could be different models that represent the same phenomenon</li> </ul>
Model improvement	<ul style="list-style-type: none"> <li>•The teacher asks students to improve their models by creating a new model in Stagecast Creator</li> </ul>
Phenomenon interpretation	<ul style="list-style-type: none"> <li>•The students observe the shadow formation through a simulation and are asked to explain the mechanism that controls the shadow formation with an emphasis on the linear propagation of light</li> </ul>
Investigation	<ul style="list-style-type: none"> <li>•The teacher prompts students to improve their Stagecast Creator models by incorporating the mechanism of shadow formation</li> <li>•The teacher asks students to identify the components of their model and classify them into objects, variables, processes, and interactions</li> </ul>
Model improvement	<ul style="list-style-type: none"> <li>•The teacher asks students to improve their Stagecast models by incorporating the findings from their investigation (addition of the temperature variable of the solvent to the rules that control the dilution of the substance)</li> </ul>
Metacognitive knowledge about the modeling process	<ul style="list-style-type: none"> <li>•The teacher prompts students to summarize the steps followed for creating their model</li> </ul>

Figure 21. Shadow formation and linear propagation of light in Derek's reconstructed activity sequence

Observe phenomenon	<ul style="list-style-type: none"> <li>The students study a video that illustrates the direction of a parallel beam of light penetrating a convex lens</li> </ul>
Investigation	<ul style="list-style-type: none"> <li>The students are asked to replicate the experiment they observed in the video and keep records of the distance of the lens from the light source and the distance between the point that the light rays converge and the lens</li> </ul>
Model formulation	<ul style="list-style-type: none"> <li>The students create models in Stagecast Creator to illustrate how the parallel beam of light converge after penetrating the convex lens</li> </ul>
Concept introduction	<ul style="list-style-type: none"> <li>The teacher introduces the terms "focal point" and "focal length", and asks students to locate them in their models</li> </ul>
Observe phenomenon	<ul style="list-style-type: none"> <li>The students use a candle, a convex lens, and a screen and create the image of the candle with the use of the convex lens</li> </ul>
Model creation	<ul style="list-style-type: none"> <li>The teacher asks students to create a graphical model to illustrate the mechanism of image formation with the use of a convex lens and a candle</li> <li>The teacher prompts students to use light rays to explain why the image is formed in an upside position compared with the real object</li> </ul>
Model improvement	<ul style="list-style-type: none"> <li>The students improve their graphical models by creating dynamic models in Stagecast Creator</li> </ul>
Investigation	<ul style="list-style-type: none"> <li>The teacher asks students to move the candle in different locations and record the changes of the image in each case (measure the image and the distance of image from the lens)</li> </ul>
Model testing and improvement	<ul style="list-style-type: none"> <li>The students test if their model can be used to predict the size and distance of the image when the object is placed at different locations</li> <li>The students improve their model accordingly</li> </ul>
Concepts introduction	<ul style="list-style-type: none"> <li>The students are prompted to identify the commonalities and differences among the images that are formed when the object is placed at different locations</li> <li>The teacher introduces the terms "real" and "virtual" image and asks students to associate them with their models</li> </ul>
Phenomenon interpretation	<ul style="list-style-type: none"> <li>The students are prompted to think a possible mechanism that applies at the case of image formation with the use of a convex lens</li> <li>The students use their final models to support their interpretations</li> </ul>
Metacognitive knowledge about the modeling process	<ul style="list-style-type: none"> <li>The students are prompted to reflect on the steps followed for creating and improving their models</li> </ul>
Metamodeling knowledge: nature and purpose of models	<ul style="list-style-type: none"> <li>The students are prompted to reflect on the nature and purpose of models based on their experiences (e.g., what is a model, what do models represent, what are the purposes for creating a model, etc)</li> </ul>

Figure 22. "Geometrical optics" in Derek's reconstructed activity sequence

In sum, comparing the activity sequence from the national curriculum unit in Figure 20 with Derek's activity sequence in Figure 22, and taking into account the preceding activities that Derek designed for helping students developed an important prerequisite concept before entering the study of geometrical optics (see Figure 21), it becomes obvious that curriculum designs, whose the nature and the degree of reconstruction was similar to the one that Derek proposed, emerged through a total reconstruction of the national curriculum unit, and gave priority to modeling as the approach through which important learning goals could be achieved.

#### **4.4.3. Types of designed activities and role of modeling in the curriculum**

After the characterization of the teaching orientation that teachers followed for designing their curriculum, and the identification of the degree and type of reconstruction they chose to apply during designing their curriculum, the next step was to examine the types of the designed activities and the role of modeling that teachers chose to incorporate within their curriculum designs. Three major types of activities were found from the examination of teachers' designed activities. These were *inquiry-oriented*, *modeling-oriented*, and *conceptually-oriented* activities. Although teachers' curriculum designs shared this commonality, the nature or format of these activities, as well as the overall role of modeling within the curriculum designs revealed differences that enabled the classification of the curriculum designs into three levels. The three levels that emerged from the analysis of teachers' curriculum materials in relation to the types of designed activities and the role of modeling in the curriculum are presented and elaborated below.

*Level 1 – Types of designed activities and role of modeling in the curriculum: “Didactic” activities- Modeling as a means for “mimicking” others’ models.* Level 1 pertains to the case of teachers who followed a *teacher-directed* philosophy for the design of inquiry, modeling, and conceptual oriented activities in their curriculum designs (see Table 44 for details).

Table 44. Types of activities and associated learning objectives of Level 1 curriculum designs

Type of activity	Objective of the activity
Closed-ended inquiry	Observation of a phenomenon (direct observation)
	Presentation of a model to observe a phenomenon under study
	Data circulation to students
	Reflection on observations
Modeling-oriented	Experiment demonstration by the teacher
	Model formulation
	Model evaluation and formulating ideas for improvement
Conceptual-oriented	Comparing and contrasting models of the same phenomenon
	Description of the technical steps followed for creating a model
	Elicit students' prior experiences or ideas
	Introduction of a concept through lecturing
	Phenomenon interpretation

As Table 44 indicates, the inquiry activities that were designed were characterized as “closed-ended”, because even though the students would engage in inquiry activities like observing or interpreting a phenomenon under study, they were neither allowed to investigate a phenomenon through hands on experimentation nor were given the opportunity to collect and interpret data from the experiment for answering a question or confirming/rejecting a hypothesis. For instance, the examination of Martin’s curriculum activities that were designed in the context of “Friction and Motion” indicated that the teacher was responsible for both the performance of the experiments and the collection of data that would later distribute to his students for use during creating their models.

Likewise, the modeling activities that were proposed did not depart from the need on behalf of the students to develop a model that would help them in interpreting the phenomenon under study or use their model for hypothesis/prediction testing about certain aspects of the phenomenon being modeled. Although the learning objectives that were formulated for the associated modeling activities that were designed pertained to fundamental aspects of the modeling ability framework (e.g., model formulation skill, or model evaluation and formulating ideas for improvement skill), the way they were designed designate that modeling was used as a means for “mimicking” ready-made models that were presented by the teacher. In Martin’s curriculum design, for instance, the modeling activities that were designed embodied the following pattern; after the teacher presents a phenomenon or an experiment to students, he moves on to present a model that he previously built in Stagecast Creator and asks students to replicate it while building their own models. Hence, it becomes obvious that the students in Martin’s curriculum would not experience modeling as a tool through which their interpretations for the



phenomena they study would be facilitated; instead modeling appears to be used as a “carbon-paper”-like method that helps in copying a “prototype” model.

As far as the design of conceptual-oriented activities is concerned, the examination of the curriculum designs that were clustered in Level 1 revealed that even though there were some rare instances that the teacher would attempt to elicit students’ prior ideas about a phenomenon under study, the absence of designed activities that relate to monitoring students’ conceptual development throughout the curriculum indicates that this learning and teaching objective was not a priority for the teachers of Level 1. Additionally, the introduction of new concepts in the curriculum was accomplished either through teacher lecturing or through content-delivery statements without giving the opportunity to students to sense the need to develop operational definitions for the concepts they would experience.

In summary, the teachers whose curriculum designs were clustered in Level 1 showed a poor understanding of MCSI as an instructional approach, since the types of the inquiry and modeling oriented activities they proposed were not aligned with the philosophy and principles of MCSI.

*Level 2 – Types of designed activities and role of modeling in the curriculum: Fewer “didactic” and more “hands-on” activities - Modeling as a vehicle for representing and interpreting phenomena in a superficial manner.* The curriculum designs that were clustered in Level 2 entailed fewer “didactic” activities compared to those grouped in Level 1, and more “hands-on” activities that were used for verification or discovery purposes. These “hands-on” activities differentiate from the “didactic” activities in that the students are given authority over the use and manipulation of the materials and equipment that are provided by the teacher, when performing investigations. Nevertheless, the teacher still remains in the center of the learning process to control students’ learning pathways, as the teacher appears to constantly telling the students, either directly or through the curriculum, what they are supposed to see or learn.

On the other hand, there was a significant shift in the way modeling was used from Level 1 to Level 2, because the teachers of Level 2 designed modeling activities through which the learners would create models to represent and interpret a phenomenon under study. However, although the teachers of Level 2 paid a lot of attention to the representational

complexity of models, their proposed modeling activities fell short in the interpretive aspect of models. Specifically, the main emphasis was on approaching the interpretive aspect of models only through a “mechanistic” perspective (e.g., *how* the phenomenon functions?), and not through a “causal” perspective (e.g., *why* the phenomenon functions the way it appears through the model?).

Christina’s curriculum design, which was based on the context of “Thermal Interactions”, is a representative example of a curriculum that was clustered in Level 2. The types of activities in conjunction with the objectives of specific activities from Christina’s curriculum are provided in Table 45 and are discussed henceforth.

Table 45. Types of activities and associated learning objectives of a teacher’s curriculum design clustered in Level 2

Type of activity	Objective of the activity
A. Modeling-oriented	<ol style="list-style-type: none"> <li>1. Model formulation</li> <li>2. Identification of model components</li> <li>3. Comparing and contrasting models of the same phenomenon</li> <li>4. Model evaluation and formulating ideas for improvement</li> <li>5. Model validation</li> <li>6. Description of the technical steps followed for creating a model</li> </ol>
B. Inquiry-oriented	<ol style="list-style-type: none"> <li>1. Presentation of ready-made models to observe and elaborate on a phenomenon under study</li> <li>2. Observation of a phenomenon (e.g., direct or through a video)</li> <li>3. Reflections on observations</li> <li>4. Investigation through experimentation</li> <li>5. Data collection</li> <li>6. Data analysis</li> <li>7. Testing of predictions/hypotheses through the use of students’ models</li> </ol>
C. Conceptually oriented	<ol style="list-style-type: none"> <li>1. Presentation of a model to introduce a concept</li> <li>2. Introduction of a concept through lecturing</li> <li>3. Elicit students’ prior experiences related to the phenomenon</li> <li>4. Phenomenon interpretation</li> </ol>

According to Table 45, Christina’s curriculum encompassed several modeling-oriented activities that relate to the development of five modeling skills (e.g., *model formulation, identification of model components, comparing and contrasting models of the same phenomenon, and model evaluation and formulating ideas for improvement*), and another modeling-related activity (e.g., *description of the technical steps followed for creating a model*) that served, not as a scaffold for the development of metacognitive knowledge about the modeling process (e.g., reflection on cyclical and iterative process followed for creating a model), but as a technical activity that does not promote any important modeling objective. Nevertheless, the modeling activities that were designed were superior to those

found within the curriculum designs of Level 1 in two ways; firstly, the prevalence of the modeling activities in the curriculum designs of Level 2 were more frequent compared to those appeared in curriculum designs of Level 1, and secondly, the type, the format, and the place of the modeling activities in the curriculum designs of Level 2 were better aligned with the principles and the philosophy of MCSI.

Furthermore, Christina's modeling activities aimed at guiding students to develop models that represented the change in volume and temperature of a certain mass of water in a beaker, when a new mass of water was added in the beaker. The models she expected from her students to develop would represent these changes (e.g., visual increase of the volume of the water in the beaker, and visual display of the final temperature of the mixture), and would encompass a mechanistic interpretation (e.g., the rules that control the function of the model would focus on the formula that takes into account the mass and the initial temperature of each quantity of water to calculate the final temperature of the mixture). Hence, the models she proposed would lack a causal interpretation for *why* the resulting temperature of the mixture is affected by the mass and the initial temperature of the mixing quantities of water.

As far as the inquiry-oriented activities of Christina's curriculum are concerned, the way the activities were designed indicate a priority to hands-on activities through which students would be given the opportunity to investigate themselves a phenomenon under study, collect and analyze data, and use their own models for testing their predictions or hypotheses. These activities were completely new compared to the closed-ended inquiry activities that were met in teachers' curriculum designs of Level 1, but the way they were designed designate that the teacher constrains students' "moves" for creative thinking during investigating a phenomenon under study, even though the students themselves perform the experiments, collect and analyze their own data. The following extract from Christina's curriculum supports this assertion.

### Experiment 2

Perform the following experiment:

1. Put 50ml of water in a beaker (Beaker 1) and heat it until its temperature is 40° C.
2. Put 50ml of water at room temperature (20° C) in a beaker (Beaker 2)
3. Pour the water of Beaker 1 and the water of Beaker 2 in Beaker 3.
4. Put a thermometer in the beaker and record the temperature of the mixing water when it stabilizes.
5. Write your records in the following table.

Temperature of water in Beaker 1	Temperature of water in Beaker 2	Beaker 3: Final temperature after mixing water from Beaker 1 and Beaker 2
40° C	20° C	
60° C	20° C	
80° C	20° C	

6. Repeat the experiment with same quantities of water at 60° C and 80° C and write each time the final temperature after mixing the two quantities of water in the table above.

7. Can you use the model you created for Experiment 1 to illustrate what you observed in Experiment 2? Put the value of temperature of Beaker 1 and Beaker 2 in your model and see if the final temperature that your model provides is consistent with your observations.

.....

- Investigation through experimentation
- Data collection

- Model testing

8. As you have already concluded, the model you created for Experiment 1 cannot calculate the correct value of the final temperature after mixing the two quantities of water. Hence, we need to create a new model to account for our observations. The following calculations will help you to figure out the resulting final temperature after mixing two equal quantities of water of different temperature.

A. Let's focus on Beaker 1 and Beaker 2 prior to mixing (1<sup>st</sup> try).

What is the sum of the temperature of the water in Beaker 1 and Beaker 2 prior to mixing?

B. What is the final temperature after mixing the 2 quantities of water?

C. According to your findings, what would you like your model to do, when mixing 2 equal quantities of water of different temperature?

.....

9. Read what George answered in the above question.



In our new model the temperature of the water in Beaker 3 should be half of the sum of the temperature of the water in Beaker 1 and Beaker 2, since the water in Beaker 1 gives heat to the water of Beaker 2 and the water of Beaker 2 receives heat from water of Beaker 1.

Discuss George's response with your group peers and write down if his response could be a possible explanation for how the final temperature of the mixing quantities of water is produced. Explain your reasoning.

.....

10. If the temperature of water in Beaker 1 was 90° C and the temperature of water in Beaker 2 was 20° C, what would be the final temperature after mixing the two quantities of water? Explain your reasoning.

.....

- Guided data analysis that aims to reach at a possible interpretation for how the final temperature is produced

- Provision of a ready-made interpretation and reflection

- Use of the given interpretation for prediction

Figure 23. An extract from Christina's curriculum activities in the context of "Thermal Interactions" (the text in the right relates to the objective of the activity)

According to Figure 23, Christina would ask her students to investigate how the initial temperature of two quantities of water of equal mass affects the final temperature of the mixing quantities of water. In doing this, the students would engage in hands-on activities for measuring the volume and the temperature of specific quantities of water prior to mixing and after mixing them together, and they would also record their data in a table that is provided through the curriculum. After doing this, they would be prompted to use their previously built model (e.g., a model that was built to represent the resulting temperature after mixing two quantities of water of equal mass and equal temperature) to test if the model can estimate the resulting temperature of mixing water of same mass but different temperature. Although the subsequent activity she designed (e.g., guided data analysis through which the students would be scaffolded to reach at a possible interpretation for how the final temperature is produced) served as a scaffold to help her students identify the relationship between the initial temperature of each quantity of water and the final temperature of the mixing water, both the way it was introduced and its position in the activity sequence empowers the notion that Christina chose to navigate the students in a learning pathway that she preconfigured of what they were supposed to see, discover or learn. In addition, the activity that followed (see Activity 9 in Figure 23) is also aligned with the previous assertion, since the students are provided with a ready-made explanation that illustrates how one could calculate the final temperature after mixing two quantities of water of equal mass and different temperatures.

Consequently, it becomes obvious that Christina neither engaged her students in productive collaborative discourse when analyzing the data collected from their experiments nor gave them the opportunity to go over the data themselves and come up with a relationship for the initial and final temperature of the mixing quantities of water. For instance, she could have designed an intermediate activity between Activities 7 and 8 through which she could prompt her students to collaboratively examine their data and try to figure out the relationship between the initial temperature of the two quantities of water and the final temperature of the mixing quantities. Then, the students could be prompted to test if their hypothesis was correct by applying it in every case of their data, and they could also be given new data (e.g., initial temperature of two quantities of water of equal mass) to predict the resulting temperature. The latter suggestion appears as Activity 10 in Christina's curriculum (see Figure 23 for details).

*Level 3 – Types of designed activities and role of modeling in the curriculum: Guided inquiry and Modeling-Centered Scientific Inquiry activities - Modeling as a vehicle for representing, interpreting and predicting phenomena.* Level 3 refers to those curriculum designs which encompassed *guided inquiry* and *modeling-centered scientific inquiry* activities that both impacted on promoting modeling as a vehicle through which students were supported in representing and interpreting phenomena under study, and use their models for testing of predictions. *Guided inquiry* activities, as defined by Magnusson et al. (1999), are developed around a learning community-centered approach; “the teacher and students participate in defining and investigating problems, determining patterns, inventing and testing explanations, and evaluating the utility and validity of their data and the adequacy of their conclusions. The teacher scaffolds students’ efforts to use the material and intellectual tools of science, toward their independent use of them” (p. 101). Likewise, *modeling-centered scientific inquiry* is “guided inquiry focused around creating and using models to predict and explain phenomena and then comparing those models with those from canonical science. These scientific models frequently embody patterns in data and have an explanatory component” (Schwarz & Gwekwerere, 2006, p. 184).

Jane’s curriculum that was developed in the context of “Earthquakes” is a representative example of a curriculum that encompassed both guided inquiry and modeling-centered scientific inquiry activities (see Table 46 for details). Although the context of earthquakes is not included in the primary science education national curriculum, as it is a topic that is approached in a superficial manner in the context of Geography (e.g., the students are provided with several photographs and graphical illustrations of earthquakes, and receive fragmented knowledge about the factors that affect or impact on the formation of earthquakes), Jane’s decision to work on developing curriculum materials around earthquakes departed from a personal interest on this context. The following extract from the introduction of her curriculum design, in which she explained the rationale behind the selection of this context, is particularly revealing.

*“The selection of earthquakes as the context of my curriculum development stemmed from a research paper I recently read titled “Children’s beliefs about earthquakes”. In this paper, the authors asserted that elementary school students hold misconceptions about earthquakes, when they were asked to respond to questions like “What is an earthquake?”, “What causes an earthquake?” or “What happens on, and beneath earth’s surface when an earthquake occurs?”, and so on. Students’ believed that an earthquake occurs because of the motion of earth’s nucleus, or because of the motion of plate tectonics, or because of the eruption of volcanoes. Hence, I thought that I could develop a unit on this interesting topic using modeling as the instructional approach, through which my students would be*

*supported in developing conceptual understanding about issues related to earthquakes, and on the other hand, they would be given the opportunity to develop their modeling ability. Additionally, this was a challenge for me to deepening my understanding about earthquakes, because there were interpretations about the formation of earthquakes that I was not aware of.”*

Table 46. Types of activities and associated learning objectives of curriculum designs of Level 3

Type of activity	Objective of the activity
Modeling-Centered Scientific Inquiry	<ol style="list-style-type: none"> <li>1. Model formulation</li> <li>2. Identification of model components</li> <li>3. Comparing and contrasting models of the same phenomenon</li> <li>4. Model evaluation and formulating ideas for improvement</li> <li>5. Model validation</li> <li>6. Meta-modeling knowledge with respect to the nature of models</li> <li>7. Meta-modeling knowledge with respect to the purpose or utility of models</li> <li>8. Metacognitive knowledge about the modeling process</li> <li>9. Modeling ability scaffolds: explicit epistemological statements concerning model evaluation or model improvement, etc</li> <li>10. Naming a model and reflection on the rationale behind the given name of the model</li> <li>11. Description of the steps followed for creating the model</li> <li>12. Presentation of ready-made models to represent a phenomenon under study</li> <li>13. Peer evaluation of models</li> </ol>
Guided inquiry	<ol style="list-style-type: none"> <li>1. Elaboration on a driving question</li> <li>2. Observation of a phenomenon</li> <li>3. Reflections on observations</li> <li>4. Investigation through experimentation</li> <li>5. Data collection</li> <li>6. Data analysis</li> <li>7. Testing of predictions/hypotheses</li> <li>8. Inventing and testing of explanations</li> <li>9. Inquiry scaffolds (e.g., data organization, identification of patterns, relationships between phenomenon variables, etc)</li> </ol>
Conceptually oriented	<ol style="list-style-type: none"> <li>1. Elicit students' prior experiences or ideas related to the phenomenon</li> <li>2. Use of students' created models or other ready-made models to introduce concepts</li> <li>3. Phenomenon interpretation</li> <li>4. Formulation of operational definitions</li> <li>5. Conceptual understanding scaffolds (e.g., application of concepts in students' models)</li> </ol>

Consequently, Jane's personal interest on earthquakes, combined with her confession that she was not acquainted with the several existing interpretations (or "theories") of earthquake occurrence, challenged her to study multiple resources about earthquakes (e.g., simulations, maps, geological science data, research papers, internet databases, etc) that she later incorporated within her curriculum. Examples of some of the teaching sources that were found in her curriculum materials are provided below.



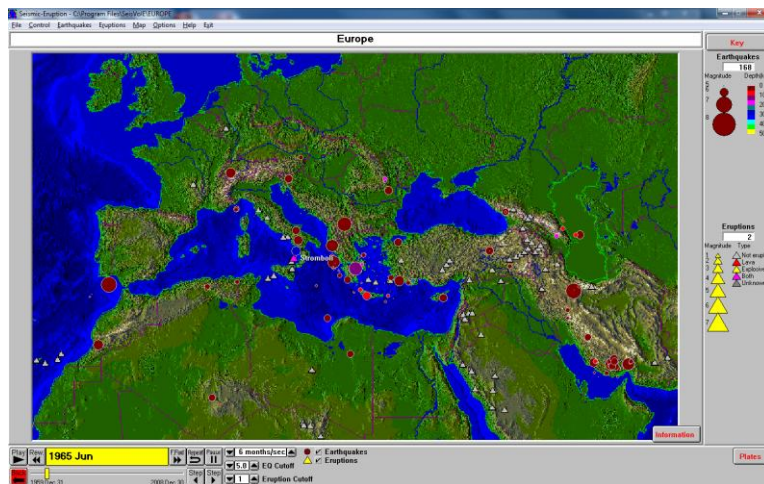
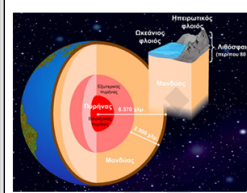


Table 7. Earthquakes That Occurred on January 1, 1993 as listed in "Preliminary Determinations of Epicenters," USGS-NEIC

Time*	Latitude	Longitude	Depth (in km)	Magnitude**	Location
<b>North Latitudes and West Longitudes</b>					
2:09	36 N	5 W	10	2.0	Strait of Gibraltar
4:12	60 N	153 W	10	3.1	Alaska
5:08	36 N	82 W	4	3.0	North Carolina
5:36	31 N	114 W	10	3.6	Gulf of California
6:07	18 N	64 W	10	4.0	Virgin Islands
14:25	64 N	149 W	6	2.8	Alaska
15:27	48 N	112 W	5	3.4	Montana
<b>North Latitudes and East Longitudes</b>					
1:35	39 N	29 E	10	2.7	Turkey
2:05	39 N	29 E	10	2.8	Turkey
2:23	4 N	126 E	86	4.4	Talau Islands
4:18	39 N	22 E	10	—	Greece
4:30	53 N	158 E	170	4.2	Kamchatka
5:35	38 N	15 E	10	—	Sicily
5:40	43 N	6 E	10	2.4	Coast of France
5:43	44 N	8 E	10	—	Italy
7:20	39 N	29 E	10	2.8	Turkey
8:19	39 N	143 E	37	4.7	Coast of Japan
14:25	38 N	27 E	10	3.1	Turkey
16:11	42 N	20 E	10	2.7	Albania
18:46	43 N	14 E	10	3.8	Italy
19:16	45 N	7 E	10	2.0	Italy
20:49	38 N	27 E	10	3.1	Aegean S
21:00	43 N	5 E	10	3.6	Coast of France
21:26	3 N	122 E	536	4.4	Celebes I
21:46	35 N	33 E	13	3.4	Cyprus re
23:49	23 N	95 E	96	4.3	India/Nepal
<b>South Latitudes and West Longitudes</b>					
3:46	32 S	178 W	33	5.1	Kermadec I
4:02	32 S	68 W	100	—	Argentina
4:34	31 S	179 W	48	4.7	Kermadec I
5:48	28 S	177 W	65	4.7	Kermadec I
8:26	33 S	176 W	33	4.7	So. of Kermadec
9:17	32 S	69 W	120	3.5	Argentina
9:56	32 S	72 W	27	5.4	Chile
10:06	36 S	74 W	100	4.0	Chile
13:09	25 S	178 W	203	5.2	So. of Fiji I
17:29	31 S	68 W	10	—	Argentina
<b>South Latitudes and East Longitudes</b>					
2:56	26 S	28 E	5	2.5	Rep. of So.
5:00	6 S	138 E	33	—	Banda S
5:19	7 S	131 E	68	4.6	Banda S
6:34	6 S	147 E	74	4.7	New Guin
8:58	7 S	144 E	23	5.2	New Guin
10:56	7 S	132 E	122	—	Indones
12:35	39 S	177 E	59	4.4	New Zeal
12:48	38 S	179 E	182	—	New Zeal
21:36	67 S	164 E	10	5.6	Balleney Islands



Διαβάστε προσεκτικά τις πιο κάτω πληροφορίες:

Το εσωτερικό της Γης διαιρείται σε τρία βασικά τμήματα: το στερεό φλοιό, το μανδύα και τον πυρήνα. Ο **φλοιός** είναι το στερεό εξωτερικό περίβλημα της Γης που διακρίνεται σε **ηπειρωτικό** με πάχος 35 km περίπου και **ωκεάνιο** με πάχος 7 km· κάτω όμως από τις μεγάλες οροσειρές μπορεί να φτάσει τα 60 – 70 km. Ο φλοιός μαζί με μέρος του ανώτερου μανδύα αποτελούν τη **λιθόσφαιρα** πάχους 80 km περίπου. Ο **μανδύας** συμπεριφέρεται σε ρευστό που κυκλοφορεί και μεταφέρει μεγάλα ποσά θερμότητας. Ο **πυρήνας** στο κέντρο του πλανήτη είναι ακόμη πιο καυτός από το μανδύα και πιστεύεται ότι αποτελείται από ένα εξωτερικό υγρό τμήμα και ένα εσωτερικό στερεό.

(Γαμπό, 1993· Κουσκουάν-Τσιμιτσίδου, Πετρουπόλος & Τσουνάκος, 2006  
<http://www.conceptum.gr/seismopolis/index.html>)

Διαβάστε προσεκτικά τις πιο κάτω πληροφορίες:

**Εστία ή υπόκεντρο** ονομάζεται το σημείο της λιθόσφαιρας από το οποίο ξεκινά η διάρρηξη των πετρωμάτων.

**Επίκεντρο** είναι η κατακόρυφη προβολή της εστίας στην επιφάνεια της Γης.

**Εστιακό βάθος** είναι η απόσταση ανάμεσα στο υπόκεντρο και στο επίκεντρο του σεισμού.

**Ρήγμα** είναι η επιφάνεια κατά τη διεύθυνση της οποίας σπάει ένα πέτρωμα όταν ξεπεράσει το όριο αντοχής του ελαστικής κίνησης των λιθόσφαιρικών πλακών. Στην περίπτωση αυτή δημιουργούνται δύο τμήματα πετρώματος, τα οποία πραγματοποιούν απότομη κίνηση μεταξύ τους.

**Υγρός ρήγματος** είναι η επιφανειακή εκδήλωση του ρήγματος. Σε ορισμένες περιπτώσεις δηλαδή τα ρήγματα φτάνουν μέχρι την επιφάνεια της Γης και μπορούμε να τα μελετήσουμε με απευθείας παρατήρηση, σε άλλες όμως όχι.

(<http://www.conceptum.gr/seismopolis/index.html>)

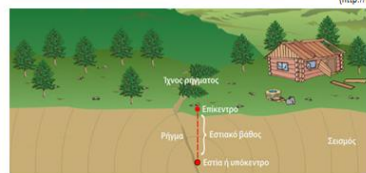


Figure 24. Representative examples of teaching resources found in Jane’s curriculum about “Earthquakes”

Jane chose to begin her curriculum with the presentation of a video that her students would observe the event of an earthquake captured by a video-camera in an office with four employees during working on their computers. Then, she would prompt her students to discuss in their groups three important questions like “what caused the earthquake”, “what happens on earth’s surface during the occurrence of an earthquake”, and “how earthquakes are formed”. Right after, she would orchestrate a whole class discussion to give the opportunity to students to announce their hypotheses. Within this introductory activity, Jane sets the grounds for the foundation of a *learning community* who will work as a whole, including herself, for *inventing* and *testing explanations* about the origins and nature of earthquakes. Jane’s participation in the learning community is also evident in a

subsequent activity that she presents herself in a situation where she discusses with a colleague about their own explanations about the formation of earthquakes. Instead of using two imaginary students to present the two different explanations, she uses herself in an attempt to make her students understand that even adults (here the two teachers) might invent different explanations about the function of a specific phenomenon. In addition, the way she designed this activity reveals her personal epistemic understanding about the possible existence of different theories that can explain the same phenomenon. This particular activity, as it was found in her curriculum, is provided below.

Figure 25. Different interpretations about the earthquake formation in Jane's curriculum

Due to fact that an earthquake or its associated concepts (e.g., plate tectonics) cannot be accessed through direct observations, Jane decided to incorporate in her curriculum several analogical models or experiments through which the students would gain an understanding of how an earthquake-related issue look like. For instance, in order to make her students sense how plate tectonics or the inner earth layers are, she designed the following activity.

Figure 26. Extract from Jane's curriculum that illustrates the use of an analogical representation for conceptualizing the plate tectonics

Similarly, in order to give students a tangible sense of how the depth of focus and the distance from the epicenter affect the magnitude of the earthquake, Jane designed an activity to give students the opportunity to investigate how these factors affect the magnitude of the earthquake through a simulated experiment. The students are instructed to place six miniature houses on top of a wooden box (see Figure 27), one on each of the six zones that represent the variations in distance from the epicenter of the earthquake. They are also asked to mark the smaller side of the box with Zone 1 through 3 to represent the depth of focus. Then, the students would hit with a stone on Zone 1 and record the damages of the collapsed houses. This procedure would be followed for every zone of the depth of focus, and at the end the students would examine their data and conclude that the bigger the depth of focus and the bigger the distance from the epicenter, the smaller the magnitude of the earthquake.

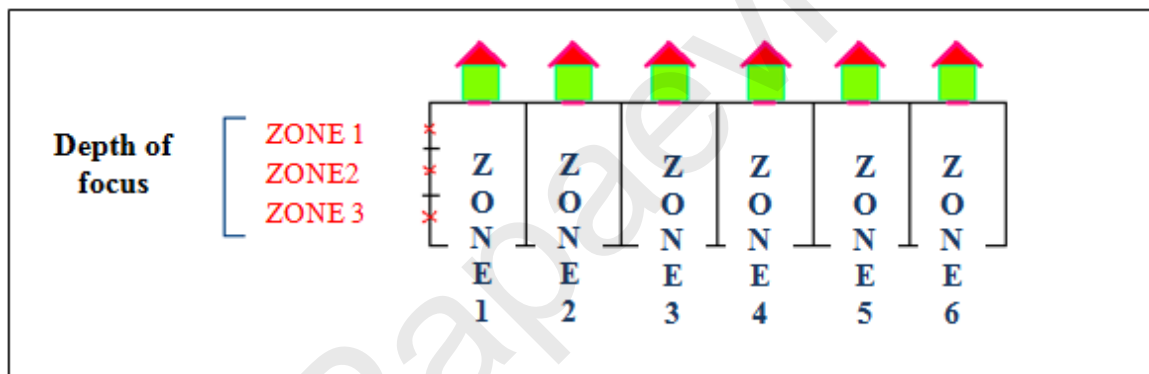


Figure 27. A simulated experiment in Jane's curriculum to test how the depth of focus and the distance from the epicenter affect the magnitude of the earthquake

To sum up, the examples provided above to illustrate how specific aspects of the guided inquiry approach appeared in Jane's curriculum, in conjunction with several other guided inquiry-oriented activities presented in Table 40, demonstrate a significant shift from the closed-ended inquiry activities found in curriculum designs of Level 1 and the hands-on activities of Level 2 curriculum designs.

As far as the modeling-centered scientific inquiry activities are concerned, Table 46 indicates that the curriculum designs that were clustered in Level 3 entailed a variety of productive modeling-oriented activities, through which the students would be scaffolded to create, revise, validate, and use models to predict and interpret phenomena under study. In addition, the curriculum designs encompassed modeling activities that aimed at enhancing students' metacognitive knowledge about the modeling process (e.g., reflection on the

iterative and cyclical steps followed during modeling natural phenomena), and epistemic understanding with respect to the nature, purpose, and utility of scientific models. Representative examples from Jane's modeling activities to document these findings are provided in Figure 24.

Throughout the curriculum, Jane planned to engage her students in the development of eleven models to gradually represent various aspects of the phenomenon of earthquakes. Specifically, the aspects that would be studied and then incorporated in the revised models were as follows:

- A. Factors that affect the magnitude of an earthquake: (i) composition of the ground, (ii) the depth of focus, and (iii) the distance from the epicenter of the earthquake
- B. Plate tectonics motion during an earthquake
- C. The motion of plate tectonics results from convection current in earth's mantle
- C. Inner layers of the earth
- D. Earthquakes occur at the boundaries between plate tectonics
- E. When the dynamic energy of both plate tectonics and the rocks of earth's crust reaches a maximum, the earthquake occurs
- F. Relationship between the magnitude of an earthquake and the height of a resulting tsunami
- G. The height of a tsunami increases as it approaches the seashore

Jane designed the modeling activities in such a way that every subsequent model would entail all previously identified aspects of the earthquake, which were studied from multiple data sources or through the performance of simulated experiments. At the end the students would come up with a model that unifies all earthquake related aspects that were studied, it would entail a mechanism that explains how the earthquakes are formed, and it could be used for testing of predictions or hypotheses.

Furthermore, Jane designed several modeling scaffolds at certain points in her curriculum to mediate students' modeling activity. For instance, after students would be gradually introduced to the model evaluation criteria, and for every criterion the students would be prompted to test if their model satisfies each criterion, for every new model they would build or revise, they would be asked to evaluate it according to the model evaluation criteria they were previously introduced. In their first attempts, the model evaluation criteria would appear in a box to serve as a reminder (see activity 41 in Figure 24 for

details), at a later stage the students would be prompted to go back to the curriculum where these criteria are summarized, and by the end of the curriculum these scaffolds would faint out, as the students would be able to spontaneously recall these criteria during evaluating their models.

It is also noteworthy to state that the learning community centered approach, which was documented in the case of the aforementioned guided inquiry activities, was also followed for the design of the modeling-centered activities. Specifically, to help students interact and thus to enhance fruitful collaboration and interaction among them, Jane designed in a systematic way peer review activities at specific points in her curriculum. One example of such an activity, through which the students are asked to exchange their models with their peers for providing and receiving feedback, is presented in Figure 24 (see activities 42 and 43 for details).

36. According to your observations and conclusions based on Experiment 5, answer the following:  
How does the composition of the ground affect the magnitude of the earthquake?

---

37. Based on the response provided above, discuss with your group peers how you are planning to proceed for improving your model. Write the improvements you are planning to do in your model below.

---



Discuss your responses with your teacher!

Create a revised model in Stagecast Creator by applying your abovementioned suggestions for improvement. Name your model and explain why you choose this name.

38. Use your revised model in Stagecast Creator to answer the following.

- Explain how and when the earthquakes are formed.

---

- How does the distance from the earth epicenter affect the magnitude of the earthquake?

---

- How does the composition of the ground affect the magnitude of the earthquake?

---

40. Write below your model's constituent components (if you don't remember the four different types of components go to page 26).

---

Elaboration on data from an experiment

Reflection on model improvement

Model formulation

Interpretation of the phenomenon through the use of the created model

Identification of model components

41. Describe your model. In describing your model, try to address the model evaluation criteria provided below.

---

Three major model evaluation criteria:

1. Does the model **REPRESENT** the phenomenon under study? E.g., does the model entail the basic components of the phenomenon?
2. Does the model provide an **EXPLANATION/INTERPRETATION** for the phenomenon under study? E.g., does the model explain the functions or mechanism of the phenomenon?
3. Can the model be used for the **FORMULATION** and **TESTING OF PREDICTIONS** for the changes that occur to the different aspects of the phenomenon?


42. Ask from the group of students that you are collaborating with to give you their model's components and the description of their model. Based on the model evaluation criteria provided above, evaluate their model and write your feedback on the accompanied flyer.

43. After receiving the feedback from your collaborating group, discuss with your group peers about how you are going to improve your model based on the received feedback. Write down your suggestions and then proceed on revising your model.

44. Compare your final model with the real phenomenon that you observed through the video file. What are the similarities and differences between the two?

Similarities	Differences

Discuss your responses with your teacher!



Model description (evaluation of metamodeling knowledge about the nature of models)

Modeling scaffold (reminder of the model evaluation criteria that were previously introduced and used in the curriculum)

Peer evaluation of models

Model improvement

Comparing a model with its target

Figure 28. Modeling-centered scientific inquiry activities in Jane's curriculum about earthquakes (the text in the right relates to the objective of the activity)

#### 4.4.4. Integration of the modeling ability framework

One of the requirements for the curriculum reconstruction project that teachers had to attain to was to design modeling activities through which learners' modeling ability would be enhanced. In doing so, they had to keep in mind the components of the modeling ability framework that was introduced in Phase 2 of the PDC, and find ways to integrate these components in their curriculum designs. The examination of teachers' MCSI curriculum materials, in relation to the ways and the degree of integration of the modeling ability framework, revealed three levels of increased sophistication that are presented and discussed below.

*Level 1 – Integration of the modeling ability framework: Superficial cultivation of a limited number of the modeling ability framework components – the “lethal mutations” effect.* Level 1 entails teachers' curriculum designs that encompassed a limited number of the components of the modeling ability framework and whose cultivation was superficial. The most predominant activities that were found pertain to the *model formulation skill*, the *identification of model components skill*, the *model evaluation and formulating ideas for improvement skill*, the *comparing and contrasting models of the same phenomenon skill*, and the *metacognitive knowledge about the modeling process*. Consequently, Level 1 curriculum designs appear to have integrated four out of five modeling skills of the modeling ability framework (no evidence of the integration of the *model validation skill* was found), and the *metacognitive knowledge about the modeling process*, but omitted the integration of activities that would facilitate the development of students' epistemic understanding about the nature, purpose, and utility of models. However, a close examination of the frequency of the activities, their position in the activity sequence, and their nature or format revealed two important findings.

The first finding, which relates to the frequency and the position of the activities in the curriculum, indicates that no serious effort was invested for the development of learners' modeling ability. This finding can be explained by both the limited number of the modeling activities that were designed, and the dominant role of the teacher who appeared to use modeling as a tool for fulfilling his/her own teaching needs. Moreover, the curriculum designs that were grouped in Level 1 implemented the modeling ability framework in a superficial manner, since there was no strong coherence between the learning objective that was set and the corresponding modeling activities. More specifically, there were a lot of instances in the examined curricula that even though the



teachers were setting a goal towards the development of a specific modeling ability component, the activity (or activities) they designed afterwards for fulfilling this goal were neither closely linked to the specific goal nor the students were supported enough to develop that particular modeling ability component. The following activity from Debbie's curriculum in the context of "Motion and Newton's Laws" is provided as an example to help clearing up this finding.

Learning objective	Description of the activity	Actual activity
The students are expected to develop metacognitive knowledge about the modeling process	Once the students would have finished creating their model, I will ask them to write down the steps followed for creating their model.	<i>"Now that you have finished creating your model, write down the steps that you followed for creating your model. It is important to provide all necessary information that someone who does not know how to create a model about Newton's second law to use your steps as a guide."</i>

Figure 29. Fostering the development of learners' metacognitive knowledge about the modeling process: a corresponding activity from Debbie's curriculum design

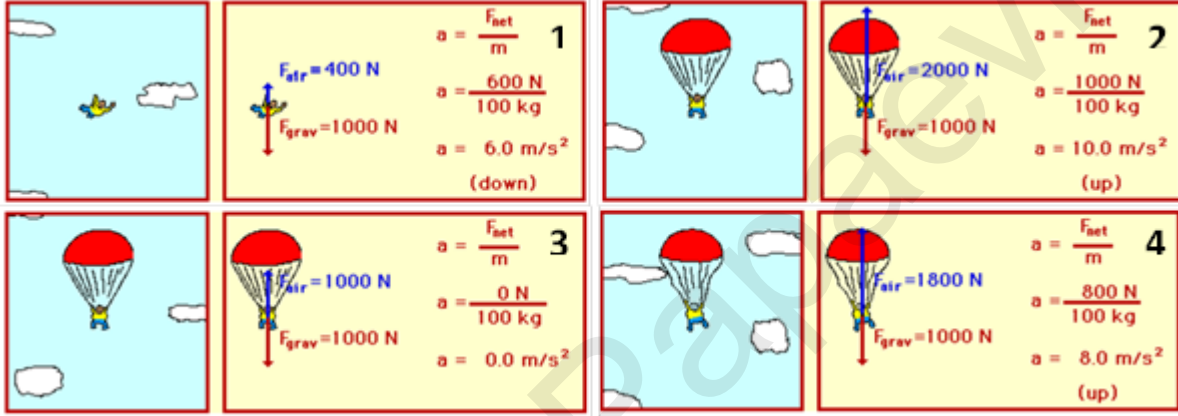
Although the activity presented in Figure 16 might look reasonable and well linked to the learning objective that Debbie formulated, its position in the activity sequence in relation to the activities that preceded denote that this learning objective cannot be achieved at this point and through this activity. This is because in order for a learner to develop metacognitive knowledge about the modeling process, s/he needs to have been offered opportunities to engage in the *cyclical* and *iterative* process of scientific modeling and then to prompt him/her to reflect on the steps followed for creating a model. In the case of Debbie's curriculum, the students are merely engaged in the process of creating a model to represent Newton's second law and right after they are asked to reflect on the process followed for creating their model. Accordingly, metacognitive knowledge about the modeling process cannot be enhanced at this point of Debbie's curriculum, since students would lack crucial steps of the modeling process like comparing and contrasting the model with its referent for evaluating both model's representational, interpretive, and predictive power, model revision or improvement, new cycles of evaluation, and so on.

The second finding, which came up after examining the nature and format of the modeling activities that were designed to enhance students' modeling ability, pertains to "the lethal mutations effect". The term *lethal mutations* (originally suggested by Brown, 1992) is used to describe those cases when individuals misapply a learned strategy in ways that misrepresent the epistemology of theory. As a result, the true meaning of a theory gets so

distorted by misplaced practices that is no longer recognizable. In the context of this study, the term *lethal mutations* is used to denote the instances where the teachers “mutated” (or misunderstood) the content and rationale of a specific modeling ability component, and this was reflected in their designed activities. These “mutations” of the modeling ability framework are considered as *lethal*, because since they falsify the content and rationale of specific modeling ability components, students’ modeling ability would not only be distorted but fragmented as well.

Three modeling activities from teachers’ curriculum designs that were considered as examples of lethal mutations are provided in Table 47.

Table 47. Modeling activities from teachers' curriculum designs that are considered as "lethal mutations" of the modeling ability framework

Modeling ability component	Teacher designed modeling activity to promote the development of the modeling ability component	Why the activity is considered as a "lethal mutation" of the modeling ability framework?
Model formulation skill	<p>[Debbie, "Motion and Newton's Laws"]</p> <p><i>Observe carefully the phenomenon that your teacher is going to show you.</i></p> 	<p>The <i>model formulation skill</i> pertains to the ability of a learner to develop an external representation of a physical phenomenon or a system or an object after s/he has collected various types of information either by directly observing the reference phenomenon or, indirectly, through making measurements or using secondary sources.</p> <p>The principle that is violated in Debbie's model formulation activity relates to what she considers as a "phenomenon" that she later incorporates it in her curriculum. What she provides to her students as the phenomenon under study is not the phenomenon per se, but an animation through which the phenomenon is presented in a simulated fashion, and most importantly, it entails several components (e.g., the vectors or the forces, mathematical formulas) that are associated not with the phenomenon per se, but with its representation.</p> <p>Consequently, Debbie's choice to present a ready-made model instead of the phenomenon violates the principles of the model formulation skill.</p>

Now that you observed the motion of a paratrooper, build a model in Stagecast Creator to represent this phenomenon.

[Note: The phenomenon of a paratrooper who at the beginning follows a free fall motion, then a vertical motion with constant velocity, and then a deceleration is provided through an animation. The four screen-shots above represent the four main stages of the phenomenon]

Identification of model components skill [Doris, Motion and Newton's Laws]

Below there is a picture of an experiment that illustrates the boiling of water.



Name the basic components of the model in relation to the phenomenon that represents. For each component provide 2 examples from the given model.

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The *identification of a model components skill* pertains to the learner's ability to identify a model's objects, variables, processes and interactions among its constituent components that correspond to the various identified components of the phenomenon under study.

Doris designed the activity to the left to be used as an evaluation of students' identification of a model components skill after the implementation of her curriculum. In doing so, she presented an experiment through a photo and asked students to identify the model components. The principle of the identification of a model components skill that is violated through her designed activity relates to what Doris used as the "model" through which the students would identify its components. It is obvious that Doris used the real phenomenon, which was depicted in a photo, as the means through which her students would use for identifying its components, and not a representation of any type through which the phenomenon of boiling water would be represented. Therefore, her misinterpretation between models and real phenomena lethally mutates the rationale behind the design and administration of such a task to the students.

Metacognitive knowledge about the modeling process [Bill, electric circuits]

*Now that you are done creating your model in Stagecast Creator, write down all the steps followed for creating your model in Stagecast Creator. Pay attention to the rules you created, the variables, and the characters you used.*

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Metacognitive knowledge about the modeling process refers to the capability of a learner to explicitly describe and reflect on the major steps of the scientific modeling process, e.g., one starts with observing the phenomenon that is of interest, collects information from the phenomenon, formulates a model by implementing the collected information, contrasts the formulated model with the phenomenon as a means of evaluating the model, revises the model in light of new information that has not been implemented during the original formulation, repeats the previous steps in an iterative and cyclical manner with the purpose of refining the model to make it consistent and rigorous and to be able to use it to test hypotheses and make predictions.

Bill designed the activity to the left and stated that the modeling objective that would be promoted through this activity was the development of learners' metacognitive knowledge about the modeling process. The principle of the metacognitive knowledge about the modeling process that appears to have been violated in Bill's activity relates to his misunderstanding of what this type of knowledge entails, as, according to his activity, he seemed to have perceived this type of knowledge as the knowledge about the description of the technical steps followed for the creation of model in SC.

Consequently, students' metacognitive knowledge about the modeling process cannot be enhanced through Bill's activity, because they are not prompted to reflect on the iterative and cyclical process that modeling entails.

*Level 2 – Integration of the modeling ability framework: Moderate cultivation of all components of the modeling ability framework components – the “modeling for modeling’s sake” effect.* The curriculum designs that were clustered in Level 2 encompassed activities through which all modeling ability framework components were sought to be enhanced, but some components were either superficially approached or the place of some of the activities in the curriculum that were designed to promote specific components was not appropriate. Level 2 is superior to Level 1, as there was a stronger emphasis on the design of activities that are aligned with every component of the modeling ability framework, and no instances of “lethal mutations” were found among the curriculum designs of Level 2. However, some components of the modeling ability framework were either superficially approached or the place of the modeling activities within the curriculum that were aligned with specific modeling ability components was not appropriate. Specifically, there were instances that a specific modeling ability component appeared very early in the activity sequence and thus its cultivation could not be promoted, because some other modeling ability components, which were considered as prerequisites for the effective development of this modeling ability component, should have been preceded. Likewise, there were other instances where the modeling activities that preceded had the potential to fertilize the ground for the development of a specific modeling ability component, but such an attempt was omitted from the activities that followed. Additionally, in some other cases the activities that were designed for the development of a specific modeling ability component were very sparse throughout the curriculum, and thus the development of this component could not be granted. Finally, the combination of the previous characteristics that were common among the curriculum designs of Level 2, in conjunction with the fact that some of the modeling activities made an insignificant contribution to learners’ modeling ability, revealed that teachers’ priority during designing their curriculum materials was to design modeling activities for the *sake of modeling* (the “modeling for modeling’s sake” effect), and not for the effective development of learners’ modeling ability. To clarify these findings, Debra’s curriculum is used as an example.

Debra, who chose the context of geometrical optics as the context of her curriculum development, designed several modeling activities through which the students would be scaffolded to create models to represent how images are formed with the use of a convex lens, and what factors affect the nature, the size, and the distance from the lens of the image of an object that is placed in front of a convex lens. The examination of the frequency of the activities that were aligned with the development of each modeling ability

component indicate that there was not a well balance between the frequency of the activities that were designed for each modeling ability component (see Table 48 for details). The most predominant ones were those that related to the model formulation skill and the identification of model components skill, followed by the model evaluation and formulating ideas for improvement skill, and the metacognitive knowledge about the modeling process activities. The rest of the modeling components appeared only once in the activity sequence, and thus their cultivation is considered as superficial.

Table 48. Frequency of the modeling activities in relation to the modeling ability components in Debra's curriculum

Objective of the activity	Frequency
1. Model formulation skill	5
2. Identification of model components skill	5
3. Comparing and contrasting models of the same phenomenon skill	1
4. Model evaluation and formulating ideas for improvement skill	3
5. Model validation skill	1
6. Meta-modeling knowledge with respect to the nature of models	1
7. Meta-modeling knowledge with respect to the purpose or utility of models	1
8. Metacognitive knowledge about the modeling process	2

Although the limited number of designed activities that relate to specific components of the modeling ability framework might not denote poor development of a specific component, the format and the position of the sole activity that Debra designed to foster students' comparing and contrasting models of the same phenomenon skill cannot confirm this claim. The activity, as it appears in Figure 30, taken together with the preceding and the subsequent activities in the activity sequence, falls short in promoting the related modeling ability component in two ways. Firstly, at the point that this activity appears in the activity sequence the students neither had already been engaged in evaluating their models according to a set of given criteria nor were scaffolded in identifying and using their own criteria for evaluating their models. As a result, the comparison of their own model with the given one would probably focus on aesthetic criteria or, at best, on the representational coherence between the two models. Secondly, none of the preceding activities focused on the development of students' epistemic understanding about the nature of models (e.g., what is a model, what do models represent, what types of models do exist, and so on), and therefore the students might keep wondering if the picture in their book (e.g., a picture that illustrates the direction of a ray of light prior to and after penetrating a convex lens) can be considered as an example of a model. Consequently, students' lack of epistemic understanding about the nature of models, in conjunction with the absence of activities pertaining to the development of the evaluation of models skill

that should have been preceded, might hinder the effective development of the comparing and contrasting models of the same phenomenon skill.

**Activity 4: «Comparing models of the same phenomenon»**

Aim:

- To compare two models that represent the same phenomenon.

**Instructions:**

- Observe carefully the picture in your book and the drawing you created to show how the convex lens functions (model 4).
- Write below the similarities and differences between the picture and model 4.

Similarities	Differences

Figure 30. Debra’s designed activity to enhance students’ comparing and contrasting models of the same phenomenon skill

Even though the activity presented in Figure 30 was used as an example to declare the superficial development of a specific component of the modeling ability framework, it can also be seen as an example of an activity that strengthens the argument of the “modeling for modeling’s sake effect” that was a characteristic of curriculum designs of Level 2. This particular activity, as well as two other activities that appeared at the end of Debra’s curriculum, indicate that Debra might have used the modeling ability framework in the form of a “checklist” while designing her curriculum activities. The two activities that appeared at the end of her curriculum were in the form of two questions (e.g., “What is a model?” and “Why is it important to build models like the ones you did?”) through which Debra sought to enhance students’ development of meta-modeling knowledge about the nature and purpose of models. Surprisingly, even though there was a fruitful ground at earlier stages of her activity sequence that she could prompt her students to reflect on the nature of models (e.g., at the stage when students created their first, second or third model) or on the purpose of models (e.g., at the stage when students might have used their model to test their predictions), Debra placed these two important modeling objectives at the end of her curriculum, and most importantly, she did not incorporate any scaffolds to help the students reflect on their learning experiences from specific previous activities for answering the questions. Hence, the fulfillment of the learning objectives that are associated with these modeling ability components cannot be granted.



*Level 3 – Integration of the modeling ability framework: Efficient transformation of the modeling ability framework into pedagogically potent modeling activities.* Level 3 entails those curriculum materials that the examination of their designed activities revealed that the modeling ability framework was efficiently transformed for the design of fruitful learning activities through which learners' modeling ability would be enhanced. Each component of the modeling ability framework was fostered through productive modeling activities that were placed in a meaningful order in the activity sequence, and were also well interwoven with the rest of the activities in the curriculum. To illustrate the modeling activities that were designed to foster the development of learners' modeling ability in terms of their frequency, position, and chronological order, Lucy's modeling activity sequence that was designed in the context of geometrical optics was selected as an example (see Figure 31 for details).

According to Figure 31, Lucy designed 55 modeling activities (cumulative frequency of the eight modeling components' frequency that appears at the end of the timeline of each component) through which learners' modeling ability would be enhanced. Although the frequency of each modeling component activity varies, this does not designate that the development of each component could not be granted. Specifically, Lucy made a serious attempt to create significant learning spaces for the integration of each modeling ability component in the activity sequence, and used several types of scaffolds to facilitate the gradual development of learners' modeling ability in unison. These modeling ability scaffolds were more frequent in the beginning of the cultivation of each modeling ability component and faded out when a modeling activity was becoming a modeling "habit" for the students. For instance, in order to facilitate the development of learners' *model evaluation and formulation of ideas for improvement skill* Lucy would first let her students use their own evaluation criteria right after finishing with the creation of their first model, then she would orchestrate a classroom discussion to give her students the opportunity to present their models and announce their evaluation criteria, and then she would direct her students through questions and prompts to focus on their model's representational complexity, interpretive potential, and predictive power. For each evaluation criterion she introduces in her curriculum, Lucy would ask her students to examine their own created models and seek evidence to justify whether their model satisfies each criterion or not. She would also ask her students to share their models and evaluation to the corresponding criteria with their peers for peer assessment purposes. At a later stage when her students would create new or improved models about the image formation with the use of convex or

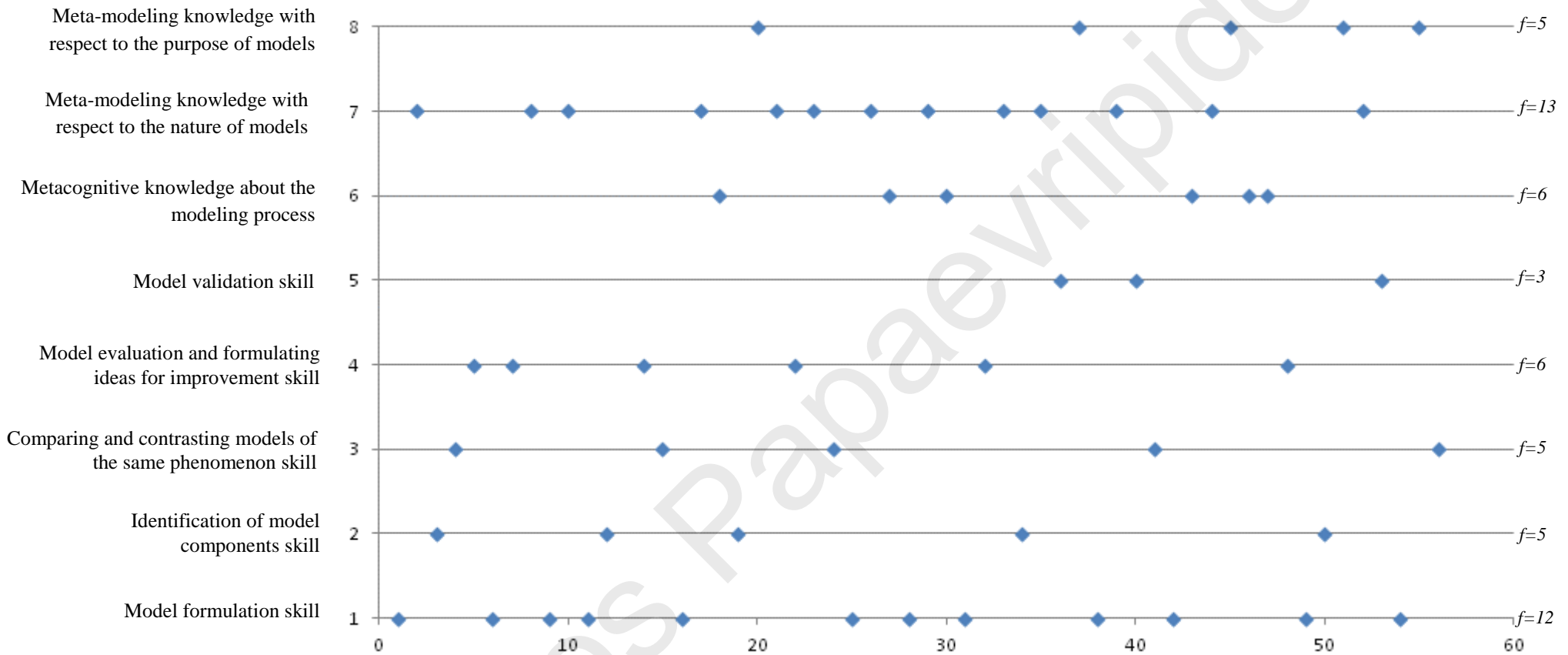


Figure 31. Frequency and chronological order of the modeling ability components in Lucy's curriculum

concave lenses, Lucy would revisit the model evaluation and formulating ideas for improvement skill and would ask her students to evaluate their new models. This time, instead of providing the evaluation criteria that were introduced in a previous activity she would ask her students to first evaluate their models and at a subsequent activity she would ask the students to go back in their curriculum at the point that the evaluation criteria were introduced and check if their evaluation contained references on each evaluation criterion.

The abovementioned procedure was found to be followed at every later stage of model evaluation and, by the end of the curriculum, this type of scaffold would faint out as the students are expected to have developed understanding of the model evaluation strategy and would apply it spontaneously for every new model evaluation.

Another interesting finding that came up from Lucy's attempt to enhance learners' modeling ability and merits attention relates to a design pattern that was revealed after mapping her modeling activity sequence in the graph presented in Figure 31. More specifically, whenever Lucy sought to engage her students in creating a new model or revising and improving a previous one, she designed modeling activities that adhere to the following pattern: (i) model formulation; (ii) identification of model components; (iii) comparing and contrasting models of the same phenomenon; and (iv) model evaluation and formulating ideas for improvement. Furthermore, this design pattern was enriched by the integration of activities that point to the development of meta-modeling knowledge about the nature of models (see Figure 31 for details), as this came out from the frequent design of activities that relate to this purpose. For instance, at the point when the students would have finished creating their first model, Lucy would prompt her students to discuss with their peers the relationship between the model they created with the corresponding phenomenon, aiming to help them understand that models are constructs created by individuals to better understand a phenomenon under study. Later on, when the students would be dealing with comparing and contrasting the models created for representing the same phenomenon, Lucy added a prompt for reflection about whether two groups of students could create different models to represent the same phenomenon, even though they were studying the same data. Consequently, these two examples of activities that relate to the development of students' meta-modeling knowledge about the nature of models designate that Lucy neither designed and integrated the activities for the fulfillment of a specific modeling objective in isolation with the other modeling activities nor approached the modeling ability framework as a "checklist" in the way that the teachers of

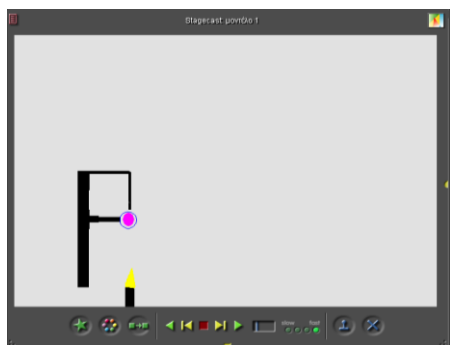
Level 2 might have used. Instead, Lucy exploited every single opportunity in her activity sequence that there was fruitful ground for the cultivation of the meta-modeling knowledge about the nature of models, and designed fundamental activities that made a good fit with the rest of the activities.

#### **4.4.5. Models' progression**

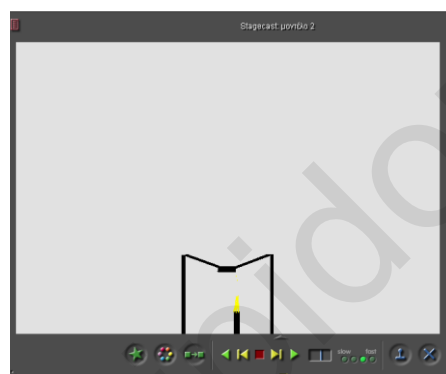
One of the requirements of the curriculum reconstruction project that teachers had to attain was to create themselves all the models they anticipated from their students to develop when implementing their curriculum. This task was essential for two reasons. Firstly, the teachers would experience at first hand the modeling pathways their students would go through when creating a specific model they suggested through their curriculum, and thus they would receive feedback for themselves about the appropriateness and fitness of the model creation activity with the broader rationale of their curriculum. Secondly, teachers' sequence of models or *models' progression* would serve as a rich data source for capturing the rationale behind their decisions for engaging students in the productive act of model creation. Consequently, the fifth dimension through which teachers' curriculum designs were examined pertains to how *models' progression* looked like in their suggested curriculum. In doing so, all models that a teacher suggested in his/her curriculum were examined in relation to both the relationship between the model and the phenomenon it represents, and the relationship between each model with its preceding and subsequent models along the model progression in the curriculum. The levels that emerged from this analysis are presented and elaborated below.

*Level 1 – Models' progression: Development of various independent models to represent different but related phenomena.* The teachers who were classified in Level 1 were those who selected a variety of related phenomena to be modeled through the activities they proposed. For each phenomenon they incorporated in their curriculum, they suggested a new model that the students should create, and they did not make an attempt to unify all different but related models in a broader model that could apply to phenomena of the same class. Because teachers decided to integrate several but related phenomena in their curriculum, and because for each phenomenon the students would make observations, then create the model, and then proceed to the next phenomenon, and so on, it appears that this approach is not aligned with the rationale and the principles of MCSI, and thus the development of students' conceptual understanding about the phenomena they would be

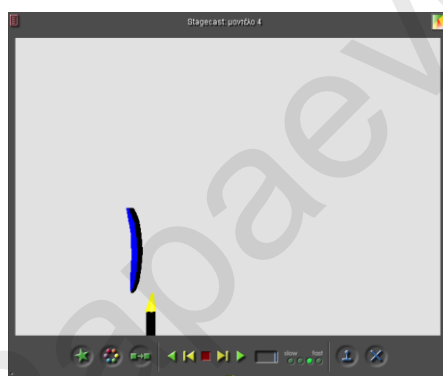
studying cannot be granted. To illustrate how models' progression of Level 1 looked like, Molly's proposal about modeling phenomena in the context of "expansion and contraction of solid materials" was selected and discussed below.



1. Cubic expansion



2. Linear expansion



3. Bimetal strip

Figure 32. Screenshots from Molly's models created in SC to represent three phenomena in the context of "expansion and contraction of solid materials"

Molly chose three different but related phenomena in the context of "expansion and contraction of solid materials" for the development of her unit. As shown in Figure 32, Molly would begin with the study of cubic expansion, then she would proceed with the linear expansion of a piece of metallic cord, and in an extension activity she would introduce the bimetal strip as an example of object whose function is based on the linear expansion of solid materials. Although the three phenomena that her students would engage with are closely related, the corresponding models that she expects from the students to create for each of the phenomena indicates that Molly does not use model creation as a means through which students' conceptual understanding about the

phenomena under study could be better facilitated. Instead, Molly's models' progression designate that each subsequent model neither builds on nor relates to a previous model, and accordingly, the students could not appreciate the creation of models as a means through which individuals use for interpreting and explaining physical phenomena. This argument is also strengthened if we look at the nature of models that Molly suggested for each of the expansion and contraction phenomena she incorporated in her curriculum. All three models that appear in Figure 32 were built as animations, since none of them involve a mechanism of any type that provides an interpretation of the way each phenomenon functions the way it visually appears on the computer screen. Each model runs with a programmable behavior that has been set by the creator of the model, and does not allow any modifications or alterations in its programmable routine.

Molly's models' progression would be better aligned with the principles of MCSI, if she had started her activity sequence with the study of a single phenomenon in the context of expansion and contraction of solid materials (e.g., linear expansion of a metallic strip), and designed activities through which her students would create a series of interrelated models in such a way that each new model would be an improved version of a previous one in terms of its representational complexity, interpretive potential, and predictive power. At the stage that her students would have created a model that fulfilled these criteria, she could have introduced a new phenomenon of the same class (e.g., cubic expansion) and prompt her students to test the validity of their model by applying it to the new phenomenon. Consequently, although this suggested models' progression sounds similar to the one Molly proposed in her curriculum, the rationale behind the development of each model, as well as the relationship between each model with its preceding and subsequent models along the model progression in the curriculum are significantly different.

*Level 2 – Models' progression: Development of various independent models to represent different aspects of a single phenomenon.* While the models' progression of Level 1 pertained to the development of various independent models to represent different but related phenomena, Level 2 models' progression refer to the development of various independent models to represent different aspects of a *single* phenomenon. More specifically, the teachers whose models' progression was clustered in Level 2 chose to study a single phenomenon (in contrary with those of Level 1), proposed the creation of different independent models to illustrate different aspects of the phenomenon under study, and failed to come across with way to merge all aspects from the different models into a

unified model that would illustrate, explain, and generate new predictions that can be tested against data from the phenomenon it represents.

Martin's modeling progression is a representative example of the abovementioned characteristics of Level 2. The context of his curriculum was "Friction and Motion", and planned to engage his students in investigations about the factors that affect the friction that is exerted between an object and a surface when the object is pushed on it. For each factor, the students would perform a controlled experiment, collect and analyze data, formulate conclusions about the factor and the friction, and at the end they would create a model to illustrate their findings. The two models that Martin expected from his students to develop when implementing his curriculum are presented in Figure 33 and Figure 34. Figure 33 entails the model that represents how the type of a surface affects the friction force between the surface and a sliding object, whereas Figure 34 concerns the model that illustrates how the mass of an object affects the friction force exerted between the surface and the object. Albeit both models are essential in that they provide a representation of two aspects of the phenomenon under study (e.g., how the type of surface and how the mass of an object affect the friction force exerted on an object when moving on a surface), entail a relationship between the testing factor and the friction that can be considered as a mechanism that explains how the phenomenon functions, and can be used in some way for testing of predictions (e.g., how far the object would move if its mass is doubled), they fell short in that their applicability and universality are very limited. Martin's models' progression would be more fruitful and significant, if he attempted to help his students not to build separate models for each aspect of the phenomenon of friction, but to improve their first model through incorporating the new factor and its relationship with the friction. If that were the case, then students' final models would be robust enough to represent in a more advanced way the phenomenon of friction, their interpretive potential would be more sophisticated, and they could be used to test more complex predictions for questions like "How does the displacement of an object with a mass of 50g moving on a surface with a friction coefficient of .20 and an object with a mass of 25g moving on a surface with a friction coefficient of .40 compare?"

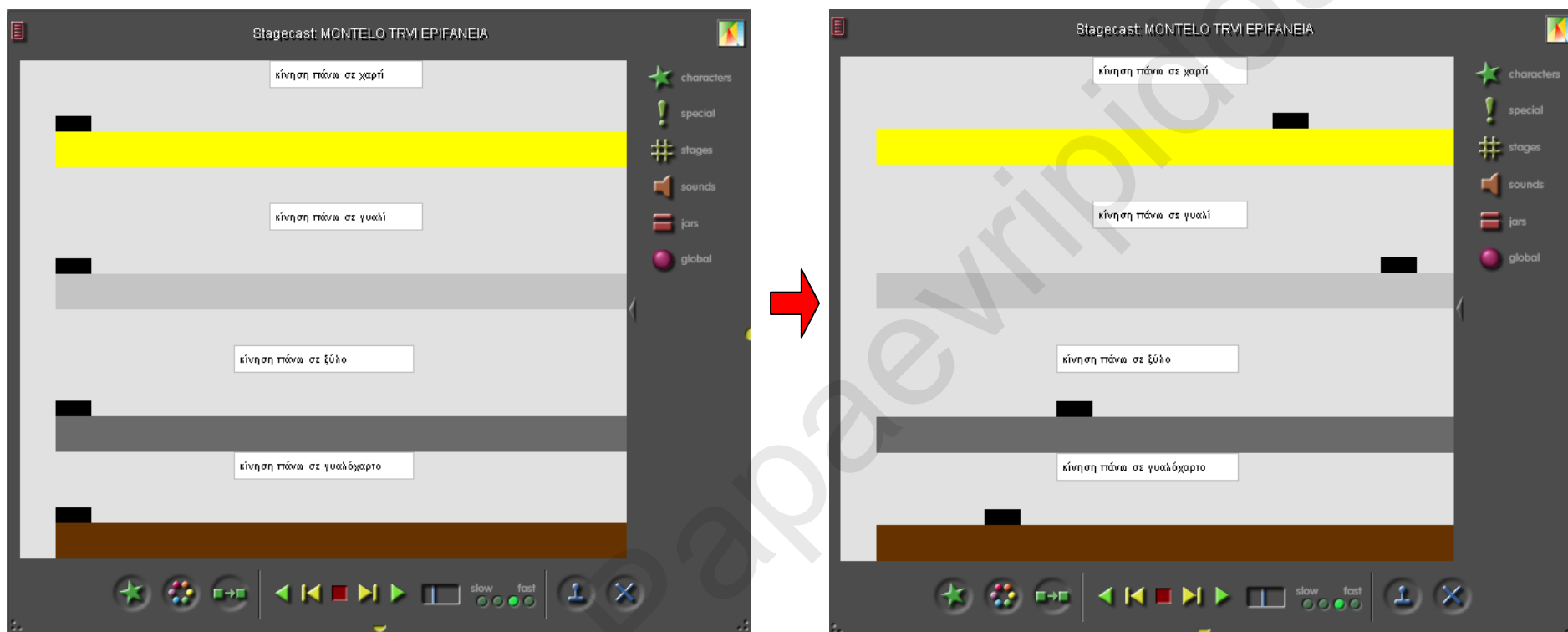


Figure 33. Martin's model on how the type of a surface affects the friction force between the surface and a sliding object

Note: The screenshot on the left shows the initial stage of the model, whereas the screenshot on the right shows the final stage of the model. In the initial stage of the model, four identical objects are placed on four different surfaces (paper, glass, wood, sandpaper) of equal length. In the final stage of the model, the objects appear at the new position after the same force has been exerted on each of them. The displacement of the object in each surface appears as follows: Glass>Paper>Wood>Sandpaper.



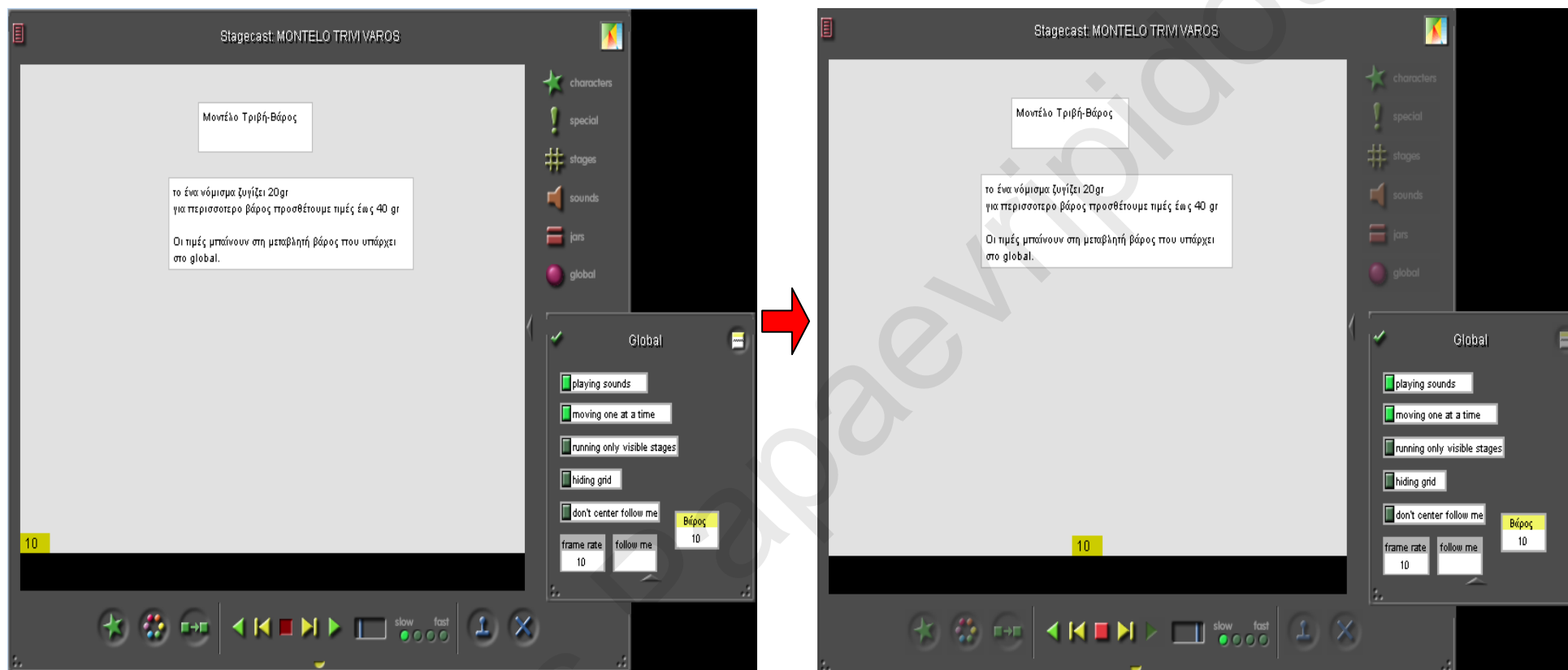


Figure 34. Martin's model on how the mass of an object affects the friction force between the surface and the object

Note: The screenshot on the left shows the initial stage of the model, whereas the screenshot on the right shows the final stage of the model. In the initial stage of the model, the user can set the value of the mass of the object in the window of the Global Variables of the model. In the final stage of the model, the displacement of the object with a specific mass is shown. The user can reset the model, set a new value for the mass of the object, and observes the new displacement of the object.

*Level 3 – Models’ progression: Development of a sequence of interrelated models with a gradual complexity and applicability to represent various aspects of a phenomenon.* Level 3 pertains to the case of curriculum designs which encompassed a sequence of interrelated models with a gradual complexity and applicability to represent various aspects of a phenomenon under study. The teachers who followed this approach made a serious attempt to engage students in multiple iterative cycles of model development and deployment of a natural phenomenon or a system, and thus the resulting models’ progression entailed a series of models, each of which was an improved or a revised version of the previous model that has been created. Consequently, the final models that would derive by the end of the implementation of the proposed curriculum would represent several aspects of the phenomenon under study in unison, would entail a robust interpretive mechanism for how the phenomenon functions, and would enable the formulation and testing of predictions and hypotheses for a family of phenomena of the same class.

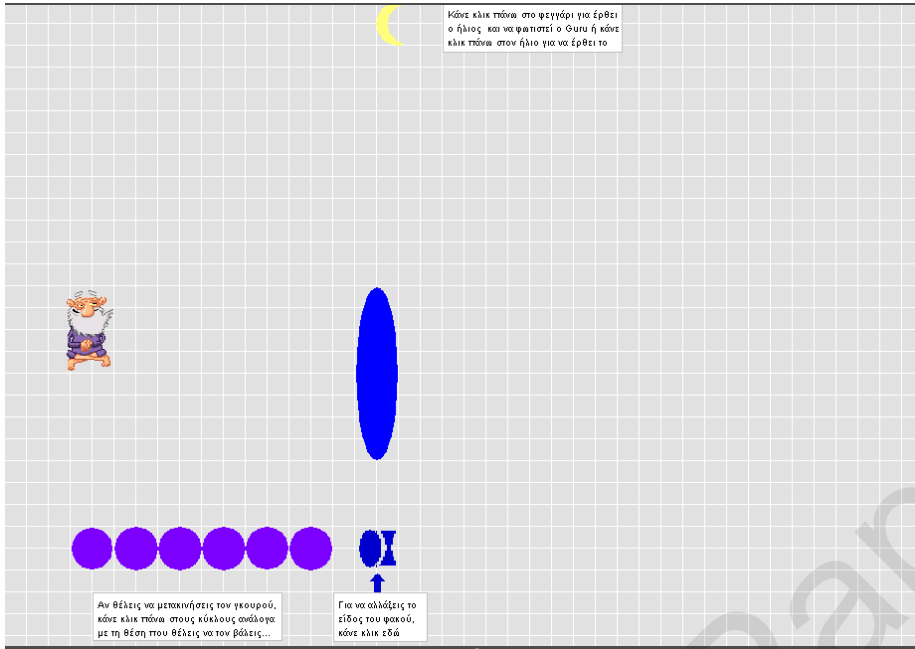
The models’ progression found in Derek’s curriculum design in the context of “geometrical optics” is a representative example of Level 3 models’ progression. Derek’s models’ progression is presented in Table 49 and is elaborated henceforth.

Table 49. Derek’s models’ progression in the context of “geometrical optics”

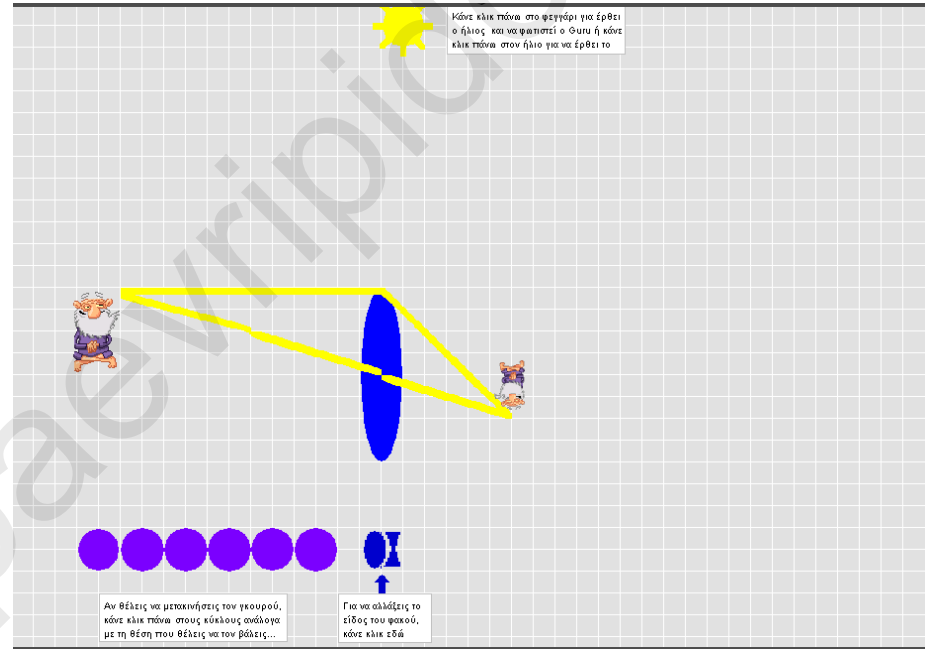
Phenomenon	Models’ progression
Image formation with the use of a convex lens	1 <sup>th</sup> model (SC): representation of the direction of an incident beam on a <i>convex</i> lens
	2 <sup>nd</sup> model (SC): representation of image formation when an object is placed at a long distance from a convex lens
	3 <sup>rd</sup> model (SC): improved model 2 to account for image formation when an object moves towards a convex lens
	4 <sup>th</sup> model (SC): improved model 3 to account for image formation when an object is placed at various locations away from a convex lens
Image formation with the use of a concave lens	5 <sup>th</sup> model (SC): representation of the direction of an incident beam on a <i>concave</i> lens
	6 <sup>th</sup> model (SC): representation of image formation when an object is placed at a long distance from a concave lens
	7 <sup>th</sup> model (SC): improved model 6 to account for image formation when an object moves towards a concave lens
	8 <sup>th</sup> model (SC): improved model 4 to account for image formation when an object is placed at various locations away from a concave lens
Image formation with the use of convex and concave lenses	9 <sup>th</sup> model (SC): a model that unifies model 4 and model 8 and enables both the representation of image formation with the use of a <i>convex</i> and a <i>concave</i> lens

According to Table 49, Derek's curriculum entailed a series of nine models that could be clustered in two subgroups. The first subgroup refers to a sequence of four interrelated models through which the image formation with a use of a convex lens is approached. The second group follows the same modeling pattern as the first subgroup, and relates to the image formation with the use of a concave lens. In both subgroups, each subsequent model builds on the previous model, and emerges after the collection of new data from students' further experimentation with the convex or concave lenses. The final model that is anticipated to be developed would be a combination of the final validated models that emerged from modeling the image formation with the use of a convex and a concave lens. This model, as it appears in Figure 35, encompasses an object (here a "Guru" is used as the object), a lens that can be chosen between a convex or a concave lens by clicking on the lens symbol behind the lens, and the condition of light that can be altered by clicking on the moon or the sun to change the state of light. The model also enables the change of the distance of the object from the lens by clicking on the corresponding circle that appears below the object. To run the model, the user needs to click on the "Play" button of SC, then choose the position of the object, and then click on the moon to enable the appearance of the sun. Once these steps are followed, light rays that depart from the object travel through the lens, and at their intersection the image of the object is formed.

Two examples of image formation with the use of a convex lens and a concave lens are presented in Figure 36 to illustrate how the image that is formed in each case of lens looks like, when the object is placed in the same distance from the lens. In Screenshot A, the image is formed behind the lens, it is real and inverted, and it is bigger in size compared to the size of the object because it is located in a distance between  $F$  and  $2F$ . In Screenshot B, the image is formed in front of the lens, it is virtual and erect, and it is smaller in size compared to the size of the object.



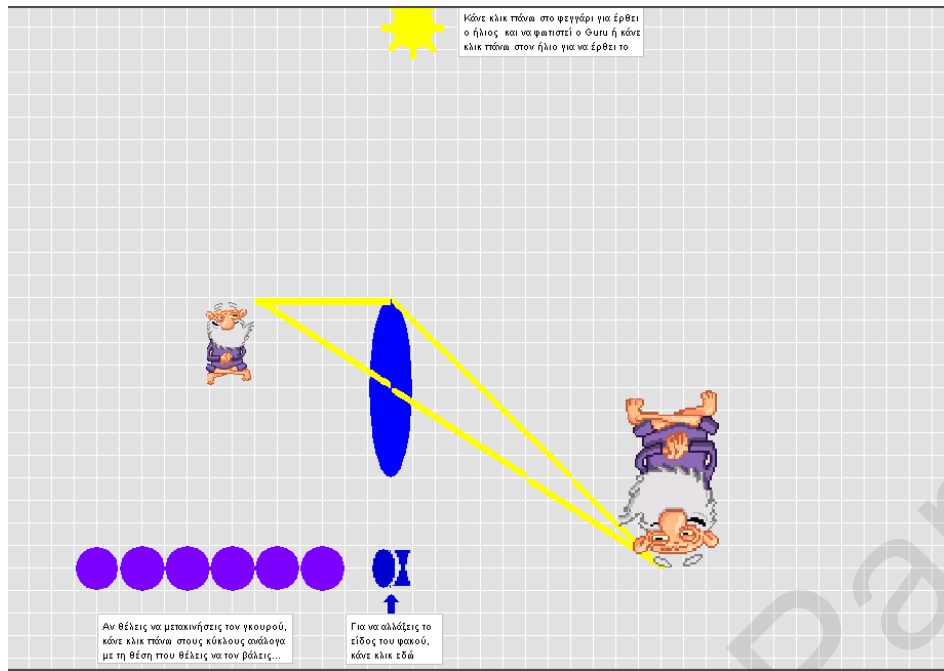
Screenshot A



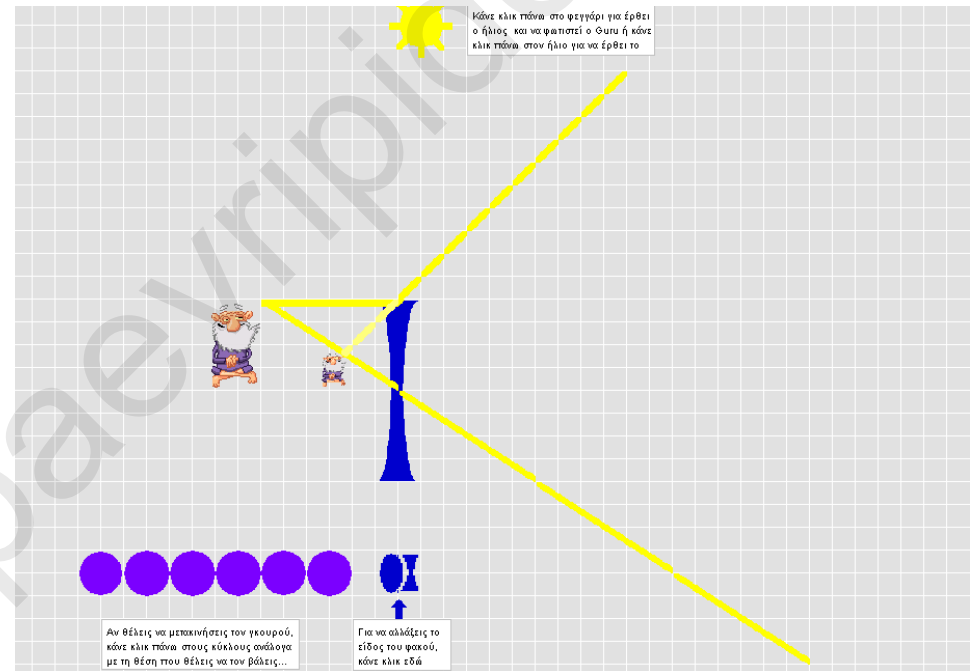
Screenshot B

Figure 35. Derek's image formation with the use of a convex lens model

Marios Papadimitriou



Screenshot A



Screenshot B

Figure 36. Derek's image formation with the use of a convex (Screenshot A) and a concave lens (Screenshot B) model

Note: For comparative purposes, the object (the "Guru") is placed at the same distance from the lens in each case in order to illustrate the differences between the image that is formed in each case.

#### 4.4.6. Nature of suggested models

After the characterization of the models' progression presented in the previous section, the nature of the models that teachers created and expected to be developed by their students when implementing their curriculum designs was examined. Through this examination, an attempt was made to gain insight into teachers' transformations of epistemic understanding about the nature of models, when designing modeling activities that focus around model development. Thus, the focus of the analysis of teachers' suggested models was on the three criteria that a scientific model should fulfill: (i) representational comprehensiveness; (ii) interpretive potential; and (iii) predictive power. Three levels of increased sophistication were revealed from the analysis of the nature of teachers' suggested models, and are discussed in the subsequent sections.

*Level 1 – Nature of suggested models: “Animation”- like models.* Level 1 entails those models which were found to represent only observable patterns from a phenomenon, lacked a mechanism that could reveal how the phenomenon functions the way it visually appears to the observer, and lacked predictive power. Given the fact that every function of the model has been programmed a priori by the model creator, and also the rules that have been created to control the function and behavior of the components of the model entailed no variables that the user of the model could manually alter their value, these types of models were characterized as “animation”-like. An example of a model that was clustered in Level 1 is presented in Figure 37.

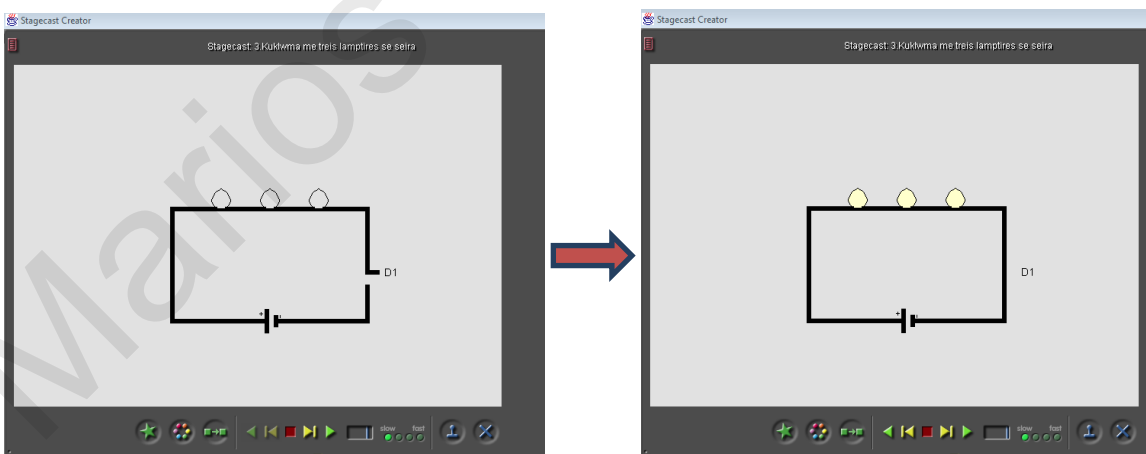


Figure 37. An “animation”-like model in the context of electric circuits

The model in Figure 37, created by Bill in the context of electric circuits, entails a symbolic representation of a three light bulbs in a row circuit, which can be controlled with

a switch. Once the switch is turned on, the three light bulbs are lit and their brightness is equal. The function of this model is controlled by the single rule that Bill created, and had the following format: “If the switch is turned on, then the three light bulbs will change appearance” (e.g., change from grey to yellow). Consequently, it becomes obvious that the model lacks a mechanism that explains *why* the light bulbs are lit and, also, does not allow the formulation and testing of predictions like “What would happen if a light bulb is removed from the circuit?”

Given the fact that Bill created the model in a way that he anticipates his students to follow when building their own model, it appears that he conceptualized models as substitutes of real phenomena whose purpose is to visually reproduce what an individual gains from a phenomenon when observing it, and not as tools through which one aims to interpret the way a phenomenon functions. This assertion explains the rationale behind characterizing the models of Level 1 as *animation-like*.

*Level 2 – Nature of suggested models: “Simulation”- like models.* The models clustered in Level 2 were characterized as “simulation”-like models, because significant emphasis was placed on their representational complexity and predictive power, whereas their interpretive potential was based only on a *mechanistic* interpretation for the phenomenon they represented. More specifically, both the representational format of the models and the syntax of the rules that were created to control their behavior were constrained to provide only an explanation that accounts to *how* the phenomenon functions the way it has been represented through the model. Thus, the models lacked of another type of explanation, namely a “causal interpretation”, that would explain *why* the phenomenon behaves as it does. On the other hand, these models were robust enough to enable the formulation and testing of a variety of predictions, since they were not built on a fixed programmable routine like the models of Level 1. Instead, for programming the function of these models, the teachers created several variables that they later incorporated in the syntax of the rules they formulated for the control of the behaviors and functions of their models. This mode of programming would enable at a later stage the modification of the value of specific variables and the study of the changes that this alteration might cause to the outcomes of the model.

Consequently, the nature of the models grouped in Level 2 point to a strong resemblance with the format, the nature, and the scope of computer-based simulations, because both

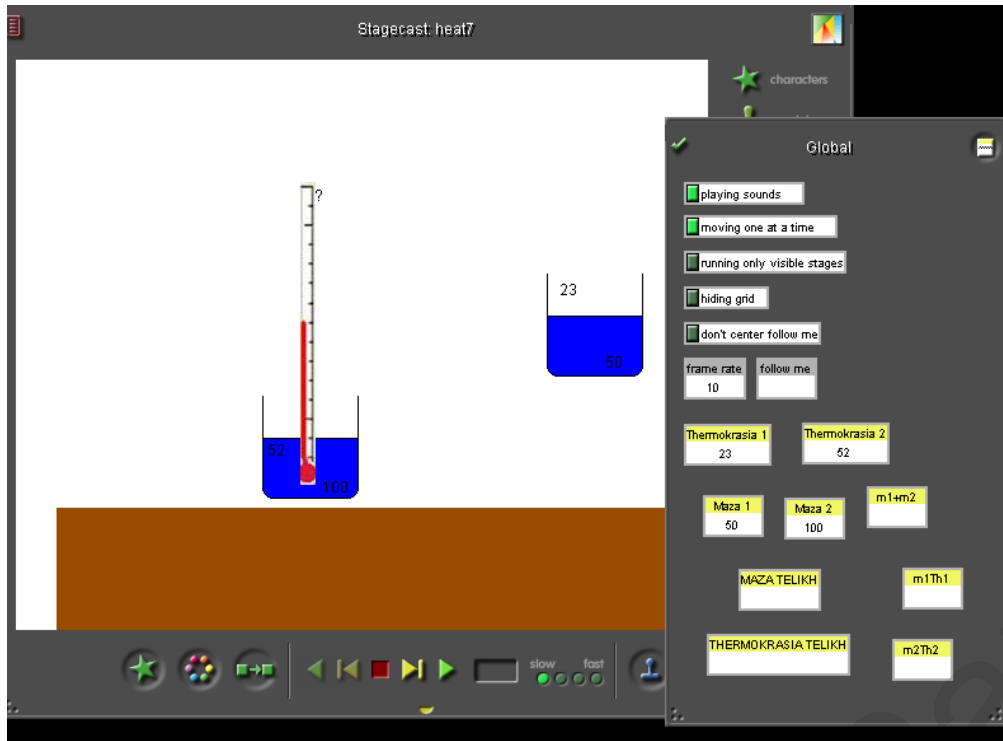
computer-based simulations and the models of Level 2 do not provide an explanation for why a phenomenon functions the way it visually appears through the simulation or the model, even though they entail the representation of a phenomenon and enable the manipulation of the values of the variables that control the function of the simulated phenomenon for testing of predictions. To make this comparison more transparent, a representative example of a model created by George in the context of “Thermal Interactions” is selected (see Figure 38 for details).

The model in Figure 38 pertains to the case of mixing two quantities of water of different temperature, and calculates the final temperature of the mixing water. The user can set the value for the temperature and the mass for each quantity of water (see Screenshot A in Figure 38) and when the model runs, the right beaker moves towards the left beaker, empties its containing water inside the left beaker, and the final temperature of the mixing water is calculated and appears on the screen. For calculating the final temperature of the mixing water, the teacher who created this model formulated a series of rules based on the following equation:

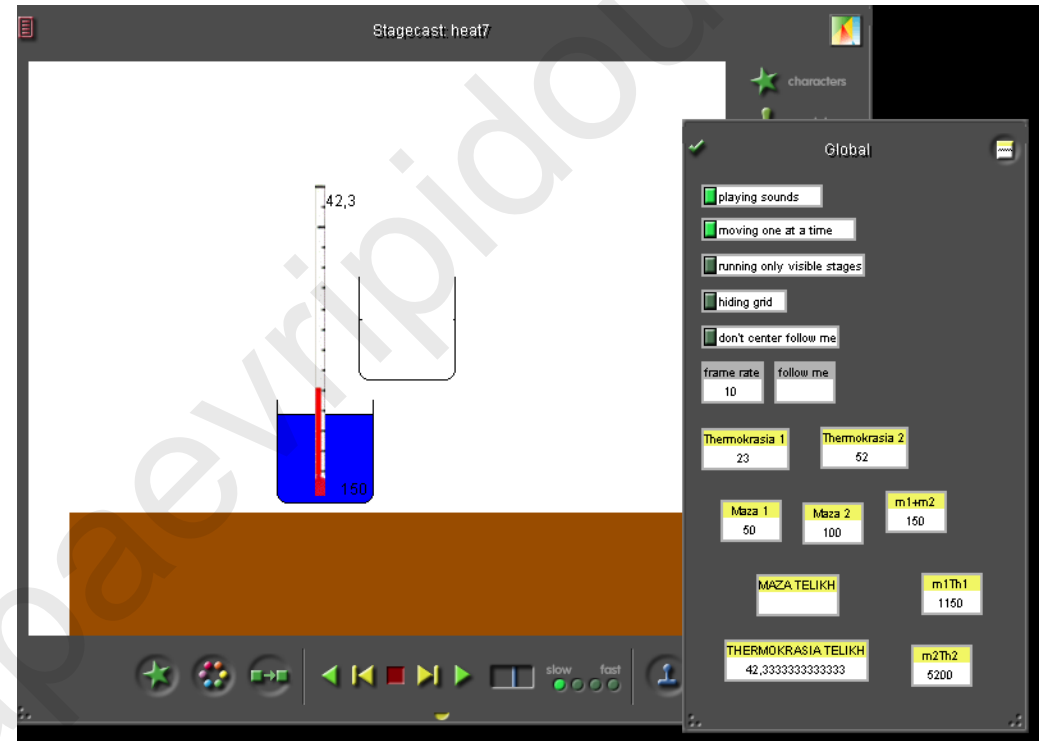
$$m_1 \Delta T_1 = m_2 \Delta T_2 \quad (\Delta T_1 = T_{\text{final}} - T_{\text{initial1}}, (\Delta T_2 = T_{\text{initial2}} - T_{\text{final}})$$

Although the model provides a realistic representation of the phenomenon (or experiment) of mixing water of different mass and temperature, and calculates the final resulting temperature of the mixing water using a scientifically correct formula, it does not entail a mechanism that explains the rationale behind the calculation of the resulting final temperature of the mixing quantities of water. It does, however, provide an explanation for *how* the calculation is undertaken, if one goes behind the model and study its internal workings (e.g., variables, rules, etc).





Screenshot A



Screenshot B

Figure 38. A “simulation”- like model in the context of thermal interactions

*Level 3 – Nature of suggested models: Models consistent with the definition of scientific models.* The models that were clustered in Level 3 fulfilled all three criteria that scientific models should entail. These criteria pertain to a model's *representational complexity* (e.g., the model encompasses those components that are necessary for the comprehensive representation of the related phenomenon), *interpretive potential* (e.g., the model entails both a mechanistic and a causal mechanism through which the function or the behavior of the phenomenon can be explained), and *predictive power* (e.g., the model enables the effective formulation and testing of predictions for changes in the phenomenon that were not directly observed). Models' interpretive potential was the main difference between Level 2 and Level 3, because as it was stated before, the models of Level 2 embodied only a mechanistic interpretation for the phenomenon under study, whereas models of Level 3 encompassed both a mechanistic and a causal mechanism interpretation to account for how a particular phenomenon functions.

The model presented in Figure 39 is a representative example of Level 3 models. It was suggested by Alex and is based in the context of "Buoyancy". This model is supposed to emerge after a series of experiments through which the students would investigate the factors that affect the sinking or floating of objects, firstly in the water and then in other liquids. The examination of this model according to its nature was found to be consistent with the definition of scientific models in the following ways:

- A. *Representational comprehensiveness*: The model entails all necessary components that a scientific model should encompass. These are the *objects* (e.g., solid materials like a piece of wood, a coin, a small marble sphere, a Styrofoam cube, a star-shape object for which the user can manually set its mass and volume, the water, and the basin), the *variables* (e.g., the mass, the volume, and the density for each of the objects that are placed inside the water, the Weight of each object and the Buoyancy force that is exerted on each object, the density of the liquid), the *processes* (e.g., the objects sink, float or suspend, when placed inside the liquid of the basin), and the *interactions* (e.g., the objects interact with the liquid of the basin, the density of an object interact with the density of the liquid, etc).
- B. *Interpretive potential*: The model encompasses both a *mechanistic* and a *causal* interpretation for how the phenomenon of sinking or floating occurs. The *mechanistic* interpretation relates to *how* the phenomenon functions, whereas the *causal* interpretation relates to *why* the phenomenon functions the way it does. Both types of interpretations can be extracted if one goes behind the visual appearance of the model

and study the “internal workings” of the model that the creator of the model developed during constructing the model. Consequently, the two types of interpretations that were revealed from studying the syntax of the rules that have been created for controlling the behavior of sinking and floating of the objects of the model are as follows:

- a. *Mechanistic interpretation.* In creating his model, Alex created a set of variables (see representational comprehensiveness subsection above) and then integrated these variables in the syntax of the rules he created to control the sinking or floating of each object. Consequently, when an object is placed inside the liquid of the basin, the following rules are executed:
  - i. *If the density of the object is greater than the density of the liquid, then the object will move upwards and stay at the surface of the liquid.*
  - ii. *If the density of the object is smaller than the density of the liquid, then the object will move downwards and stay at the bottom of the basin.*
  - iii. *If the density of the object is equal to the density of the liquid, then the object will remain at the position it was originally placed inside the liquid.*

The syntax of the rules that Alex created indicate that the sinking or floating of an object will be determined through comparing the density of the object with the density of the liquid that the object is placed inside. This type interpretation was characterized as *mechanistic*, because it informs us *how* the phenomenon of sinking or floating occurs.

- b. *Causal interpretation.* To explain *why* the phenomenon functions the way it does (e.g., why a certain object sinks or floats when placed inside a specific liquid?), Alex created the *buoyancy* and the *weight* variables that pertain to the forces exerted on an object when placed inside a liquid and are compared each time the model runs. Although these variables are not represented in a graphical way in Alex’s model, their value is calculated by the model and the comparison between their values is used as the interpretation for why a specific object would sink or float inside the liquid. In a previous model, Alex stated that he would prompt his students to represent these two forces acting on an object while it floats or sinks in a way that their magnitude would define the object’s final state. In the model presented in Figure 39, Alex explained that the simultaneous representation of the forces exerted on each object with the downwards or upwards motion of each object would be a difficult task for students to accomplish, because the syntax of the rules and the associated

changes in the appearance of each object would be a very complex and a demanding task. Hence, he decided to leave aside the representation of the forces, and use only their numerical values that would be calculated during running the model as an explanation to support why an object would sink or float when placed inside a specific liquid. Consequently, even though the function of the model is determined by the comparison between the density of an object and the density of the liquid (that is the mechanistic interpretation that the model entails), it also provides the values of the forces of buoyancy and weight for each object whose comparison is used as the causal interpretation for the phenomenon of sinking or floating.

- C. *Predictive power.* The way the model was built enables the formulation of a variety of predictions that could be tested through altering the values of specific variables and observing the resulting outcomes. This is feasible because Alex did not situate the creation of his model around the behavior of specific objects when placed inside a specific liquid. Instead, Alex model is considered as a universal model that applies to any object with a known mass and volume (or a known density) that is placed inside any liquid with a known density. For instance, for the five objects that are used in his model (see Figure 39 for details) he has defined a priori their mass and volume, and created a rule that would calculate their density and then compared its value with the density of the liquid. The liquid's density can be set manually, and thus the model can be used to test the sinking or floating status of the five objects when placed inside water, alcohol, oil, and so on. The model also moves beyond the sinking/floating behavior of the five objects that were used during the investigations, as it entails a star shape object whose volume and mass can be set manually, and thus, this can be done for any object that its mass and volume are known.

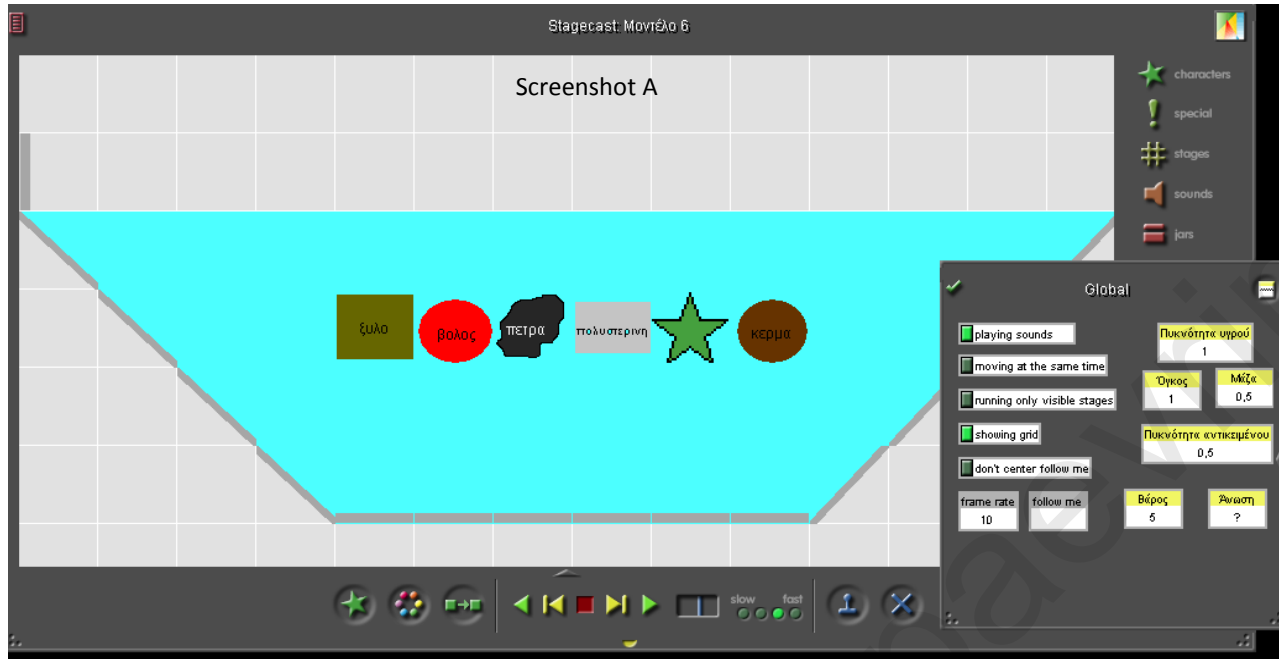
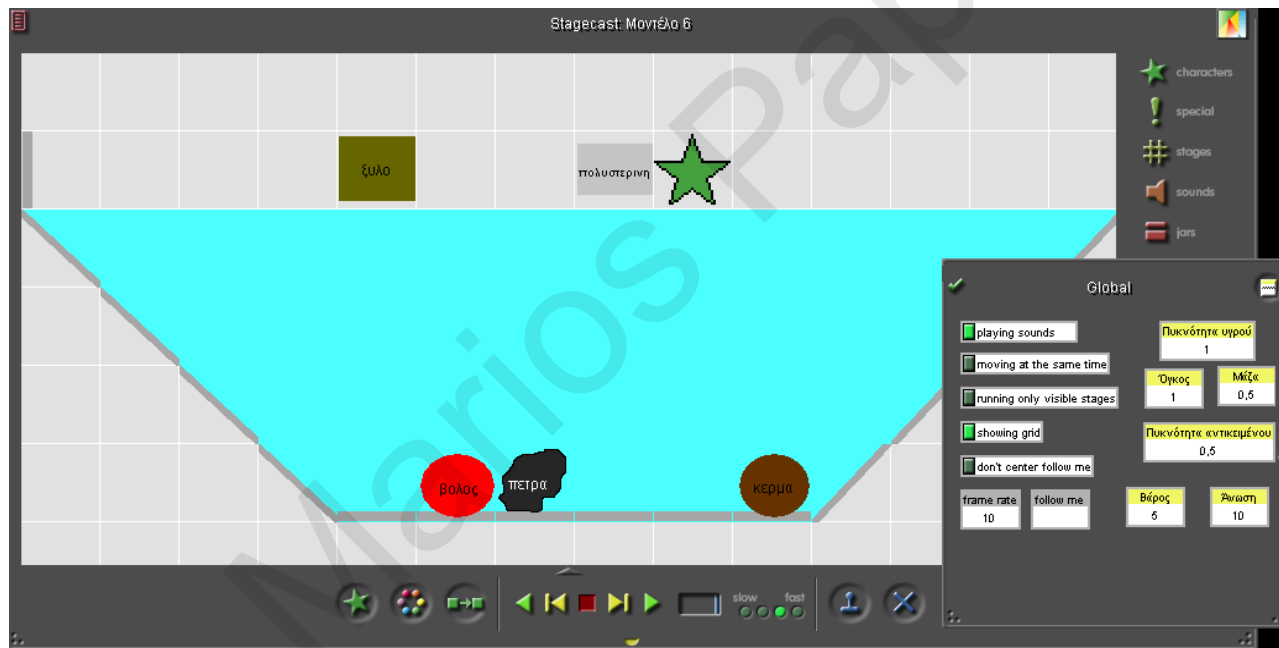


Figure 39. A model in the context of “sinking and floating” that satisfies the three criteria a scientific model should entail



#### 4.4.7. Evaluation of student learning gains

The last dimension that was used for examining teachers' curriculum designs relates to the means, the format, and the content of the evaluation tasks that teachers designed to assess the students' learning gains that would emerge as a result of their engagement with the curriculum materials. The position of the evaluation tasks in the activity sequence of the curriculum was also examined in an attempt to study whether the teachers aimed at evaluating students' prior, during, and after the curriculum implementation understandings, skills, or abilities. Three levels emerged from the analysis of teachers' evaluation tasks and are presented below.

*Level 1 – Evaluation of students' learning gains: Pre- and -post evaluation based only on students' conceptual understanding through true/false statements or closed-ended questions.* This level pertains to those teachers who designed assessment tasks to evaluate students' understandings of only concepts that incorporated within their curriculum. The evaluation was intended to be undertaken at the beginning and the end of the implementation of the curriculum, and the assessment tasks that were designed were mostly in the format of true/false statements or closed-ended questions. Even though the teachers used modeling as the teaching approach through which the development of students' conceptual understanding could be facilitated, they did not design any tasks to evaluate students' possible development of their modeling ability. Two examples of assessment tasks taken from Bill's means of evaluation are provided in Figure 40.

The first extract pertains to a true/false statements task through which Bill planned to evaluate students' understandings of the concept of electric circuit (see statements a-c in the first extract in Figure 40) and the transformations of energy that take place within a closed electric circuit (see statement d in the first extract in Figure 40). Although this type of evaluation task is planned to be administered prior to and after the implementation of the curriculum that Bill designed, it falls short in capturing students' conceptual understanding status prior to his instruction or the development of their understandings after the instruction, because this type of task measures only the factual knowledge of students in relation to the electric circuits. Additionally, the examination of the learning activities that Bill designed in his curriculum revealed that none of the activities focused on energy transformations, and therefore, the fourth statement in the evaluation task presented in Figure 40 designates that there is a discrepancy between the teaching activities and students' outcomes.

The second extract from Bill's evaluation tasks is in line with the previous closed-ended task, as the students are asked to merely write down the type of each of the circuits presented in the pictures. It is also a task that evaluates students' knowledge about the types of electric circuits in a superficial manner, since the students are not prompted to explain the reasoning behind their responses and, thus, to reveal how they differentiate between the two types of circuits. As these types of evaluation tasks are commonly found in the national curriculum evaluation textbook, one might assume that Bill followed this evaluation paradigm for designing his evaluation tasks, and since there are no instances of modeling evaluation tasks in the national curriculum evaluation textbook, this might also explain why he did not design additional tasks to evaluate students' modeling ability.

Write T if the statement is True, or F if the statement is False.

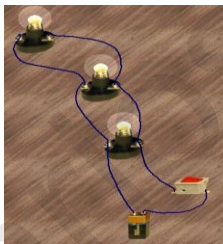
a. A light bulb is lit when the electric circuit is open.

b. A light bulb is lit when the electric circuit is closed.

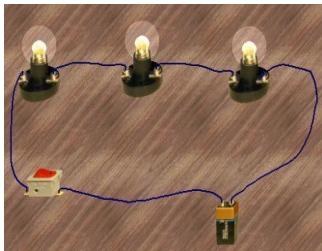
c. In an open electric circuit the wires that are connected to the positive and the negative ends of the battery are also connected to the base of the light bulb.

d. The light bulbs transform the electric energy into thermal and light energy.

What type of circuit connection is shown in the pictures below?



.....



.....

Figure 40. Extracts from Bill's evaluation tasks in the context of electric circuits

*Level 2 – Evaluation of students' learning gains: Initial and final evaluation of students' development of modeling skills and conceptual understanding in the context of the curriculum.* While the evaluation of students' learning gains of Level 1 was superficial, as

it focused around students' understanding of factual knowledge about concepts introduced through the curriculum, the evaluation tasks that were grouped in Level 2 pertained to the evaluation of students' development of both modeling skills and conceptual understanding. Both types of evaluation tasks were designed in the context of the curriculum that they departed from, and their administration was set at the beginning and the end of the implementation of the curriculum.

Although there was a significant shift from the evaluation tasks of Level 1 to those of Level 2, the examination of the tasks that were designed to evaluate students' modeling skills in the context of the curriculum they were associated with revealed two important findings. Firstly, given the fact that teachers designed assessment tasks to evaluate students' development of modeling skills and omitted the evaluation of their meta-modeling knowledge and metacognitive knowledge about the modeling process might designate that the teachers did not consider those two types of knowledge as important aspects of students' modeling ability and thus to design evaluation tasks to capture their development. The second finding that merits attention relates to the fact that since teachers chose the context of their curriculum as the context for the design of the evaluation tasks, the development of students' modeling skills might not be granted, because the evaluation of students' development of modeling ability needs to be pursued in context other than this of the instruction.

George, who chose the "thermal interactions" as the context of his curriculum design, was one of the teachers' whose evaluation tasks were clustered in Level 2. Two examples of assessment tasks that were designed to evaluate students' modeling skills in the context of "thermal equilibrium" are provided in Figure 41.

As far as the conceptual understanding evaluation tasks that were designed are concerned, the examination of the nature and format of these tasks indicate that the teachers designed tasks that students' comprehensive understanding of concepts related to the context of the curriculum could be assessed. Figure 42 entails an evaluation task created by George to assess students' understandings in the context of "thermal interactions".



- 1) Create a model in Stagecast Creator that will enable the calculation of the final temperature of mixing two quantities of water of different mass and temperature.
- 2) Which are the major components of the model you described above?
- 3) Do you think that the model described above is better than the graphical model presented below? Explain the reasoning behind your response and write the criteria used for your selection.

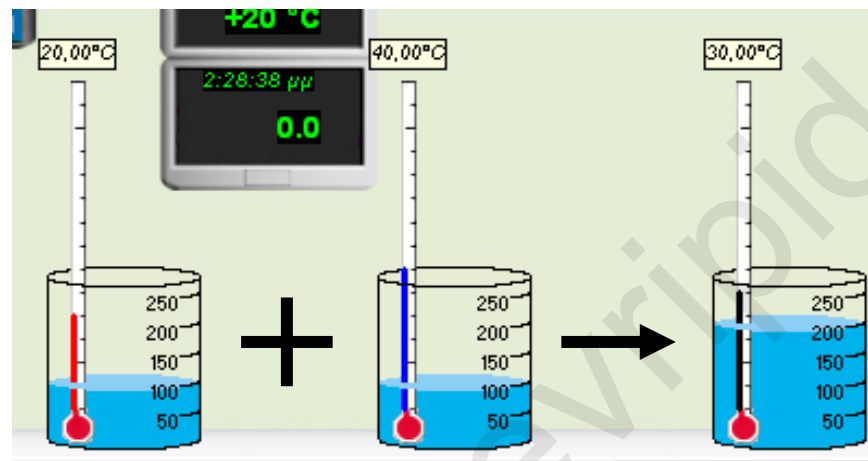
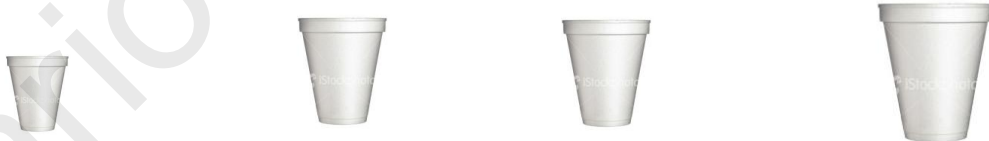


Figure 41. George's evaluation tasks to assess students' (1) model formulation skill, (2) identification of model components skills, and (3) comparing and contrasting models of the same phenomenon skill

Below there are four samples of water:



**K:** 50 g T= 20 °C      **X:** 100 g T= 20 °C      **Ψ:** 100 g T= 30 °C      **Z:** 150 g T= 40 °C

The following are mixed together: **K-X, K-Ψ, X-Ψ, Z-X**

Rank the resulting mixtures starting with the one with the lowest temperature. Explain the reasoning behind your ranking.

Figure 42. George's evaluation task to assess students' conceptual understanding in the context of "thermal interactions"

*Level 3 – Evaluation of students’ learning gains: Initial, ongoing and final evaluation of students’ development of modeling ability and conceptual understanding in new contexts.*

Level 3 entails the case of teachers who designed assessment tasks for initial, ongoing and final evaluation of students’ development of modeling ability and conceptual understanding in new contexts. These teachers’ proposals for evaluation of students’ learning gains differed from Level 2 teachers’ evaluation tasks in three ways. Firstly, the teachers of Level 3 not only designed pre- and post- assessment tasks to capture students’ development of conceptual understanding and modeling ability, but they also designed intermediate tasks through which students’ ongoing understandings and modeling ability could be captured. These tasks were in the form of reflective diaries, concept maps, or asynchronous discussions in an online learning platform that the students would complete at certain instances in the curriculum. Secondly, contrary to the teachers’ of Level 2 who designed evaluation tasks to capture students’ fragmented modeling ability (e.g., only modeling skills were sought to be evaluated), the teachers of Level 3 designed assessment tasks to evaluate students’ modeling ability in unison. Thirdly, the teachers of Level 3 appeared to have comprehended that in evaluating learners’ development of modeling ability, one should aim to situate their evaluation in new contexts in order to assess if students are able to far transfer their modeling ability in unfamiliar contexts. Another interesting finding that emerged during examining teachers’ evaluation tasks and their position in the activity sequence relates to the fact that in designing their pre-, post, and ongoing modeling ability evaluation tasks, the teachers of Level 3 followed the format and structure of the modeling ability tasks that they completed as *learners* during Phase 1 of the PDC. Consequently, this finding designates that the teachers appeared to have appreciated the role and scope of the modeling evaluation tasks designed for the purposes of the PDC, and they used them as a benchmark for the design of their own evaluation tasks.

Representative examples of evaluation tasks designed by Derek to assess students’ development understanding in the context of “geometrical optics” and their modeling ability are presented in Figure 43 and Figure 44 respectively.

Name: \_\_\_\_\_ Date: \_\_\_\_\_

Evaluation task 5

Name the following lenses according to their external characteristics, and draw the path of each light ray after passing through the lens.

Figure 43. Derek's evaluation task to assess students' understanding of the types of lenses and their impact on a parallel light beam

**EVALUATION TASK 10**

Below there is a representation of a food chain.

Φυτικοί μικροοργανισμοί  
 Γαστερόστεος (σταυρίδι)  
 Μικρά οστράκοδερμα  
 Πέρκα

Name three reasons for which representations like the one above could be beneficial for us. Explain.

EVALUATION TASK 7

Below there is a diagram that illustrates the phenomena of photosynthesis and respiration.



Name the major components of the model above in relation to the system that represents. Provide 2 examples for each component you identified.

EVALUATION TASK 12

1. Circle each one that you think is a scientific model. Explain why all these that you circled are examples of scientific models.

<p>A ground plan of a basketball field</p>	<p>A bridge</p>	<p>The double helix of DNA created with balls and sticks</p>
<p>A raised-relief globe sphere</p>	<p>A geography map</p>	<p>A porcelain mug</p>
<p>A cell-phone toy</p>	<p>“The thermal resistance of a material is proportional to the thickness and the density of the material and inversely proportional to the thermal conductivity of the material”</p>	<p>A recipe for how to make a cake</p>

Figure 44. Three modeling ability evaluation tasks designed by Derek

[Note: Task 10 relates to the evaluation of students’ meta-modeling knowledge about the purposes of models, Task 7 evaluates students’ identification of model components skill, and Task 12 relates to students’ meta-modeling knowledge about the nature of models]

#### **4.4.8. Teachers' distribution along the seven dimensions of analysis of their curriculum materials and across the emerged levels**

After the examination of teachers' characteristics across the seven dimensions of analysis, and the description of the levels of increased sophistication that emerged, the distribution of the twenty participating teachers along the seven dimensions of analysis of their curriculum materials and across the emerged levels was calculated (see Table 50 for details). All but four teachers' curriculum designs (see Martin, Lucy, George, and Bruce in Table 50) were classified in the same emerged level across the seven dimensions of analysis, indicating a consistency in the degree of sophistication of their curriculum designs. Martin's curriculum materials were classified in Level 1 in all but one dimensions of analysis (his *models' progression* was classified in Level 2), whereas Lucy's, George's, and Bruce's curriculum materials were classified mostly in Level 3, except for the *nature of suggested models* (Lucy) or the *nature of suggested models* and *evaluation of students' learning gains* (George and Bruce). Consequently, the sixteen remaining teachers, for whom there was homogeneity in the classification level of their curriculum designs across the seven dimensions of analysis, are classified as follows; four in Level 1, six in Level 2, and six in Level 3. On the other hand, if we consider Martin, whose curriculum design was classified mostly in Level 1, and Lucy, George, and Bruce, whose curriculum designs were clustered in Level 3 for the majority of the curriculum dimensions, the calculation of the total Level 1 curriculum designs is increased to five, and the total Level 3 curriculum designs is increased to nine. Nevertheless, in either case these findings designate that the format of the PDC had a moderate impact on teachers' development of curriculum design capabilities in the context of MCSI.

Table 50. Teachers' distribution along the seven dimensions of analysis of their curriculum materials and across the emerged Levels

Teacher	Dimensions of analysis of teachers' MCSI curriculum materials						
	Overall teaching orientation	Degree and type of reconstruction of the national curriculum unit	Types of designed activities and role of modeling in the curriculum	Integration of the modeling ability framework	Models' progression	Nature of suggested models	Evaluation of students' learning gains
<i>Bill</i>	L1	L1	L1	L1	L1	L1	L1
<i>Molly</i>	L1	L1	L1	L1	L1	L1	L1
<i>Doris</i>	L1	L1	L1	L1	L1	L1	L1
<i>Debbie</i>	L1	L1	L1	L1	L1	L1	L1
<i>Martin*</i>	L1	L1	L1	L1	L2	L1	L1
<i>Dina</i>	L2	L2	L2	L2	L2	L2	L2
<i>Mary</i>	L2	L2	L2	L2	L2	L2	L2
<i>Christina</i>	L2	L2	L2	L2	L2	L2	L2
<i>Marlene</i>	L2	L2	L2	L2	L2	L2	L2
<i>John</i>	L2	L2	L2	L2	L2	L2	L2
<i>Debra</i>	L2	L2	L2	L2	L2	L2	L2
<i>Lucy*</i>	L3	L3	L3	L3	L3	L2	L3
<i>Alex</i>	L3	L3	L3	L3	L3	L3	L3
<i>George*</i>	L3	L3	L3	L3	L3	L2	L2
<i>Susan</i>	L3	L3	L3	L3	L3	L3	L3
<i>Jane</i>	L3	L3	L3	L3	L3	L3	L3
<i>Bruce*</i>	L3	L3	L3	L3	L3	L2	L2
<i>Lucas</i>	L3	L3	L3	L3	L3	L3	L3
<i>Ann</i>	L3	L3	L3	L3	L3	L3	L3
<i>Derek</i>	L3	L3	L3	L3	L3	L3	L3
Frequency	L1=5, L2=6, L3=9	L1=5, L2=6, L3=9	L1=5, L2=6, L3=9	L1=5, L2=6, L3=9	L1=4, L2=7, L3=9	L1=5, L2=9, L3=6	L1=5, L2=8, L3=7

## Notes:

1. L1, L2 and L3 correspond to Level 1, Level 2, and Level 3 as defined in Table 43.

2. The symbol \* next to a teacher's name denotes a teacher whose curriculum characteristics were not clustered in the same emerged Level (see the grey color Levels in Table 50) across the seven dimensions of curriculum analysis.

## CHAPTER 5: DISCUSSION

### 5. 1. Introduction

The purpose of this thesis was to investigate the impact of a strategically designed PDC on teachers' development of modeling ability, CK about models and modeling, and CuK for MCSI. Additionally, this thesis sought to identify and describe the characteristics of teachers' MCSI curriculum designs in an attempt to investigate the types of transformations that were enacted by the participants in their effort to apply the theoretical perspectives of MCSI for the design of their own curriculum materials. The three research questions that this thesis aimed to address were as follows:

- 1. How does teachers' modeling ability compare prior to and after their participation in the PDC?*
- 2. How do teachers' content knowledge and curricular knowledge about models and modeling change as a result of their participation in the PDC?*
- 3. What are the characteristics of teachers' modeling-centered curriculum designs?*

The findings that emerged from the analysis of the data collected for answering each research question were presented in Chapter 4. The present chapter aims to discuss these findings in light of their significance and contribution to the existing literature.

### **5.2. How does teachers' modeling ability compare prior to and after their participation in the PDC?**

For answering this question, both qualitative (phenomenography) and quantitative (Wilcoxon test) analyses were followed. The findings that were revealed from the phenomenographic analysis of the data collected were presented in three sub-sections (see Sections 4.2.1.1., 4.2.1.2, and 4.2.1.3), according to the three constituent components of the modeling ability framework (modeling skills, metacognitive knowledge about the modeling process, and meta-modeling knowledge). In each sub-section, the levels that emerged from the phenomenographic analysis of teachers' responses to the sixteen modeling assessment tasks administered prior to and after Phase 1 of the PDC were presented, followed by teachers' distribution across the emerged levels prior to and after to

the PDC. The findings from the quantitative analysis that made use of the Wilcoxon test procedure were provided at the end of the qualitative findings. These findings demonstrate if the PDC impacted on the development of teachers' modeling ability, and also if the aspects of the modeling ability framework are content dependent or not.

Both qualitative and quantitative findings designate that the PDC had a great impact on the development of all components of teachers' modeling ability in unison. This is documented by both: (i) the Wilcoxon test procedure that revealed that the rank scores on each set of the post-assessment tasks that evaluated the same aspect of the modeling ability framework were statistically higher than the corresponding scores on the pre-assessment tasks; and (ii) the comparison of teachers' distribution across the emerged levels for each aspect of the modeling ability framework prior to and after Phase 1 of the PDC that indicate a significant shift of teachers to the upper emerged levels for every modeling ability component. A closer examination, however, at the number of teachers who succeeded on transiting to the most superior level that emerged for specific modeling ability components demonstrates that the majority of teachers either did not manage to develop a component of their modeling ability at the most sophisticated level (see for example the case of *model evaluation and formulating ideas for improvement skill* in Table 14), or for specific modeling ability components there was a discrepancy between the number of teachers who were clustered in the most superior level for both post-assessment tasks that evaluated the same modeling ability component (see for example the cases of *model formulation skill* in Table 8, the *model validation skill through comparison of the same phenomena skill* in Table 16, and the *meta-modeling knowledge with respect to the purpose or utility of models* in

Table 20). All findings that emerged for answering the first research question, in conjunction with the abovementioned considerations, are elaborated below.

### **5.2.1. Model formulation skill**

Although the examination of teachers' model formulation skill was not performed through monitoring their actual "modeling moves" during constructing the models in the corresponding assessment tasks (e.g., projectiles and volumetric expansion, see Appendices II and III respectively), the analysis of the resulting models they created within the context of the assessment tasks enabled the inference of valuable evidence that illuminated the level of their model formulation skill. Prior to the PDC, the majority of the



teachers created models in both contexts through which the phenomena that were illustrated within their models were superficially represented, and most importantly, they lacked interpretive potential and predictive power. This finding is in line with previous research reports (e.g., Crawford & Cullin, 2004; Justi & Gilbert, 2002a; 200b; Schwarz & Gwekwerere, 2007; Van Driel & Verloop, 1999; 2002; Windshittl & Thompson, 2006) that point to teachers' poor understanding and naive conceptualization of the nature and role of models. Likewise, teachers' tendency to focus on the mere representation of the phenomenon, and not on its other epistemic elements, might be attributed to the lack of understanding of what modeling entails and what is the scope of modeling. Put differently, the teachers at the beginning of the course ignored that "modeling begins with a need to describe, predict, and/or explain some phenomenon. In designing explanatory models, [they] must use their current understanding to simplify the world by determining the objects and rules of interaction that they deem important. That is, observations of the natural world motivate the construction of models, in turn motivating further observations and driving the resulting interpretations" (Penner, 2000/2001, p. 10).

At the end of Phase 1 of the PDC (the "Teachers as Learners" Phase), teachers' model formulation skill was enhanced, since for both assessment tasks that evaluated this skill the teachers progressed from the lowest to the upper levels that emerged (see Table 8 in the chapter of Findings for details). In general, the teachers' created more sophisticated and elaborated models of the phenomena they observed, as they paid attention not only on the representational aspect of their models, but also on the underlying mechanism that helps in explaining *how* and *why* the phenomenon functions the way it is conceived through our senses, and also on models' feasibility to enable the formulation and testing of predictions. Specifically, in creating their models the teachers incorporated more *objects*, *variables*, *processes*, and *interactions* among models' constituent components than they did so when creating the same models at the beginning of the PDC. Given the fact that their models entailed a more comprehensive representation of the phenomena being modeled, I assume that teachers' engagement in modeling 1-D collision phenomena during the PDC impacted on the development of their knowledge of the constituent components of a model, as they appeared to be able to transfer and transform this knowledge when building models in different contents of the assessment tasks. This finding is consistent with the stance made of van Borkulo (2009), who claimed that when creating a model "one needs to know how to define a new variable, how to use the different types of variables, and how to relate all components into an effective model" (p. 22).

As far as teachers' models interpretive potential are concerned, it was found that this was the one of the two aspects of models that determined the significant difference between teachers' distribution in the emerged levels in the two assessment tasks designed to evaluate teachers' model formulation skill. Specifically, as Table 7 and Table 8 in the chapter of Findings indicate, while the majority of teachers' projectile models encompassed both a *mechanistic* interpretation that accounts for *how* the phenomenon functions, and a *causal* interpretation that explains *why* the phenomenon functions the way it does, the majority of teachers' volumetric expansion models entailed only a mechanistic interpretation to account for how the expansion of a metal sphere occurs. The *mechanistic interpretation* for *how* the phenomenon functions pertains to the description of the overall behavior of a mechanism that controls the function of the phenomenon, without providing evidence that accounts to *why* the phenomenon functions the way it does. Put differently, the mechanistic interpretation has a "phenomenological" attribute, since it aims to provide only information of what a mechanism is doing and not to explain the way it produces it. On the other hand, the *causal interpretation* provides clarification to the rationale the development of the model was grounded, as it reveals the mechanism which underlies or causes the phenomenon behavior.

These two different modes of interpretation, that were extracted from the analysis of teachers' models were used by Penner et al., (1997), Clement (1989), and Colella et al., (2000) to distinguish models into two or three distinct categories. For instance, Penner et al., (1997) suggested the distinction between *perceptual* and *functional* models. *Perceptual* models represent the different parts of a phenomenon, focusing on the overall static depiction of the phenomenon, whereas *functional* models are representations of the mechanism underlying the phenomenon. Likewise, in evaluating the extent to which a model provides access to the mechanism underlying the phenomenon represented, Clement (1989) classified models in *expedient* and *explanatory* models. The *expedient* models simulate the behavior of the phenomenon without allowing access to the mechanism underlying the behavior, whereas the *explanatory* models entail a representation of the mechanism that underlies or causes the phenomenon behavior. Lastly, Colella et al., (2000) proposed three categories of models according to the extent to which they enable access to the phenomenon's underlying mechanism. These were: (i) the *illustrative* models (e.g., models that represent a phenomenon without providing any access to the physical mechanism underlying the phenomenon); (ii) the *analytical* models (e.g., models that offer limited access to the mechanism that causes the phenomenon, but this access is limited to

altering the values of variables that were introduced in the representation of the phenomenon); and (iii) *simulations* (e.g., models that provide a representation of the underlying mechanism that users can explore or alter).

Despite the differences between teachers' models in relation to their interpretive potential in the two different content areas, it is important to underline teachers' significant shift from *perceptual* or *expedient* models created in the pre-assessment tasks to *functional* or *explanatory* models created in the post-assessment tasks. Hence, I claim that teachers' capability to draw and create mechanisms while building their models reflects their understanding to giving priority on answering questions of *how* and *why* phenomena happened, and not on *what* and *when* happened (Bamberger & Davis, 2011). This finding might also implies that teachers' ability to formulate explanations has also been enhanced, as explanations have a primary function on giving account to how or why things occur (Kitcher, 1981). Accordingly, this might be one of the most fundamental performances we would like both our teachers and students to develop during their engagement in MCSI settings (Schauble et al., 1991; Schwarz et al., 2009).

The second aspect of models that determined the difference between teachers' distribution in the emerged levels of the model formulation skill pertains to the *predictive power* of their models. Predictive power is a pivotal function of a scientific model, because a model can be used to make and test predictions, even generate new predictions that can be tested against new data from the phenomena (Schwarz et al., 2009), solve intellectual problems, and test ideas (Tregust, Chittleborough, & Mamiala, 2004). Consequently, 'a model needs to have predictive power' (Etkina et al., 2006, p. 34), and this was an aspect that I looked for in teachers' models while examining their model formulation skill. In the projectile motion task, twelve teachers' models entailed predictive power (eight teachers' models had strong predictive power, and four teachers' models had limited predictive power), whereas in the volumetric expansion task only seven teachers paid attention to their model's predictive power (four teachers' models had strong predictive power, and three teachers' models had limited predictive power) (see Table 8 in the chapter of Findings for details). The distinction between a model's *strong* and *limited* predictive power was based on the range of predictions that can be tested according to the model's structure (e.g., the format and the syntax of its rules), and the number and the format of its variables (e.g., if a model did not entail all necessary variables to control the function and the behavior of the

phenomenon being represented, and/or its variables had a limited range in terms of the values that can be altered, then the models' predictive power was considered as *limited*).

In sum, the abovementioned discussion of the findings designate that there were differences between teachers' models in terms of their interpretive potential and predictive power. These differences were also confirmed by the statistical analysis that was performed for comparing teachers' model formulation skill in the two assessment tasks that evaluated their model formulation skill (see Table 24 in the Findings chapter for details). Thus, a critical question that emerges is as follows: *Why did teachers' models differ in terms of their interpretive potential and predictive power between the two assessment tasks, or alternatively, why did teachers' model formulation skill differ between the two assessment tasks?* The statistically significant differences that were revealed between the post-assessment tasks for the *model formulation skill*, in conjunction with the qualitative differences discussed above, might be attributed to either teachers' prior background knowledge and understandings of the phenomena they were asked to model, or to the degree of transfer of their model formulation skill in new content areas, or both. If teachers' prior background knowledge and understandings of the phenomena they were asked to model (e.g., projectile motion Vs volumetric expansion) is considered as the sole origin of this discrepancy, then the same significant differences would have been yielded when their pre-assessment performance was compared. Since no significant statistical differences were found between teachers' model formulation skill in the pre-assessment tasks, this assumption can be safely rejected. On the other hand, given the fact that the content of Phase 1 of the PDC was 1-D elastic collisions, within which teachers engaged in multiple cycles of model development and deployment of five different 1-D elastic collision phenomena, and recalling the two content areas of the model formulation skill assessment tasks, we might assume that the content of the PDC was more closely related to the projectile motion than the volumetric expansion content. As a result, teacher's possible knowledge improvement in the content of mechanics might have acted as a better scaffold for their effective transfer of the model formulation skill in a *near* content (e.g., the projective motion) than in a *far* content (e.g., the volumetric expansion). Even though in a different but related context, van Borkulo et al.'s, (2012) assertion, that reasoning with a model can be influenced by the availability of related domain knowledge and thus learners' ability to reason with a model may differ in a familiar versus an unfamiliar domain, can be used as a support to the assumption made above.

### 5.2.2. Identification of model components skill

Teachers' identification of model components skill appeared to have been enhanced after the end of Phase 1 of the PDC, as teachers significantly progressed from the identification of only *objects* and *variables* as the constituent components of a model, to a more elaborated cluster of identifications that encompassed not only objects and variables, but also *processes* and *interactions* among a model's constituent components. Although Justi and Gilbert (2003) define the entities of a model in a different way (e.g., they suggest objects, events, processes, and ideas as the entities of a model), the findings of the present study in relation to teachers' identification of model components skill contradict the findings of their study, since they ascertained that when teachers discuss the entities of a model, they identify *objects* more frequently than the *events*, the *processes*, and the *ideas*.

The framework that Louca, Zacharia, Michael, and Constantinou (2011) proposed for analyzing and evaluating student-constructed models of physical phenomena and monitoring the progress of these models resembles the classification scheme of models' components used in the present study. According to Louca et al. framework, a model is comprised of: (i) physical objects; (ii) physical entities; (iii) object behaviors; (iv) interactions among physical objects, physical entities, and object behavior(s); and (v) the accuracy of the phenomenon depiction. Physical objects and interactions among model constituent components are identical in their definition to the model components used in the present study, whereas *physical entities* and *object behaviors* correspond to *variables* and *processes* respectively.

Nonetheless, the importance of the development of this modeling skill has been highlighted by Hestenes (1995) who asserted that learners extract information from a model when they proceed at the stage of model analysis. Likewise, Stratford et al., (1998) stated that, at the stage of model synthesizing, students should ensure that the resulting model represents the various aspects of the phenomenon, and thus they need to apply this skill for inspecting their models. From my perspective, this skill is essential for two reasons: firstly, the learner that has already developed this skill is empowered with the ability to perform assessments as to whether her model has reached an adequate level that includes representations of the four major model components; secondly, after searching for any missing components to the model, the learner will re-visit the physical phenomenon in an attempt to collect new evidence to further refine her model.

### 5.2.3. Comparing and contrasting models of the same phenomenon skill

Given the fact that a particular phenomenon can be modeled in different ways according to the representation medium that is used to depict different aspects of the same reality (Snir et al., 2002), *comparing and contrasting models of the same phenomenon skill* is a fundamental aspect of learners' modeling ability, because understanding the existence of different models that relate to the same target, and thinking about the advantages and disadvantages of each alternative to represent, interpret, and predict a phenomenon under study, might in turn support learners to progress from "...a primarily descriptive use of models to a beginning recognition that models can serve as instantiations of rival hypotheses" (Penner et al., 1997, p. 126). Additionally, Oh and Oh (2010) suggest *evaluative modeling* as one of student-centered approach to using models. According to this approach, students should be given opportunities to compare and contrast alternative models addressing the same phenomenon, evaluate their merits and limitations, and select the most appropriate ones to explain the phenomenon. To decide whether a model is adequate, or whether one model is better or worse than another, the learners need to evaluate models utilizing standards or criteria of model goodness (Pluta, Chinn, & Duncan, 2011), models' feasibility to accurately represent and account for patterns in phenomena, and to predict new phenomena (Schwarz et al., 2009).

In the present study, both the qualitative and the quantitative analyses of teachers' responses in the two assessment tasks that evaluated their *comparing and contrasting models of the same phenomenon skill* indicate that, after Phase 1 of the PDC, the teachers developed this skill, as they appeared to be able to successfully compare and contrast four candidate models for identifying the most (or the least) appropriate one that best represents and explains a phenomenon under study. In supporting the selection of the best or worst model among the other alternatives, the majority of the teachers made use of three important criteria that pertain to their informed understandings of the nature and purpose of models. These criteria relate to a model's: (i) *representational comprehensiveness* (e.g., are the necessary parts of the phenomenon represented in a comprehensive manner within the model?); (ii) *interpretive potential* (e.g., does the model entail a mechanism that provides an interpretation for how the phenomenon functions?); and (iii) *predictive power* (e.g., does the model enable the formulation and testing of predictions for future behaviors of the phenomenon?).

Prior to the PDC, the performance of the teachers in the two tasks that were administered for evaluating their comparing and contrasting models of the same phenomenon skill was different. Specifically, the majority of teachers in the assessment task whose content was the electric circuits used only the criterion of *model's representational completeness* for identifying the best or worst model for representing and interpreting how and why a light bulb in a simple circuit is lit. On the contrary, the majority of teachers in the assessment task that was based on the content of substance dilution in water provided responses that entailed the model's *representational comprehensiveness* and *interpretive potential* as the criteria that were used during comparing the candidate models of substance dilution. These differences might be associated with either the *content* of the assessment task or teachers' *prior background knowledge* about the topic of the assessment tasks or the *format of the candidate models* in each assessment task or teachers' *level of acquisition of this modeling skill* prior to the PDC. The first and second assumptions (i.e., the differences can be attributed to the content of the assessment tasks and teachers' prior background knowledge) can be safely rejected, because if both were true, the content of the assessment tasks and their prior background knowledge would also affect teachers' performance on these assessment tasks, when administered after the PDC. The third and fourth assumptions (i.e., the format of the candidate models in each of the assessment tasks and teachers' level of acquisition of this modeling skill prior to the PDC) can possibly explain the differences in teachers' performance that were revealed, because even though in both assessment tasks the format of models that were used was the same (e.g., a graphical model, a verbal model, a computer-based model, and a model made with real materials), the best (or the worst) model in each assessment task was in different format. Specifically, in the electric circuits task the best model was the one in the verbal format, whereas in the substance dilution task the best model was the computer-based model. When the assessment tasks were administered at the beginning of the PDC, the majority of teachers chose the computer-based models in both assessment tasks as the models that would best represent and interpret the phenomenon under study, but they did not use the same criteria for supporting their responses. For instance, in the electric circuits task the teachers used only the criterion of representational complexity of the model, since this model did not entail a mechanism that explained how and why the light bulb is lit, whereas in the substance dilution task they used both model's representational complexity and interpretive potential. Consequently, if we assume that the teachers entered the PDC with already developed criteria for selecting a model among other candidate models that best describes and interprets a phenomenon under study, then it appears that the format of the available models that were provided for

comparison purposes might have constrained their ability to compare the models on the basis of these criteria. In other words, these findings indicate that the teachers, at the beginning of the PDC, considered the computer-based models as the ones that best represent a phenomenon, without studying the potential and the advantages of the rest of the models in representing, interpreting, and permitting the formulation and testing of predictions in a better way.

Pluta, Chinn, and Duncan (2011) were confronted with a similar experience as above, when analyzing the epistemic criteria for good models posed by middle-school students. In trying to interpret why students' responses appeared to have been associated with the specific models they evaluated in the orientating activity, they postulated that "...seventh-grade students have existing ideas or resources for evaluating epistemic artifacts, honed during non-epistemic evaluative activities [...] students may have general 'evaluative resources' developed through everyday activities such as judging favorite music, fiction, or choosing a best or favorite superstar soccer player. Students have few opportunities to engage with these ideas during epistemic practices such as choosing between alternate scientific models; the model evaluation task may have prepared students to restructure their existing evaluative resources around the epistemic aim of evaluating models (p. 506). To document their assertion, they draw on recent research (e.g., Engle, Nguyen, & Mendelson, 2011; Scherr & Hammer, 2009) that examined how different contexts, activities, and instructions may lead students to approach activities in different ways, and concluded that the orientating activity that the students engaged with might have appropriately reframed the criteria generation for them in such a way that enabled the use of the types of knowledge and norms which made a better fit with the task.

#### **5.2.4. Model evaluation and formulating ideas for improvement skill**

Model evaluation and formulating ideas for improvement skill pertains to a learner's ability to examine a given or an own created model on the basis of certain criteria, and suggesting improvements or revisions on the basis of model's deficiencies that have been identified. Model revision or improvement entails modifying parts of an existing model in a way that better describes the related phenomenon, or explains in a more sophisticated manner a given situation, or making additions to existing models by embedding a model in a larger model or adding more parts to it; e.g., addition of new physical objects, processes and/or entities that are part of the physical system studied (Louca, Zacharia, &



Constantinou, 2011). Learners who appear to be able to apply effectively the model formulation skill are likely to have developed epistemic knowledge with respect to the nature and scope of scientific models, because “understanding how to evaluate a model is clearly influenced by understanding why models are initially created and how they are used to develop knowledge” (Schwarz et al., 2009, p. 652).

In the present study, teachers’ model evaluation and formulating ideas for improvement skill has been significantly enhanced, as they shifted from using aesthetic criteria or a limited number of criteria for evaluating the models of the assessment tasks prior to the PDC, to the evaluation of models based on the identification of limitations of model’s *representational completeness*, *interpretive adequacy*, and *predictive power*. The levels that emerged from the phenomenographic analysis of teachers’ responses on the two assessment tasks, which were administered for evaluating this skill, varied mostly in the types of the representational components that were identified as missing from the given models. These representational components were similar to those extracted from the analysis of teachers’ responses within the context of evaluating their identification of model components skill, and pertain to objects, variables, processes, and interactions among model’s constituent components. Nevertheless, the most superior level that emerged and illuminates teachers’ development of model evaluation and formulating ideas for improvement skill shares a lot of commonalities with the highest level in Schwarz et al. (2009) learning progression for understanding models and changeable entities. This level is described as follows:

*“Level 4: Students consider changes in models to enhance the explanatory power prior to obtaining evidence supporting these changes. Model changes are considered to develop questions that can then be tested against evidence from the phenomena. Students evaluate competing models to consider combining aspects of models that can enhance the explanatory and predictive power”.* (p. 647)

Prior research revealed a variety of criteria that should be used when evaluating a model, some of which are congruent with the findings of the present study. For instance, Lehrer and Schauble (2006) and Windschitl, Thompson, and Braaten (2008) suggested that the evaluation of a model should be based on standards of usefulness, predictive power, or explanatory adequacy. In a more recent study, Pluta, Chinn, and Duncan (2011) reported that the middle-school students used criteria like accuracy, explanatory scope, parsimony, and communication, when evaluating the models they were provided with. While accuracy (accuracy resembles representational comprehensiveness of a model in the present study),

predictive adequacy, and explanatory power were the criteria that the participants in this study used for evaluating a model, no evidence of the criteria of usefulness and parsimony was found in teachers' model evaluations. The absence of these criteria within teachers' responses might be attributed to the format of the assessment tasks that were used to capture teachers' model evaluation and formulation of ideas for improvement skill. More specifically, in the assessment tasks that were used in the present study, the teachers were not explicitly prompted to propose the criteria that could be used for evaluating a scientific model; instead, they were provided with a flawed model and asked to state whether the model is consummate. In case their response was negative, they were prompted to state the information or aspects from the phenomenon that were omitted from the model. Consequently, teachers' statements were based mainly on the identification of the flaws that the presented models entailed, and not on the diversity of standards that are used for evaluating scientific models in general.

As it has already been stated, both the qualitative and quantitative findings revealed significant differences between teachers' level of acquisition of the evaluation of models and formulating ideas for improvement skill prior to and after Phase 1 of the PDC. However, the number of teachers who used all three epistemic criteria for evaluating the models of the assessment tasks (e.g., model's representational complexity, interpretive potential and predictive power) was relatively low. A closer examination of teachers' distribution along the levels that emerged designate that the less frequent criterion that was evident in teachers' model evaluations was the *predictive power*, since the rest of the criteria were used by the majority of teachers when evaluated the models from the assessment tasks. A similar finding was revealed in the study of Van Driel and Verloop (1999) who reported that while in-service teachers used various criteria for deciding what qualifies as a model, they rarely commented on the important role played by models in enabling the formulation and testing of predictions.

Given that predicting means to infer the future behavior of a system/physical phenomenon from a given state or to speculate the changes in behavior of a system/physical phenomenon as a consequence of possible changes in parameters (Van Borkulo, 2009), and that the purpose of revising models is to increase their explanatory and predictive power, taking into account additional evidence or aspects of phenomena (Schwarz, Reiser, Acher, Kenyon, & Fortus, 2012), one might assume that the majority of the teachers, at the end of Phase 1 of the PDC, did not combine models' predictive power with the rest of the

evaluative criteria that they developed during the PDC. On the other hand, the majority of the teachers appeared to have integrated this criterion in the epistemic aspects a scientific model should fulfill, when they were asked to reflect on the nature of models in other assessment tasks (see section 5.2.7 below). Accordingly, the format of the model evaluation assessment tasks can be used to explain the relatively low reference on models' predictive power, as during evaluating the models in the assessment tasks the teachers searched mainly for elements (e.g., objects, variables, processes, interactions) or functions (e.g., a mechanism that explains how the phenomenon functions) that were missing from the models, and not for "qualifications" that those models should fulfill (e.g., predictive power).

### **5.2.5. Model validation through comparison with phenomena of the same class skill**

Model validation through comparison with phenomena of the same class skill was the fifth skill that teachers appeared to have developed at the end of Phase 1 of the PDC. This skill pertains to a learner's capability to abstract a model from the prototypical phenomenon and apply it in a new situation, possibly in phenomena of the same class of the original phenomenon being studied (Halloun, 1996; Hestenes, 1992; 1995). The levels that emerged from the analysis of teachers' responses in the two assessment tasks that were designed and administered at the beginning and end of Phase 1 of the PDC indicate that teachers' development of this modeling skill progressed from "local" to "global" evaluation of the models provided in the assessment tasks. The term *local evaluation* is used to denote an uninformed view of model validation that emerges through evaluation of the model in relation to its fitness with the single phenomenon that it derived from, whereas *global evaluation* pertains to validating a model through decontextualizing it from its original context, transferring it in a range of related phenomena, and examining its applicability and robustness in situations other than those its development was based upon. For example, the lowest levels that emerged (see Levels 1 and 2 in Table 15, p.134) relate to validation of a model through evaluating if certain aspects of the phenomenon have been incorporated in the model in a correct manner, whereas the higher emerged levels (see Levels 3 and 4 in Table 15, p.134) concern the validation of a model through testing model fitness with new data, or through applying it in a total new case of a phenomenon and study if model is congruent with this new case.

Furthermore, it is important to state that the most superior level that emerged and designates teachers' development of the model validation skill is in accordance of the stance of Halloun (1996), who articulated model validation as a process that entails "(i) using a given model to describe, explain, and/or predict new physical situations pertaining to the system(s) in the problem; (ii) inferring implications for other referents of the model; (iii) extrapolating the current model to build new ones" (p. 1028).

### **5.2.6. Metacognitive knowledge about the modeling process**

Because modeling practice is a *nonlinear* and *iterative* approach to learning science content, within which learners are anticipated to take evidence-based roles for reshaping their own conceptual understandings of the science content (Schwarz et al., 2009), it is of pivotal importance to examine if learners who experience this kind of learning can simultaneously develop *metacognitive knowledge about the modeling process*. This type of knowledge might impact on the development of learners' epistemic awareness with respect to models, as they will come to understand that "models can be evaluated and refined through an iterative cycle of comparing their predictions with the real world and then adjusting them, thereby potentially yielding insights into the phenomenon being modeled" (NRC, 2012, p.57).

The findings of the present study demonstrate that teachers' active participation in the PDC as learners, and specifically, the multiple cycles of model development and deployment of 1-D elastic collision phenomena they followed, enabled them to shift from a minimalistic and linear view of the steps followed during modeling, to a conceptualization of the modeling process as a process that involves various cyclical and iterative steps. This is documented by the classification of the majority of teachers in most superior emerged level that entailed the following steps: (i) collecting information about the phenomenon (e.g., performing observations, identification of the objects, variables, processes and interactions of the phenomenon); (ii) selection of the best appropriate means for building the model; (iii) building a model based on the data collected; (iv) comparing the model and the real phenomenon or the model with other models; (v) evaluation of the model according to its representational completeness, explanatory potential and predictive power; (vi) improving the model, (vii) testing the validity of the model; (viii) repetition of the steps iv through vii. This rich reflection on the various steps that are followed during constructing and validating models highlights not only teachers' advancement of metacognitive knowledge about the modeling process, but also their understanding that models are constructed

through a series of iterative modeling cycles in which trial ways of thinking are tested and revised repeatedly (Lesh et al., 2003).

### 5.2.7. Meta-modeling knowledge with respect to the nature of models

Evidence from both qualitative and quantitative findings with respect to teachers' meta-modeling knowledge about the nature of models designates that the PDC had a significant impact on helping teachers develop sophisticated epistemic understandings about the nature of models. Specifically, in explaining why the drawing of "cell division" and the computer simulation of "color light vision", which were presented in the assessment tasks, could be considered as examples of scientific models, the majority of the teachers expressed that a scientific model should *describe, represent* and *explain* (e.g., entails a possible mechanism of how the phenomenon functions) a phenomenon under study, and can be used to *test predictions* about specific aspects of the phenomenon. This epistemic understanding is consistent with the definition of models reported elsewhere (Bamberger & Davis, 2011; Gilbert, Boulter, & Rutherford, 1998a; 1998b; Halloun, 1996; Halloun, 2004; Pluta, Chinn, & Duncan, 2011; Passmore & Stewart, 2002; Schwarz et al., 2009; Shen & Confrey, 2007), and is aligned with the primary goals of science which are the description, explanation and prediction of the natural world (Oh & Oh, 2010). In addition, given that teachers referred to *description* and *explanation* as distinct functions of models, this finding indicates that teachers came to distinguish between *how* (e.g., *descriptions* are answers to the ontological question of *what* exists) and *why* (e.g., *explanations* are answers to the causal question of *why* things happen) things exist or behave (Halloun, 2007; Oh & Oh, 2010).

Another finding that merits attention relates to teachers' meta-modeling knowledge with respect to the nature of models prior to the PDC. According to the findings presented in Table 19 and Table 20 (p. 144), the teachers entered the PDC with already developed epistemic awareness of models as *representations* of physical phenomena, as they used statements like "*This drawing or this computer-program represents ...*" to explain why the drawing of cell division or the simulation of color light vision are considered as scientific models. To interpret this finding, Oh and Oh (2010) declared that the term 'representation' is commonly used to explain what a model is. On the other hand, prior to the PDC, half of the teachers mentioned models' predictive power, and less than half of the teachers referred to the explanatory potential of models in their statements. These findings concur at some point with the findings yielded in the study of the Van Driel and Verloop (1999),

who reported that the teachers in their study stressed more frequently the explanatory function and the descriptive function of models, but contradicts with their finding that the predictive power of models was rarely mentioned by the participants of their study.

It is also important to state at this point that in reflecting about the nature of scientific models, one might make use of several other characteristics that point to the nature of models that were not suggested by the participating teachers of this study (e.g., models can represent non-visible and non-accessible processes and features; different models can have different advantages; models are representations that have limitations in what they represent about phenomena; models can be changed to reflect growing understanding of the phenomena, and so on). Although the criteria that were evident in teachers' responses are considered among the major criteria that define the nature of a model, the reference on other epistemic criteria was limited probably because of the format of the assessment tasks that were used to evaluate this aspect of teachers' meta-modeling knowledge. Specifically, the teachers were asked to explain whether the given representation in each of the assessment tasks could be a case a scientific model, and they used their meta-modeling knowledge to support their claims. Hence, if the format of the task was more open-ended (e.g., what is a scientific model?), the teachers might have elaborated on more epistemic criteria when responding in such a task.

#### **5.2.8. Meta-modeling knowledge with respect to the purpose or utility of models**

The second aspect of teachers' meta-modeling knowledge, *epistemic understanding of the purpose or utility of models*, was also found to be advanced as a result of their participation to the PDC. This is documented by the levels that emerged from the analysis of their responses that point to an increased sophistication in quantity and quality of epistemic awareness in relation to the purpose or utility of models, and the comparison of their distribution across these levels prior to and after the PDC. At the beginning of the PDC, the teachers considered models as tools that help in mimicking *reality* and for *information delivery*. The first purpose reflects a naive conception for the purpose of models, as it implies a "1:1" association of the model and the phenomenon it represents (Grosslight et al., 1991). The latter purpose that pertains to models as vehicles for information delivery can be considered among the many purposes that models play in science teaching and learning, but it is not one of the primary purposes for developing models in science. These

naive perceptions in relation to the purpose of models were revealed in previous studies by participants (teachers or students) who were not previously engaged in MCSI instructional settings (see for instance Schwarz & White, 2005; Van Driel & Verloop, 1999; Windshitl & Thompson, 2006).

Another purpose of models that was evident in the majority of the teachers' statements at the beginning of the PDC, concerns the purpose of models as *instructional aids*, a notion that is common among teachers who introduce ready-made models within their instruction to help their students gain insight to phenomena that are difficult to be approached through direct observations (Barab, Hay, Barnett, & Keating, 2000; Erduran, 2001; Snir, Smith, & Raz, 2003). Although this purpose was maintained in teachers' statements when completing the post-assessment tasks, the arguments used to explain this role of models changed to highlight the integration of models in science instruction through an *exploratory modeling* approach (Van Joolingen, 2004). Exploratory modeling, according to van Joolingen, refers to the case when students investigate a phenomenon through a model by changing parameters and observing the effects of these changes.

Besides improving their understanding of the role of models as instructional aids, and incorporating this role within their statements in the post-assessment task, the majority of the teachers expressed several other arguments that illuminate the development of their meta-modeling knowledge about the purpose or utility of models. These were as follows: models serve as: (i) *simulations* (e.g., the teachers mentioned that models can often substitute the setup of an experiment for investigating a phenomenon, or models facilitate the experimentation for the phenomenon being modeled, or models can be used for making additional observations or collecting data about a phenomenon that is not easily accessed); (ii) *vehicles for enhancing our understanding about a phenomenon* (e.g., the teachers mentioned that models mediate our understandings of how a phenomenon functions, or provide an explanation of a possible underlying mechanism of the phenomenon they represent, or help in interpreting a phenomenon); (iii) *communication tools* (e.g., a model serves as a communication tool through which its creator disseminates his ideas to the public); (iv) *external representations* (e.g., models enable the representation of a complex phenomenon, models make things "visible", and models help in decomposing a phenomenon into its constituent components); and (v) *platforms that enable the formulation and testing of predictions* (e.g., after studying a model, one can formulate a prediction for an aspect or a condition of the phenomenon that was not directly observed,

alter the value of a variable or change the conditions of a process that is executed within the model, and observe the results or the consequence of these changes to the overall behavior and function of the model).

Each of the aforementioned purposes that scientific models play in science teaching and learning, and in the discipline of science in general, have been highlighted in previous research. For instance, it has been claimed that models are created for the purposes of understanding, communicating, and/or generating predictions about the system or phenomena in question (e.g., Gilbert & Boulter, 2001; Harrison & Treagust, 2000). Also, Oh and Oh (2010) declared that “a scientific model as a thinking and communicative device serves the purposes of describing, explaining and predicting natural phenomena and communicating scientific ideas to others” (p.8). To underscore the communicative role of models, Pluta, Chinn, and Duncan (2011) purport that “a brilliant, empirically successful model that is presented in a way that other scientists cannot understand will not gain acceptance” (p.501). Also, to exemplify the role of models as simulations, Carmichael (2000) asserted that computer-based models offer opportunities to experimenting virtually in complex environments or idealized situations.

#### **5.2.8. Transferability of modeling ability**

Since the evaluation of teachers’ modeling ability, prior to and after the PDC, was accomplished in a variety of content areas that differed to the one experienced during the PDC (e.g., elastic collisions), the findings that were revealed from the analysis of their responses in the modeling ability assessment tasks indicate not only the development of their modeling ability, but also their capability to transfer all components of their modeling ability into new and unfamiliar contents. More specifically, the findings of the present thesis indicate that the teachers who engaged as *learners* in the strategically designed MCSI setting of the PDC developed modeling skills (e.g., model formulation, identification of model components, comparing and contrasting models of the same phenomenon, model evaluation and formulating ideas for improvements, model validation through comparison with phenomenon of the same class), metacognitive knowledge about the modeling process, and meta-modeling knowledge with respect to the nature and purpose or utility of scientific models, and succeeded on transferring all of these modeling performances across content areas. The PDC equipped teachers with skills and knowledge to construct, compare, evaluate and validate models that illuminate their evolved modeling



ability, not only in the content of the PDC, but also of mostly<sup>3</sup> *far transfer-in-situation* topics. Teachers are considered to have *far-transferred* the components of their modeling ability, because they were asked to apply their learning from situation A (e.g., 1-D elastic collision phenomena) to a different content in situation B (e.g., electric circuits). Bamberger and Davis (2011) define *transfer-in-situation* "...for challenges that occur with the same situation, when the connections between the two cases are clear to the learner by their context. The context for all of the problems is the same, and ... [the learner] use similar knowledge, skills or practices in order to solve the series problems. Transfer, in that case, is far from spontaneous, and encouraged by the context. Transfer-in-situation is a common tool in instruction. One important characteristic of transfer-in-situation is that there can be various degrees of how similar or different the situations are." (p. 6)

### **5.3. How do teachers' content knowledge and curricular knowledge about models and modeling change as a result of their participation in the PDC?**

For answering this research question, open coding techniques from grounded theory methodology were followed for analyzing the data obtained from multiple data sources to capture teachers' initial, evolved, and final CK and CuK about models and modeling. The findings that emerged were presented in Chapter 4 in two consecutive sections. The same line is followed in this Chapter for discussing the findings in an attempt: (i) to address how teachers' CK and CuK about models and modeling changed as a result of their participation in the PDC; (ii) to highlight how specific characteristics of the PDC influenced the changes in teachers' knowledge bases under discussion; and (iii) to inform the literature on teachers' CK and CuK about models and modeling through contrasting the findings of the present study with findings resulted from previous similar research attempts.

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<sup>3</sup> In discussing the findings in relation to the differences between teachers' model formulation skill in the post-assessment tasks (see page 260), it has been claimed that the differences in terms of teachers' models interpretive potential in the two different contents of the assessment tasks can be attributed to the proximity of the content of 1-D elastic collisions with the projectile motions. Thus, it has been explained that teachers performed better in the projectile motion assessment task, because of the near transfer of their model formulation skill. This was the single case that near transfer-in-situation could we used to explain the findings.

### 5.3.1. Teachers' CK about models

As it was stated in Chapter 4, to characterize teachers' overall CK about models, four major lenses were used. These lenses pertained to teachers: (i) definitions of scientific models; (ii) knowledge about the possible existence of two models to represent the same phenomenon; (iii) knowledge about models' feasibility to represent the "absolute reality"; and (iv) knowledge about model evaluation criteria. The findings that emerged in the context of the aforementioned lenses are discussed henceforward.

#### 5.3.1.1. Definitions of scientific models

The initial definitions of models provided by the participants were consistent with those of beginning and experienced science teachers in similar studies (Crawford & Cullin, 2004; Danusso, Testa, & Vicentini, 2010; DeJong & Van Driel, 2001; Grosslight et al., 1991; Smit & Finegold, 1995; Windshitl & Thompson, 2006). Even after extensive undergraduate coursework in science<sup>4</sup>, teachers struggled to provide a comprehensive definition of scientific models consistent with the epistemology of science, as the majority of them merely stated that models are representations of phenomena under study, while at the same time made statements that pointed to models as static forms, replicas of reality, and mental or analogical representations or confused scientific models with the term "teaching models" used in instructional settings. The fact that the term "representation" was central in almost every teacher attempt in defining what a scientific model is explained by Oh and Oh (2010) who declared that "...the term 'representation' is commonly used to explain what a model is" (p. 4).

Although teachers' definitions of scientific models at the beginning of the course were unsophisticated and not well articulated, they encompassed features that helped in uncovering their understandings of other aspects or functions of models, like the *purposes* that models play in science teaching or in science in general, the *elements* of that a model entails, and the *means* for developing models. For instance, in terms of the *purposes of models*, the teachers referred to models as: (i) means for enhancing our understanding of a phenomenon under study; (ii) instructional aids that facilitate students' learning during science teaching; (iii) platforms for interpreting our observations, (iv) tools for testing of predictions for the phenomenon being modeled; and (v) means for helping a less

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<sup>4</sup> The elementary school teachers held a specialization in science during their undergraduate studies, whereas the physics, the chemistry, and the biology teachers held a bachelor degree in physics, chemistry, and biology respectively.

knowledgeable person in understanding a particular phenomenon. The first two purposes, which were the ones reported most frequently, have been also identified in previous studies. Specifically, Crawford and Cullin (2004) considered their study participants' view that the model builder can use a model to understand the phenomenon as a positive outcome, because "this view of a model aligns with scientists' use of models — to understand and create an explanation of what happens in the world" (p. 1395). On the other hand, the view that models serve as instructional aids was not considered as a positive outcome according to Windshitl and Thompson (2006), because, as they explained, "teachers think of models as pedagogical aids but generally do not recognize the crucial role of models in thinking theoretically or guiding the generation of new knowledge" (p. 790).

As it has been stated above, whenever teachers were prompted to reflect on the question "What is a scientific model in natural sciences?", they made statements that embodied their epistemological understandings about the *nature of models*, *purpose of models*, *elements of models*, and *means for developing models*. This finding was also confirmed in the study of Justi and Gilbert (2003) who declared that the data analysis of teachers' statements on the 'notion of model' revealed seven aspects that illuminated their knowledge about "the *nature* of a model; the *use* to which it can be put; the *entities* of which it consists, its relative *uniqueness*; the *time* span over which is used; its status in respect of the making of *prediction*; and the basis of *accreditation* for its existence and use" (p. 1374). The discrepancy between the aspects that teachers' definitions of models entailed in the present study and those in the study of Justi and Gilbert can be explained by the stance made by Schwartz and Lederman (2005), who suggested that "conceptions of scientific models and their use in science may differ with context of scientific practice." (p. 14).

Teachers' definitions of scientific models were a major theme that was constantly monitored during their engagement with the modeling curriculum throughout Phase 1 of the PDC. In doing this, the teachers were systematically asked to provide their evolved definitions of scientific models within their reflective diaries, asynchronous discussions in BeEP, and their completed activity sheets. The analysis of their ongoing definitions of scientific models revealed that their personal engagement with the modeling-based curriculum activities during Phase 1 of the PDC enabled them to enrich their content knowledge about models, and at the same time to surpass their naïve conceptions about the nature of models that were expressed at the beginning of the PDC. To illustrate how

teachers' initial attributes of the nature of scientific models were enriched, revised, changed or maintained during Phase 1 of the PDC, a discussion of the emerged themes (see Table 27 in Chapter 4 for details) that were revealed from the analysis of their ongoing definitions of models during Phase 1 of the PDC is provided below.

*A model is defined by its: (i) representational completeness; (ii) interpretive potential; (iii) predictive power; and (iv) validity (applicability to phenomena of the same class).* As it was stated before, prior to the PDC teachers' definitions of scientific models were limited to entail only the aspect of *representation* as an attribute of scientific models. During Phase 1 of the PDC, the majority of teachers' definitions were expanded to include model's: (i) *interpretive potential*; (ii) *predictive power*; and (iii) *model's validity* in relation to its applicability to phenomena of the same class. The first two epistemological attributes (model's interpretive potential and predictive power) were introduced within the PDC after teachers finalized the creation of their first model and were asked to make references on the mechanism they chose to build their model upon, and also check if their model could be used for testing of predictions. These attributes, which became the criteria for evaluating their models at a later stage, were used by the teachers systematically both during model formulation and evaluation phases.

Model's validity was another evaluation criterion that was introduced, after teachers observed the second experiment of 1-D elastic collision and were asked to test if their previously built model that applied to the first case of collision could apply to the new case of collision. As a result, every time the teachers created a new model (because the previous one they built could not apply to a new phenomenon of the same class), they were spontaneously going back to the previous experiments of collisions and tested their new model's validity. This aspect of models, albeit not frequently expressed within all teachers' definitions of models at the post-CK questionnaire, designates improvements in their epistemic understanding status about the nature of models, as they came to appreciate that models can be considered as valid, if they are applicable not only to the phenomenon they originated from, but if they apply on a family of phenomena of the same class (Halloun, 1996; Hestenes, 1992).

In sum, teachers' improved understanding that representational completeness, interpretive potential, predictive power, and validity are at the core of the nature of scientific models is in line with the definition of scientific models reported elsewhere (Bamberger & Davis,

2011; Gilbert, Boulter, & Rutherford, 1998a; 1998b; Halloun, 1996; Halloun, 2004; Pluta, Chinn, & Duncan, 2011; Passmore & Stewart, 2002; Schwarz et al., 2009; Shen & Confrey, 2007).

*Models should provide an interpretation of how a phenomenon functions.* As it was stated above, interpretive potential is one of the epistemic criteria that distinguishes a scientific model from other forms of representations or artifacts that are created or used in science (Giere, 1999; Nersessian, 1999; Schauble et al., 1991; Schwarz et al., 2009). Given the significant changes evidenced in teachers' CK about this aspect of models, there is an emergent need to examine how specific learning experiences gained throughout the PDC impacted on the development of this epistemic understanding of the nature of scientific models.

During Phase 1 of the PDC, the teachers observed 5 different collision phenomena, one at a time, and were asked to either create a new model for each new case of collision or revise a previously built model to make it applicable to the new case of collision. For each of their models, the teachers were asked to reflect on the mechanism their model was built upon, and use the mechanism as the basis for interpreting the collision phenomenon they observed. By the end of Phase 1 of the PDC, the teachers came up with four models, each of which could apply to either a single case of a 1-D elastic collision phenomenon or to a range of 1-D elastic collision phenomena or to any case of 1-D elastic collision phenomena. The main difference between these four models lies in the type of mechanism the teachers developed and applied to their models. Starting from the "velocity transfer" model, that was created around the idea that during the collision of a moving cart with a stationary one, the moving cart "transfers" its velocity to the motionless cart, they moved on to create the "velocity reflect" model (e.g., two moving carts that approach each other with equal velocities "reflect" after they collide because the sign of their velocity is reversed), then they created the "velocity swap" model, that interprets the event of two colliding carts using the idea of "velocity swap" during their collision (e.g., the carts exchange their velocities during the collision), and finally they developed the "conservation of momentum" model, that takes into account the conservation of momentum of the carts as a closed system and calculates their velocities after the collision. Consequently, teachers' personal engagement in developing the abovementioned models and progressing from one model to the other, whenever their model failed to explain a new case of collision, enabled them to appreciate "interpretation" as a major aspect of the

nature of models. They came to understand, for instance, that when constructing a model one should seek to explain *how* and *why* a phenomenon occurred and not *what* and *when* happened (Bamberger & Davis, 2011; Clement, 1989; Penner et al., 1997).

Although references on the aspect of interpretation were limited in teachers' definitions of scientific models, those who used the term seemed to have understood it in a completely different manner. Specifically, this term was used as a support to the claim that one of the purposes of models should be the interpretation of our observations for a phenomenon we are studying. Reading "between the lines" when this term was introduced, and from the context of other statements made by the participants, "interpretation" for these teachers was determined as entailing the meaning of "confirmation of the validity of the observations collected from the real phenomenon". In other words, the teachers considered a model as a surrogate of a physical phenomenon that helps in confirming that the data or evidence derived from the physical phenomenon are in line with what the model produces as output, and not as a medium that illustrates an interpretation of how and why the phenomenon functions the way it does.

*Models are continually improved in light of new evidence.* Model revision entails making productive changes to a scientific model to improve how well the model meets its intended purposes and fulfills its evaluation criteria, usually in light of new evidence or ideas (Nelson & Davis, 2009; Schwarz et al. 2009). This characteristic appeared for the first time in the reflective diaries of almost all teachers after they have been working on the creation of their first models. Specifically, the teachers were asked to create a paper-and-pencil model to represent the collision experiment they observed, and after finishing their representation, they were prompted to revisit the real experiment, compare it with their model, and identify if important aspects of the real phenomenon were omitted in their initial model. Two major flaws, which were detected by all pairs of teachers, served as triggers for teachers to suggest possible improvements in their models. The first flaw related to the absence of a mechanism to account as an interpretation of how and why the two carts obtained the observed velocities after their collision, and the second flaw pertained to the static format of their model. Consequently, they proceeded on creating a model in SC and paid attention to address the previously identified flaws within their new model. This back and forth procedure (e.g., revisiting the real phenomenon after creating a model, and then back to the model for revisions and improvements) was followed in a systematic manner throughout the course, and teachers appeared highly motivated to

improve their models in the best possible manner, whenever new evidence from the real phenomenon was revealed. Further improvements of their models were also undertaken after receiving feedback from their peers through the use of the BeEP (e.g., teachers had to upload their final models in the BeEP and make comments, suggestions, and evaluations to their peers' models).

Consequently, these modeling practices that teachers followed during revising their models impacted on the development of their understanding of how, why, and when a scientific model needs further improvements to increase its interpretive adequacy. Thus, it can be claimed that the activity sequence designed and used for the purposes of this study enabled them to experience at first hand that the revision of a model is navigated by the empirical data obtained from the phenomenon under study, and at the same time the revised model acts as a generator for new hypotheses with respect to the phenomenon, thereby inducing new observations or experiments (Giere 1991; Van Driel & Van Der Valk, 2007).

*Elegance is important; simpler models may explain better than complex ones Vs simpler models may be understood better by learners.* The criterion of “elegance” of models, in terms of their structure and format complexity, was frequently used by the participants during evaluating their models, but the arguments for justifying this assertion differed among teachers' statements. For instance, there was a cluster of teachers who explained that their model should be elegant, because simpler models may explain a phenomenon in a better way than complex ones, whereas another group of teachers chose to make their models elegant enough to help the user of their model to understand the phenomenon being represented in a better way. The first point of view might associate with the teachers who experienced difficulties during creating their models, because they tended to think of and, thus, to create complex rules to control the behavior of the carts in their models. They also showed preference in using the “scientifically established knowledge” (this issue is discussed in detail in a later emerged theme) as the mechanism to explain why the carts after their collision exhibit the specific velocities, and thus their work during creating their model was becoming increasingly complex and exhausting. A similar episode was described by Hogan and Thomas (2001) who evidenced a pair of students willing to represent all of the real-world complexities they could think of during building a model of a pizza delivery system. This over-demanding task that students focused on representing what was already known instead of characterizing it “often lead students to become technically overwhelmed with trying to make the model function, so it was ultimately a

less successful approach than settling for simpler representations” (Hogan & Thomas, 2001, p. 340).

The teachers who experienced the abovementioned difficulties finally resolved the issues they struggled with, after they asked for help and guidance from the instructors, who helped them to leave aside their physics background knowledge, and prompted them to seek for a simpler mechanism that would explain the phenomenon they were trying to model, and at the same time it would be consistent with their observations. Consequently, these teachers came to understand that elegance as a feature of a scientific model is important, because simpler models, in terms of their complexity in their representational and interpretive status, may explain in a better way a phenomenon than complex ones. The same notion was pointed out by some of the participating teachers in the study of Windshitl and Thompson (2006).

The second point of view, *models should be elegant enough in order to be understood in better way by their users*, might have derived from teachers who viewed models as the final products that would be used and manipulated at a later stage by the model users. In other words, the teachers who used this argument to support the idea of model’s elegance considered models as *simulation-like* tools that are used in science teaching for the study of complex phenomena or the testing of predictions, but without allowing the user to change anything from the model that “runs” behind the simulation and controls its behavior. Their view might also imply that a model serves as a way for a more knowledgeable person to help a less knowledgeable person understand a phenomenon by looking or using a model s/he created, a standpoint that was also expressed by pre-service teachers in the study of Windshitl and Thompson (2006).

*A model should be consistent with the existing scientifically acceptable knowledge for the phenomenon it represents Vs A model might be created around an idea that even though is not consistent with the scientifically established knowledge, it interprets the phenomenon in a satisfactory level.* As it was stated in the previous sub-section, at the beginning of the PDC the teachers showed a strong preference to implement within their models their background knowledge about elastic collisions. Specifically, while they were trying to figure out a mechanism to control the behavior of the carts after they collide in the first experiment they observed (e.g., a moving cart hits on a stationary one, and after collision the moving cart remains motionless while the other one acquires an equal velocity as the



other cart, and moves away), they insisted on using the conservation of momentum law, because, according to their own words, they knew that during 1-D elastic collisions the momentum of the carts is conserved. Consequently, their previous knowledge, which was in line with the established knowledge found in physics books, “framed” their efforts to think of an alternative and more simplistic way to interpret the phenomenon they were studying. It can be also assumed that teachers’ persistence in making their model concur or replicate the existing scientific knowledge of the phenomenon might have its roots in an unformed view, also expressed in another study with prospective teachers, that “scientific models are final form devices, used to communicate or explain a concept that is already understood” (Crawford & Cullin, 2004, p. 1393).

Later on, when they encountered several difficulties in their effort to translate the conservation of momentum law into operational rules in SC, they decided to abandon their original plan, and the instructors prompted them to act like they do not know the physics behind the phenomenon under study (act in a similar way as their students would do), “think out of the box”, and invent a mechanism to interpret their data. It was at that time that the teachers decided to change their approach and suggested the idea of “velocity transfer” as an alternative mechanism for the interpretation of the collision phenomenon under study. Hence, the statement made by the majority of participants that a “*model might be created around an idea that even though is not consistent with the scientifically established knowledge, it interprets the phenomenon at a satisfactory level*” came up after this specific learning experience. This expressed view designates that teachers progressed from the naive conception of models as final form devices that are created or used for confirming previously established knowledge (Crawford & Cullin, 2004) to a sophisticated understanding of models as explanatory tools that help in thinking theoretically or guiding the generation of new knowledge (Windshittl & Thompson, 2006).

*Purposes of models.* As far as the *purposes of models* are concerned, the teachers expressed several purposes of models that, even though they are similar to those articulated within their responses in the CK pre-test, the arguments used for explaining their assertions were supported by evidence from their personal engagement with models and modeling during Phase 1 of the PDC. Specifically, the teachers appreciated the role of *models as tools for enhancing our conceptual understanding about phenomena we are studying*, as they stated that during model building they firstly had to “decompose” the phenomenon in its constituent components (e.g., objects, variables, processes), then “synthesizing” its parts

for making the model functional, and using it at the end for formulating and testing of predictions about similar cases of collision phenomena. Hence, the abovementioned empirical process they followed during modeling the 1-D elastic collision phenomena helped them in improving their understanding about the phenomenon they were studying. Teachers' appreciation of models as tools that facilitate their understanding for aspects of the phenomena they are studying has also been underscored by Schwarz et al. (2009), who advocate that "models can be used to develop new understandings, by predicting new aspects of phenomena" (p. 636).

Additionally, the teachers reflected on the role of *models as platforms through which the formulation and testing of predictions about the phenomenon represented by the model is enabled*, and made several references from their experiences during the course to support their claims. For instance, the teachers stated that after revising, refining and validating their models, these could be used in a later phase as substitutes of the phenomenon they were studying for formulating and testing of predictions. This finding is promising, as evidence from previous research (e.g., De Jong & Van Driel, 2001) indicates teachers who experienced modeling-based instruction within specially designed PDC failed to develop pronounced CK about models with respect to models' feasibility to make and test predictions.

Finally, the use of models as *vehicles for communication purposes between a more knowledgeable person and a less knowledgeable person* was also one of the purposes that emerged from teachers' statements. Prior to the PDC, the teachers merely stated that the role of models is to help someone to understand a phenomenon under study in a better way. During the course, they elaborated on this idea by using their own constructed models (for which they felt confident and satisfied for their achievement) as examples through which they could help someone (e.g., their students) who did not have the chance to observe the real experiment to understand how the phenomenon functions through studying their model. A very similar view has also been reported in the pre-module questionnaire by the participants in Crawford's and Cullin's (2004) study, although in the post-module questionnaire the emphasis shifted from the view that a model is used to help someone to understand a system or a phenomenon to the view that the model builder (himself/herself) can use a model to understand the phenomenon.

*Elements of a model.* Apart from the nature and purpose of models, teachers' definitions of scientific models embodied references that relate to the elements of models. Prior to the PDC, there was a scarcity of references on the elements of models. Specifically, there was only a single reference on the *relationships* between a model's components, and another single reference on the *processes* from the phenomenon as the elements of a model. On the contrary, during the PDC almost every teacher stated that a model encompasses *objects, variables, processes, and interactions among its constituent components*. Some others referred on the *mechanism* that explains how the phenomenon functions, as one of the elements of a scientific model, and a few others reported that a model entails *only* the aspects of the phenomenon that are necessary for *testing a theory*. Teachers' CK about the elements of scientific models was scaffolded through several curriculum activities they were engaged with during Phase 1 of the PDC. For instance, after the creation of their first model, they were asked to identify the components of their model and specify the broad categories that each component falls into. Next, they were introduced through the curriculum that a model consists of objects, variables, processes, and interactions among the three components, and were asked to find examples of components from their model. This type of activity was followed systematically after the completion of a new model. The teachers also spontaneously applied this new knowledge, whenever they were evaluating their peers' models (e.g., their first concern when they were evaluating a model was to study if the model encompassed all four types of components). This informed understanding of the elements that relate to model's representational complexity is in line with the viewpoint of Danusso et al. (2010) who purported that "a scientific model is a representation of a real or conjectured system, consisting in a set of objects with its outstanding properties listed, and a set of law statements that declare the behaviours of these objects" (p. 873).

Although there was no reference on the underlying mechanism of a model as another component of a model through the curriculum, the teachers added themselves the mechanism of a model as a fifth element that a model should entail. This might be attributed to the fact that throughout the implemented curriculum of Phase 1 of the PDC, the teachers were repeatedly prompted to reflect on the mechanism they chose to build around each of their models in order to appreciate the importance of model's interpretive potential as one of the key aspects a scientific model should entail. As a result, teachers' knowledge about the nature of models, in relation to the interpretive potential that a model should satisfy, was translated as knowledge that adds up to the elements of a model.

Lastly, a few participants indicated that the elements a model should entail should be those that are necessary for testing a theory. Although the reference on the types of model elements appears somehow vague as it does not specify what these elements should be, it reveals, however, teachers' association of *model's elegance* described in a previous subsection with the *predictive power* of models. It also highlights the connection between both these aspects of nature of models with the purpose of models that pertains to the use of models as tools for interpreting a phenomenon. Nevertheless, this view is congruent with the stance of Schwarz and White (2005) who professed that "...models are useful for envisioning or testing a theory and for deriving consequences that may be useful for solving problems" (p.172).

Overall, the emerged themes that were revealed from the analysis of teachers' definitions for scientific models during Phase 1 of the PDC indicate significant changes in their CK about models. This claim is also supported from the findings that came out from the analysis of teachers' definitions of scientific models in the CK test that was administered after the end of Phase 1 of the PDC, that point to a significant transition of teachers to themes that illuminate their informed understandings of the nature, purpose, and elements of scientific models, whereas the themes that point to uninformed views of the nature of models and were evidenced in their initial definitions of scientific models were eliminated after Phase 1 of the PDC.

#### ***5.3.1.2. Knowledge about the possible existence of two models to represent the same phenomenon***

A second lens through which teachers' CK about models was studied pertains to their appreciation of whether a phenomenon could be represented by two different models. This issue was examined by previous research through the use of questionnaires or interviews (e.g., Grosslight et al., 1991; Van Driel & Verloop, 1999), and was considered as an essential aspect to examine an individual's CK about the nature of models. It pertains to the conceptualization of the idea that several consensus models may co-exist with respect to the same target; "depending on the specific context and purpose of the research, different choices may be made, resulting in the development or selection of different models" (Van Driel & Van Der Valk, 2007, p. 323).

The findings that emerged in relation to this aspect of teachers' CK about models indicate a significant shift of the majority of teachers from poor or naive argumentation in explaining why the coexistence of two models that represent the same phenomenon could be feasible, to more elaborated and informed justifications that were used to support their claims. While at the beginning of the PDC the most predominant argument, which was expressed by less than half of the participants, related to the claim that two models might differ in relation to the representational medium used for their creation, at the end of Phase 1 of the PDC although the prevalence of this argument was increased, a more pronounced argument was expressed by  $\frac{3}{4}$  of the participants. This argument was based on the idea that the difference between the coexistence of two models that relate to the same target lies on the "personal theory" the creator of each model used for their development. The teachers who used this argument designated that, given the creator of a model develops a personal theory from the data collected that pertains to the way she/he understands or interprets the way the phenomenon functions, then two individuals who interpret a phenomenon in totally different ways might end up with two models that differ in their causal or explanatory mechanisms. This sophisticated understanding might have been developed as a result of the debate carried out in the BeEP, when the teachers were prompted to pose their view on whether it was feasible for two models to represent and explain the same phenomenon in different ways. At the beginning of the debate, the statements that were made focused on differences between the aspect of representation between the two models. As more teachers contributed to the discussion, the main focus of the debate changed to the interpretive potential of each model, and specifically, there were teachers who insisted that two models might differ because the creator of each model might have interpreted in a different way the same phenomenon they were studying. Consequently, the teachers came to understand that two or more rival models may coexist, because there are multiple ways of explaining or conceptualizing the same thing in science (Grosslight et al., 1991). To document the validity of this argument, Oh and Oh (2010) explained that "...since a model represents a target in a special way depending on the kind of problem or the intention of the modeller, different models can be constituted to represent different aspects of the same system" (p. 9). Also, this perspective was characterized as a "constructivist orientation" by Van Driel and Verloop (1999), when noticed that the participants in their study declared that due to the model creator interest or theoretical point of view, different models can be created for the same target.

Additionally, the prevalence of the argument that pertains to the idea that two models might differ with respect to the modeling medium used for their development was also increased at the end of Phase 1 of the PDC, whereas the prevalence of the argument that two models might differ with respect to the aspect of the phenomenon they represent remained the same. The first argument (e.g., two models might differ with respect to the modeling medium used for their development) was frequently found within teachers' reflective diaries, when they were prompted to compare and contrast their paper-and-pencil models with the models created in SC. They also appeared to elaborate more this issue, after they were introduced to four different representations that were used to illustrate how the same 1-D elastic collision phenomenon could be represented with the use of different means of modeling (e.g., a mathematical formula illustrating the relationship between the initial and final momentum of the closed system of the carts, a graph showing the velocity and momentum of each cart prior to and after the collision, a verbal statement that entailed the description of the momentum conservation law, and a computer-based model illustrating the event of the elastic collision of the two carts). Consequently, the increase of the prevalence of this argument might be attributed to teachers' learning experiences gained during Phase 1 of the PDC. It is important to state that this argument also points to an informed understanding of the "multiplicity" (e.g., different models can be constructed for the same target) as a characteristic of scientific models, as it has been claimed that semiotic resources, including linguistic entities, pictures, diagrams, graphs, concrete materials, animations, actions, gestures and their combinations, can be used for building scientific models (Boulter & Buckley, 2000; Gilbert, 2008; Izquierdo-Aymerich & Aduriz-Bravo, 2003).

Lastly, the argument that two models might differ with respect to the aspect of the phenomenon they represent is also considered as an additional perspective that can be used to explain the co-existence of rival models to represent the same phenomenon, because, as Oh and Oh (2010) put it, "...the fact that a model only represents selected features of a target entails that a model always has limitations and so various models are needed to provide a full-fledged explanation of a real-world system" (p. 9).

#### ***5.3.1.3. Knowledge about models' feasibility to represent the "absolute reality"***

A third aspect of teachers' CK about models concerned their understandings of whether models should represent the "absolute reality". Prior to Phase 1 of the PDC, the teachers held several misconceptions about the nature, purpose or utility of models and these were

revealed within their responses to the question “Do models represent the absolute reality?” Specifically, the statement that was most frequently found within teachers’ responses to the abovementioned question pertains to the scientifically incorrect idea that *models should represent the absolute reality, but this is not feasible because the phenomena are too complex to be modeled in such a detailed way*. This idea, which has its roots in logical positivism (Grandy & Duschl, 2007; Van Driel & Verloop, 1999), implies that the purpose or role of models should be the replication of a phenomenon under study in such a way that all visual details of the phenomenon should be retained by the model. In addition, even though the rest of the themes that emerged from the analysis of teachers’ responses entailed a disagreement about models’ feasibility to represent the absolute reality, the explanations provided to support this statement, in some cases, further reinforce the notion that models serve as replicas of physical phenomena (Grosslight et al., 1991). For instance, the theme that “*a model cannot represent the absolute reality, because the creator of the model ignored major aspects of the phenomenon or decided to encompass within the model only a few aspects of the corresponding phenomenon*”, or the theme that “*a model cannot represent the absolute reality, because there could be consistencies and inconsistencies between the model and the phenomenon it represents*”, or even the theme that “*a model cannot represent the absolute reality, because it is constrained by the modeling medium used for modeling the corresponding phenomenon*”, might entail a hidden assumption that models are created with an attempt to substitute the real phenomena, and thus they should present a 1:1 relationship with the phenomenon they represent.

The abovementioned uninformed views of teachers’ understanding of the relationship between a model and reality contradict the assertion of Smith, Maclin, Houghton, and Hennessey (2000), that “...beliefs in absolute truth are typical for high school students, radical relativist views are common during the college years, and more sophisticated constructivist views are typical only among advanced graduate students, especially in the social sciences” (p. 354). This contradiction is further supported by the identification of similar views among teachers in other similar studies. For example, Van Driel and Verloop (1999) reported that a minority of the teachers in their study stated that a model should always be as close to reality as possible. In contrast, Windshittl and Thompson (2006) conveyed that “only a few participants stated unambiguously that a model is a human construct that helps us understand a world in which reality cannot be isomorphically mapped onto such models” (p. 817).

During the PDC, and after teachers have gained substantial experiences with modeling several 1-D elastic collision phenomena, the issue of models' correspondence with absolute reality was revisited through a question in one of their reflective diaries. The analysis of responses provided for this issue (see Table 32 in Chapter 4 for details) designate that even after extensive coursework in the field of modeling some teachers maintained their initial naive views, whereas some others appeared to have progressed to more sophisticated and epistemologically informed understandings concerning models relation with the target they represent. As the findings indicate, the teachers were split into three groups according to their views about models' feasibility to represent the absolute reality. The first group pertains to the teachers who expressed the notion that models *should* represent the absolute reality, the second group pertains to the teachers who claimed that models *cannot* represent the absolute reality because this is not feasible, and the third group pertains to the teachers who reported that models *should not* represent the absolute reality. The last cluster of teachers used the argument "*a model should not represent the absolute reality because if this was the case, then the whole focus would be on the detailed design of the model and the fundamental objective of modeling, which is the interpretation and explanation of a phenomenon, would be ignored*" to explain their reasoning, which indicates the development of epistemic awareness with respect to the models and modeling. Specifically, these teachers appeared to have appreciated that a model is an abstraction of the phenomenon being studied and not a literal representation, and thus the model entails a mechanism that its creator conceived for interpreting/explaining the phenomenon (Schwarz et al., 2009).

The productive discussion around the topic of discussion in the BeEP (see Figure 15 in Chapter 4 for details) that prompted teachers to argue in favor or against between two contrasting views originated from their own reflective diaries, appeared to have a great impact on helping some teachers overcome specific naive conceptions or epistemic difficulties about the degree of relevance between a model and its target, whereas for some other teachers the discussion that was carried out enabled them to unfold some of their "well-hidden" uninformed understandings about the issue under discussion (see for example Teacher's #4 and Teacher's #20 statements and the elaboration on their statements in page 163). In addition, for some other teachers who have developed informed understandings about models' relevance with absolute reality, the topic of discussion pushed them to uncover important elements of their epistemic awareness with respect to the nature of models and the nature of science in general. For instance, these teachers



reflected on the tentative nature of theories (Lederman & O'Malley, 1990), and on approximation and idealization (Matthews, 2004; Portides, 2007) as two elements that are inherent in scientific theorizing and affect the process of model construction.

Nevertheless, while the comparison of the pre- and post- CK test findings indicate significant changes in teachers' understandings of the relationship between a model and its target, the prevalence of the most sophisticated view that emerged indicate that only half of the participants succeeded on developing this view. This view pertains to the agreement that models cannot represent the absolute reality, because since a lot of aspects of a phenomenon are "hidden" or not easily observable, models are human constructs that entail only their creator's subjective interpretation for how a phenomenon functions. Additionally, another view that was extracted by almost half of the participants' responses in the CK post-test refers to the fact that since models represent only a selected set of aspects from the phenomenon they relate with, then it is not feasible for a model to represent a phenomenon as a whole. The later view, albeit consistent with the nature of models, appears somehow vague, because the participants who expressed this view did not elaborate more on whether the external visual appearance of the phenomenon, as is perceived through the sensors, is maintained or not during constructing the model, or if the model is a construct through which individuals attempt to interpret a phenomenon through its representation. These moderate findings concur with the findings emerged in the study of Windshittl and Thompson (2006) whose declaration of the findings was particularly revealing and is listed as such below:

*"What was difficult to change was participants' beliefs that models represent an objective reality. This presented a dilemma in analyzing their understandings of models. Most participants referred to models being imperfect representations of the "real thing." It would be logical to assume that this indicated a belief in objective reality. From the context of their responses, however, it seemed that the "real thing" referred not to an objective reality but to humans' experiences of reality. This ontological dilemma notwithstanding, among participants who indicated a belief in an objective truth when explaining natural phenomena, the instruction over two quarters did little to change this belief" (p. 821).*

#### **5.3.1.4. Knowledge about model evaluation criteria**

At the beginning of the course the majority of teachers' CK about the criteria that are used for evaluating a scientific model was limited, although they posed several criteria for

evaluating a scientific model. These criteria revealed the perspective from which they viewed the role of models, and thus the evaluation criteria they proposed derived from that perspective. For instance, criteria like *a model should facilitate conceptual understanding for the phenomenon it represents* or *models' appropriateness to be used in science teaching* or *models' usability by students* point to a teacher-oriented perspective, since the models are destined for use as instructional aids within science instruction, and thus models' evaluation departs from pedagogical objectives. Moreover, the criterion *model proximity to the phenomenon it represents* (e.g., evaluation of the degree of resemblance between the model and the phenomenon) indicate a naive conception of models as replicas of real phenomena, a view that has been extensively described in previous sections of teachers' CK about models. On the other hand, criteria like models' *interpretive power* or model's *representational completeness* or models' *predictive power* reveal an epistemic-oriented perspective through which models are considered as representations that are created to facilitate our interpretations for phenomena we are interested in, and we can use them for the formulation and testing of predictions. The last cluster of criteria, albeit not expected, was suggested only by almost  $\frac{1}{4}$  of the participants. Nevertheless, the three clusters of criteria that were revealed and point to teachers' CK about the purposes of scientific models confirm the standpoint made by Schwarz et al. (2009), that "understanding how to evaluate a model is clearly influenced by understanding why models are initially created and how they are used to develop knowledge" (Schwarz et al., 2009, p. 652).

During the course, the teachers never received explicit information about the criteria used for evaluating scientific models. It was expected that their engagement with the modeling activities they had been working with during Phase 1 of the PDC would help them develop by themselves the major criteria that are used for evaluating their models. Initially, the teachers used aesthetic and technical oriented criteria for evaluating their own created models they shared with their peers. In a subsequent session, they were prompted to answer whether their model: (i) represented all major components of the collision experiment you observed; (ii) encompassed an interpretation of how the specific collision experiment you observe functions; and (iii) enabled the formulation and testing of predictions about the collision experiment it represents. Even though these questions were not explicitly stated as the aspects one should look into while evaluating a scientific model, evidence from teachers' evaluations of their peers' models indicate that teachers shifted from the aesthetic criteria and technical-related judgments to models' *representational*

*complexity, interpretive potential, and predictive power* when evaluating their peers' models. Likewise, evidence from their reflective diaries indicates that they developed more sophisticated evaluation criteria for assessing their models towards to the end of Phase 1 of the PDC. These findings, in conjunction with the findings revealed from the analysis of their responses in the post-CK test about the criteria a model's evaluation is based on, designate that the learning activities that they were engaged with during Phase 1 of the PDC (e.g., modeling curriculum, reflective journals, asynchronous discussion in BeEP, and peer-assessment of their models) impacted on the development of teachers' CK about the criteria used for evaluating scientific models. In addition, a new criterion that was mentioned by half of the teachers in the post-CK test and relates to *model validity in relation to its applicability to phenomena of the same class* was revealed in teachers' responses after the PDC.

In sum, teachers' learning gains with respect to the criteria that should be used for evaluating scientific models concur with the criteria that were explicitly introduced in other MCSI instructional settings and expected from students to use during evaluating their own or given models (e.g., Cartier, 2000). In addition, the findings that emerged are more encouraging to those obtained in the study of Van Driel and Verloop (1999). In their study, they found that although in-service teachers used various criteria for deciding what qualifies as a model, they rarely commented on the important role played by models in enabling the formulation and testing of predictions. Contrary to this finding, eighteen out of the twenty participants in the present study made reference on model's predictive power as a major criterion that a scientific model should fulfill.

### **5.3.2. Teachers' CK about modeling**

While previous research gave substantial priority to examining teachers' definitions of scientific models in terms of their nature, purpose, and other epistemic features (e.g., Crawford & Cullin, 2004; Danusso et al., 2010; Justi & Gilbert, 2002a; 2002b; Van Driel & Verloop, 1999), none of the published reports, to my knowledge, attempted to examine teachers' definitions of scientific modeling in terms of the steps and the processes followed for the development and deployment of natural phenomena or systems. Put differently, it was considered as equivalently important to examine if teachers' engagement with the various modeling activities that the PDC entailed would enable them to develop an understanding of modeling as a process through which "models can be evaluated and

refined through an iterative cycle of comparing their predictions with the real world and then adjusting them, thereby potentially yielding insights into the phenomenon being modeled” (NRC, 2012, p.57).

Consequently, the present study aimed to narrow this gap by examining teachers’ CK about the process of scientific modeling through two data sources. The first data source concerns the CK test, which entailed a question through which the teachers were asked to provide their definitions of scientific modeling, and also a second question that prompted teachers to state whether *modeling is a scientific enterprise, a teaching approach, or an ability that is developed during learners engagement with modeling activities*, and explain the reasoning behind their response. The second data source pertains to the reflective diaries that teachers’ completed after every session of Phase 1 of the PDC and encompassed a set of questions in a systematic way that sought to capture their evolved CK about modeling after each session. The format of these questions was as follows: “*What did you learn during this session about modeling? Did you learn something new? Explain. What do you expect to learn about modeling in the next sessions?*”

Prior to Phase 1 of the PDC, teachers’ CK for scientific modeling was very limited, as their definitions for scientific modeling were poor and varied dramatically. For instance, less than half of the teachers reported that *modeling pertains to the representation of a phenomenon through a computer or other means*, whereas five teachers referred to *modeling as the process for creating a model that helps in studying a phenomenon*. Although the teachers who expressed the latter view referred to modeling as a *process*, they failed in uncovering the steps that are followed during the process of modeling. This view highlights their conceptualization of modeling as a pedagogical aid (Crawford & Cullin, 2004; Windshittl & Thompson, 2006), a view that has also being expressed when teachers were asked to provide definitions for scientific models or to suggest the purposes of models. In addition, five teachers’ definitions of scientific modeling encompassed naïve conceptions about modeling (e.g., “*Modeling is a process for presenting several themes through images and concrete objects*”). On the other hand, only two teachers provided scientifically informed definitions for scientific modeling; one declared that “*Modeling is a process that is followed for creating a model for a phenomenon that helps in understanding and interpreting the phenomenon under study*”, and the other one stated the same as the previous one, and also added the notion that *the model that is created during modeling can be used for the formulation and testing of predictions*. These teachers also

reported that modeling involves several stages (e.g., *performing observations, data collection, formulating predictions or hypotheses, representation of the phenomenon, revision or improvement of the model*), and also acknowledged modeling as both a *process of learning* and a *teaching approach*.

Teachers' reflections on the modeling process, in conjunction with their evolved definitions for scientific modeling elicited from their reflective journals, served as rich data sources for monitoring their evolved understandings of scientific modeling, and also for examining how their CK about modeling was shaped throughout the PDC. The several themes that emerged from the analysis of their ongoing understandings about the nature and purpose of scientific modeling are discussed below.

After the beginning of the PDC, some teachers appeared to have associated modeling with the software used for creating their models. The notion that scientific modeling pertains to the work undertaken during programming in SC was more frequent in the first reflective diary of teachers, and can be attributed to their newly experiences gained while working with the interface of the modeling software. Moreover, because their work with SC lasted longer than the completion of the activity sheets that preceded the creation of their models in SC, their association of modeling with the technical work they had been doing in SC (e.g., creating objects and variables, formulating rules, debugging rules, etc) also explains this kind of association. It is also important to state that this view was suggested mostly by the teachers who prior to the PDC expressed uniformed understandings about the nature and purpose of scientific modeling.

In a similar way, some other teachers reflected on modeling as a complex procedure, and in explaining the rationale behind their assertion, they made references on the difficulties experienced during deciding the format and syntax of the rules that needed to create in modeling the collision experiments they observed, also on the obstacles they encountered during debugging the rules that controlled the behavior of their models. Again, this view that does not entail any references on the complex and multiple steps followed during modeling a phenomenon, as the term "complexity" was associated with the difficulties experienced during working with the modeling software, points out that the first sessions of the PDC did not enable teachers to move beyond the technicalities encountered during the model formulation stage and reflect on the various interconnected stages that scientific modeling entails.

Teachers' CK about the modeling process appeared to have been advanced from the poor understandings described above to a more elaborated view of modeling as an iterative and cyclical process that involves various interconnected stages, each of which is fundamental for the development and validation of scientific models. Specifically, after the completion of the second modeling cycle that entailed several crucial steps like: (i) testing the validity of the second model by applying it to the first collision experiment; (ii) identification of model's failure to apply to a phenomenon of the same class; (iii) formulation of a new model to apply to both phenomena of the same class; (iv) evaluation-revision-evaluation of the new emerged model; (v) application of the emerged model in a new phenomenon of the same class, the teachers made references on these steps during describing the modeling process in their reflective journals. More importantly, in describing the steps followed for creating and validating their models, the majority of the teachers referred explicitly to the iterative and cyclical nature of the modeling process, and at the same time they seemed to have appreciated the importance of each step for the development and validation of their models.

Another important outcome that emerged from the analysis of teachers' ongoing definitions for scientific modeling relates to their appreciation of modeling as a means through which their conceptual understanding in the context of 1-D elastic collisions was enhanced. Although the following extract from a teacher's reflective diary has already been used as a representative example in presenting the findings in Chapter 4, it is noteworthy to reiterate it here, because it portrays in a very vivid way the impact of the MCSI activities he engaged with to the development of robust understandings of the content of 1-D elastic collisions. It is also an authentic empirical documentation of the claims reported in the literature (e.g., Acher et al., 2007; Ergazaki et al., 2005; Halloun & Hestenes, 1987; Passmore & Stewart, 2002; Penner et al., 1997; Schwarz & White, 2005; Snir, Smith, & Raz, 2003; White, 1993) that MCSI has the potential to facilitate learners' conceptual understanding in the context that is interwoven with.

*“Approaching the elastic collisions through modeling helped me to comprehend in depth what is happening during elastic collisions, because neither we were offered ready-made pieces of existing knowledge about this type of phenomena nor we were expected to apply our physics knowledge obtained from high school for building our models. Instead, we were systematically trying to interpret each collision phenomenon in a way that was meaningful to ourselves and tested if our interpretation was consistent with our observations. Hence, we gradually passed through several interpretations to reach at the “conservation of momentum” as the best interpretation that applied to all cases of the elastic collisions we observed. Consequently, the process of modeling helped me in*

*understanding the physics behind elastic collisions in a better way than the traditional way we were taught during high school, and I'm now confident that my knowledge is more robust and permanent."*

At the end of Phase 1 of the PDC, the analysis of teachers' definitions for scientific modeling revealed that they developed sophisticated understandings about scientific modeling, since they provided more comprehensive definitions compared to those provided in the pre-CK test. More specifically, the majority of the teachers defined modeling as *the process that is followed for creating a model that helps in (i) representing a phenomenon, (ii) explaining or interpreting how the phenomenon functions, and (iii) formulating and testing of predictions/hypotheses*. Moreover, the majority of the teachers referred on the several steps that are followed during the process of modeling (e.g., performing observations, model development, model improvement, model validation, model evaluation, continuous model improvement), and most importantly, they emphasized that these steps are followed not in a linear fashion, but in a *cyclical and iterative* manner. Consequently, it can be argued that at the end of Phase 1 of the PDC the teachers made a significant shift from understanding modeling through a positivist perspective, e.g., modeling is a straightforward, rational process (Van Driel & Verloop, 1999) to conceptualizing modeling as an iterative and cyclical process (Schwarz et al., 2009; Van Driel & Verloop, 1999; 2002).

Besides examining teachers' definitions and evolved understandings of scientific modeling through the CK-test and their reflective journals, an additional question was used in the CK-test (both as a pre- and post-test) to capture their understandings of three different perspectives of scientific modeling. These three different perspectives or the three "faces" of modeling, as it was described in Chapter 2 (see p. 40 for more details), pertain to: (i) *modeling as a scientific enterprise*, e.g., understanding that modeling is an integral part of scientific enterprise from its origins, as experimentation and the broader enterprise of inquiry are profoundly situated in model building, testing, and revising (Duschl & Grandy, 2008; Giere, 1988; Kitcher, 1993; Longino, 1990; Michaels, Shouse, & Schweingruber, 2008); (ii) *modeling as an instructional approach*, e.g., engaging students in the productive act of model development and deployment of natural phenomena in specially designed MCSI settings (Louca, Zacharia, & Constantinou, 2011; Penner et al., 1997; Schwarz & White, 2005; Schwarz & Gwekwerere, 2006) grounded on the premises of the constructionist perspective (Papert, 1991); and (iii) *modeling as an ability that is developed by learners during their engagement in MCSI learning environments* (Chittleborough &

Treagust, 2007; Duit & Treagust, 2003; Grosslight et al., 1991; Harrison & Treagust, 2000).

The rationale for administering this type of question was to examine the origins of teachers' modeling knowledge prior to the PDC, and also to study if their engagement as learners during Phase 1 of the PDC could impact on the development of informed understandings about the three "faces" of modeling. Consequently, the teachers were asked to state whether modeling is a *scientific enterprise*, a *teaching approach*, or an *ability that is developed by learners during their engagement in MCSI learning environments*, and explain the reasoning behind their response.

The analysis of teachers' responses to the abovementioned question revealed that both prior to and after Phase 1 of the PDC all teachers suggested that modeling could be conceived as a scientific enterprise, an instructional approach, and an ability that is developed. However, the arguments that they used for supporting each perspective of modeling differed dramatically from the pre-CK test to the post-CK test. More specifically, prior to Phase 1 of the PDC the teachers used three different arguments to support their assertion that modeling could be considered as a scientific enterprise. The first argument, which was reported by half of the teachers, revealed a rather naive understanding of modeling as a scientific enterprise, because teachers stated that modeling follows the steps of scientific method and hence it can be considered as a scientific enterprise. Their argument seems to have originated from the term "scientific" in the statement "modeling as a *scientific enterprise*", and indicates that these teachers interpret the term "scientific" as anything that has to do with the scientific method that is declared in science text books, e.g., the scientific method is a linear procedure that involves observations, predictions, experiments, data collection and data interpretation, and so on (Grandy & Duschl, 2007), and not as an activity that is central to scientists' perennial attempts to understand and interpret the natural phenomena. A similar misinterpretation has been revealed by the participants in the study of Danusso et al. (2010). On the other hand, the second and third arguments pertain to an understanding of modeling as a scientific enterprise, as they entail references of scientists' use of modeling as a tool for sense making and interpreting the natural phenomena. The second argument, although reported by a minority of teachers, was the most comprehensive one, as it refers to modeling is a major enterprise followed by scientists while trying to understand, interpret, and explain natural phenomena, and that through modeling scientists build and revise models to test their theories (Michaels,



Shouse, & Schweingruber, 2008). The third argument, which was mentioned by seven teachers, is a simplified version of the first argument, as it refers only to the use of modeling by scientists for developing or using models to test their theories.

After Phase 1 of the PDC, the argument concerning the misinterpretation of modeling with the scientific method was eliminated as teachers' responses were split between the second and the third arguments that highlight their informed understandings of modeling as a scientific enterprise. Consequently, it can be assumed that teachers' engagement with the modeling activities during Phase 1 of the PDC impacted on the development of their understanding of modeling as a scientific enterprise.

As far as teachers' arguments for modeling as an instructional approach are concerned, the analysis of teachers' responses in the pre-CK test revealed two different types of arguments. The first argument, which was reported by half of the participants, relates to an authoritarian view of modeling, as it is conceived as an instructional tool in the possession of the teacher for better preparing her science lessons (Just & Gilbert, 2002a; Van Driel & Verloop, 2002), and not as an approach through which students could be engaged in the productive construction, revision, and validation of models while exploring a natural phenomenon. On the other hand, the remaining half of the teachers used a different type of argument to support their justification of modeling as an instructional approach. In their argument they referred to modeling as a component of scientific method followed in science settings. Although modeling lies within the broader inquiry-based teaching and learning approaches (Windshitzl & Thompson, 2006; Windshitzl, Thompson, & Braaten, 2008) the association of modeling with the scientific method that these teachers claimed does not pertain to modeling as inquiry-based approach. Consequently, it appears that these teachers were not aware of how modeling as an instructional approach should look like in an inquiry-based setting, and, hence, the association of modeling with the scientific method was created on the spot in their effort to provide an explanation for their response. To elaborate on the same finding that came out in his study, Windshitzl (2004) denoted that most of the participants subscribed to a "folk theory" of scientific inquiry in which models played no discernible role.

At the end of Phase 1 of the PDC, both arguments that were used to support the claim that modeling could be an instructional approach were substituted by an argument that entailed informed understandings about the format and the purpose of modeling as an instructional

approach. Specifically, all teachers made references on their personal experiences gained during Phase 1 of the PDC and stated that modeling is an instructional approach that is used by teachers when they seek to help their students understand and interpret natural phenomena through the development of models. They also made references on the several modeling activities that shape modeling-based instructional settings, like observation of a phenomenon, interpretation of the phenomenon, representation of the phenomenon through the use of various modeling means, comparison of the model with the physical phenomenon, model revision, comparing models of the same phenomenon, and model validation.

Lastly, the analysis of teachers' arguments in relation to modeling as an ability that is developed revealed four different types of arguments, three of which were present in their responses prior to Phase 1 of the PDC. Specifically, the ten teachers who used the scientific method related argument in their explanations to justify why modeling could be a scientific enterprise and an instructional approach, also made use of the same argument to explain why modeling could also be an ability that is developed. For instance, they claimed that during learners' engagement with the scientific method, their modeling ability could be spontaneously developed. A more informed argument to support the idea of modeling as an ability was provided by seven teachers, who stated that a learner's modeling ability is developed during creating a model of a natural phenomenon, whereas the remaining three teachers seemed to have associated the term "modeling ability" with mental modeling.

After the end of Phase 1 of the PDC, the majority of teachers changed the argument they used to support the claim that modeling could be an ability that is developed by learners when they are engaged in modeling-based activities, and provided several examples of modeling-based activities to highlight that modeling ability is not developed only during creating a model, but also through other modeling-based activities like improving models, comparing models with their target, revising models, and validating models. The rest of the teachers used only the creation of a model as the activity that enables the development of learners' modeling ability.

### **5.3.3. Teachers' CuK for MSCI**

Teachers' CuK for MCSI was evaluated through two main data sources; the CuK test that was administered both prior to and after Phase 1 of the PDC, and the several assignments that were completed at various instances during Phase 2 of the PDC (see

Figure 8 in page 104 for details). Given that almost none of the teachers had previously enrolled in a PDC that was designed around MCSI, and that their teaching experience with modeling was very limited, it was anticipated that their CuK for MCSI would also be insufficient. This assumption was confirmed from the analysis of their responses at the pre-CuK test, as their understandings of how the MCSI approach should look like in science curriculum was very limited. Specifically, the findings demonstrated that teachers perceived modeling as an instructional tool that facilitates teachers' work for creating models for the phenomena s/he would later present to students as "ready-to-eat-pieces" (Van Driel & Verloop, 2002). This approach pertains to a rather "authoritarian" view of teaching science through modeling, as it reveals that modeling is an instructional aid for the needs of the teacher while planning a science lesson, and not a student-centered approach that enables students to represent, explain and interpret a phenomenon under study. Justi and Gilbert (2002a) were confronted with a similar view of the use of modeling, as the teachers in their study reported that the teacher -and not the learner- would act as a modeler, and therefore the teacher him/herself would select the most appropriate mode of representation to create a model that would facilitate learners' understanding of the phenomenon being modeled.

Teachers' limited CuK for MCSI at the beginning of the PDC was also verified through the analysis of their responses on the types of activities a teaching unit in science curriculum should entail, and from their responses on the objectives of assessment tasks that can be used to evaluate students' modeling ability (see Figure 16 and Figure 17 in Chapter 4 for details). After their engagement with the MCSI curriculum materials of Phase 1, the majority of the teachers seemed to have developed a moderate understanding of the types of activities of MCSI curricula, and of the objectives that should be evaluated through modeling assessment tasks. Although the prevalence for most of the activities that were identified prior to the PDC was increased, and new types of activities were proposed, the prevalence for each of the modeling activities that were considered as fundamental to be integrated within a MCSI setting was not increased more than 50%. For instance, the proposed activities that relate to the *nature of models* or the *purpose of models* were very limited after Phase 1 of the PDC, indicating that teachers did not consider activities related to the epistemic awareness about models and modeling as of great importance within a MCSI setting, although they themselves experienced such type of activities during their participation in the course. In a similar manner, Justi and Gilbert (2002b) reported an

‘alarmingly high’ number of teachers who were either ignorant of, or did not pay attention to, their students’ ideas about models and modeling.

A similar trend of findings emerged from the analysis of teachers’ proposals for the objectives of assessment tasks that can be used to evaluate students’ modeling ability. However, comparing the findings that were revealed from teachers’ CuK about the modeling activities a teaching unit in the science curriculum should entail and the teachers’ CuK about the objectives of modeling assessment tasks (see Figure 16 and Figure 17 in Chapter 4 for details), it appears that there are some commonalities and some differences between the prevalence for some of the proposed modeling activities and the corresponding objectives of the modeling assessment tasks. For instance, while the *reflection on the nature of models* activity was proposed by only 10% of the teachers, the percentage of the corresponding assessment objective that was proposed was 50%. In contrast, the difference in the percentage of the prevalence of the model formulation activity and its associated assessment objective was 10% (e.g., 19 teachers suggested the formulation of models as an activity and 17 teachers suggested the evaluation of model formulation). Consequently, the dichotomy between teachers’ proposals of the modeling activities and the objectives of the modeling assessment tasks points to an uninformed pedagogical understanding in relation to the consistency between *what is taught* and *what should be assessed*. This finding can be attributed to both their limited science teaching experience in general, as all of them were beginning teachers, and to their limited or nonexistent experiences with teaching science through modeling.

Although the findings designate a moderate development of teachers’ CuK about the types of activities and the objectives of the assessment tasks that a MCSI instructional setting should entail, it is important to examine the foundations of this development, albeit moderate. To capture teachers’ aforementioned aspects of CuK, the CuK test was administered at the beginning and end of Phase 1 of the PDC, during which teachers were engaged as learners in modeling 1-D elastic collision phenomena. During Phase 1, the teachers neither received any explicit instruction on the underlying principles of MCSI curriculum nor were prompted to discuss any issues related to the rationale behind the design of the activity sequence that the curriculum they were engaged with was based on. Their role during the Phase 1 of the PDC was strictly constrained to the role of a learner in a MCSI setting, and thus the development of their CuK about MCSI can be attributed to

the personal experiences they achieved during their participation to the PDC, and to the assimilation of their emerged CuK in their existing knowledge bases.

More promising findings of teachers' CuK for MCSI were revealed from the analysis of the data collected through a set of assignments administered at various instances during Phase 2 of the PDC (for details about the assignments, see Figure 8; for details about the findings, see Section 4.3.2.2.2. , p. 193). Instead of asking teachers to reflect on open-ended questions like the ones used in the CuK test, the set of assignments that were administered were context-based and entailed previously familiar content. Specifically, in Assignment 2.1 the teachers were provided with half of the modeling ability tasks they completed during Phase 1 (one task for each of the modeling ability framework component), and they were asked to state what was sought to be evaluated through each assessment task and explain the reasoning behind their responses. Similarly, Assignment 2.4 encompassed the other half of modeling ability tasks that they also completed during Phase 1. Assignments 2.2 and 2.3 focused on examining teachers' CuK through their ability to identify the learning objectives of the activities of two MCSI curricula. The "Modeling 1-D Elastic Collisions" curriculum that was used during Phase 1 of the PDC was the context of Assignment 2.2, whereas the "Modeling Marine Ecosystems" curriculum was the context of Assignment 2.3.

In both Assignments 2.1 and Assignment 2.2, the majority of teachers seemed to be able to identify correctly most of the objectives behind the design of specific modeling activities within the MCSI curriculum (Assignment 2.1) or the objectives behind the design of specific modeling assessment tasks. For some of the activities or assessment tasks the teachers showed a moderate performance, whereas for some other activities or assessment tasks the majority of the teachers failed to identify correctly the objectives behind the design these activities or assessment tasks (see Table 39 and Table 40 in p. 179 and p. 185 respectively for details). As far as teachers' CuK with respect to the identification of the assessment objectives behind the modeling ability tasks, it is noteworthy to state that even though their modeling ability that was assessed through these modeling ability assessment tasks appeared to have been enhanced (as reported and discussed before), their CuK knowledge (or metaconceptual awareness) about the objectives of the specific assessment tasks they completed was not simultaneously developed, as one might expect. For instance, the teachers misinterpreted the objective of the model validation task, the metacognitive knowledge about the modeling process task, and the meta-modeling knowledge with

respect to the nature of models task, as described in the presentation of the Findings Chapter (see p. 179 for details).

On the contrary, the teachers appeared to perform significantly better in both Assignments 2.3 and 2.4, as the percentage of their identification status for all of the objectives of either the activities in the MCSI or the modeling evaluation tasks was increased, indicating that their CuK for MCSI has been considerably enhanced. Thus, an emergent question that comes up is *how these changes in teachers' CuK can be explained?* Looking at the continuum of the administration of the assignments along Phase 2 of the PDC, it seems that the interpolation of the theoretical paper that teachers were given to read between the administrations of Assignments 2.1-2.2 and Assignments 2.3-2.4 can be used to explain the changes of teachers CuK. Indeed, it was after teachers had read the theoretical paper, which focused on the presentation of modeling ability framework with an emphasis on the analysis and description of its constituent components, that came to resolve their misunderstandings, and appeared to perform better in the subsequent assignments. The paper served as the bridge between their personal experiences during the learner-centered activities they experienced during Phase 1 of the PDC and the theoretical perspectives that these activities or modeling assessment tasks were designed around. Consequently, the reading of the theoretical paper appeared to be a valuable intellectual resource, as the explicit and comprehensive nature of that text stimulated fundamental changes in teachers' CuK. A similar approach with similar encouraging outcomes was followed by Windshitl and Thompson (2006) in their study, who provided the teachers with a paper to help them make connections between their learning experiences and the theoretical perspectives of scientific models, and how modeling can be integrated within scientific investigations.

A final data source used to assess teachers' CuK for MCSI relates to an assignment they completed, when they were asked to study the national curriculum and choose a unit to reconstruct by adopting MCSI as the instructional approach. In doing this, they were asked to explicitly describe the criteria they used for selecting their unit and explain their reasoning. The criteria they used during evaluating the units they selected reflect four distinct lenses or outlooks that are discussed below.

The first lens that the teachers used during studying the unit they selected to reconstruct, relates to the *conceptual understanding* dimension of the unit. Specifically, more than half of the teachers reported instances of *conceptual understanding limitations* or *violations*

within the curriculum they studied, and explained that this was a major criterion to be used as an argument to claim the need for reconstructing the unit they selected. The *complexity* or the *degree of difficulty* of the concepts of the unit they selected was also used by the majority of the teachers as an argument for selecting the specific unit, because – as one of them explained – “...a modeling approach could be proved beneficial for students, as it will help them to decompose complex concepts into smaller pieces of knowledge when building their models”. A third criterion that was reported by almost half of the participants and falls under the umbrella of the conceptual understanding dimension, relates to teachers’ awareness about specific *misconceptions* that students quite often hold about the conceptual part of the unit. This knowledge departed from their prior teaching experiences or their readings of research papers about that topic and was used as a criterion for explaining why MCSI was preferable to be followed for helping students overcome specific misconceptions. The last criterion that was used among the abovementioned conceptual oriented criteria and was the least frequently reported concerns *students’ familiarity with the concepts* of the unit that was going to be approached through modeling. This stance, which was found in the reports of only two teachers, implies that modeling was not perceived as the means through which students’ conceptual understanding would be enhanced or scaffolded, but rather as the purpose per se. This view also contradicts the rationale for choosing modeling as an instructional approach, because MCSI has the potential to facilitate to study complex phenomena or systems.

The second lens through which teachers reviewed the units from the national curriculum, concerns the unit’s relevance with *inquiry-based learning*. Specifically,  $\frac{3}{4}$  of the teachers identified several flaws in relation to the processes that were followed during investigating the phenomena under study that point to the units’ failure to promote students’ procedural knowledge. Additionally, 60% of the teachers used the *fitness of the unit with inquiry* as the criterion for their unit selection and explained that modeling practices could follow the experiments that the students perform within the unit, because - as they explained - through modeling the students would be given the opportunity to incorporate data they collected from their experiments to models they build to explain how a phenomenon functions. This view concurs with Windshitl’s and Thompson’s (2006) argument for the need to transcend simple forms of school science investigation and engage learners in model-based inquiry. The affordances of Stagecast Creator, the modeling tool that the teachers used during Phase 1 of the PDC, were another criterion that was considered by the teachers when making their selection of the unit they would like to reconstruct. This criterion, which was

evident within half of the teachers' reports, reveals that teachers' engagement with this modeling tool enabled them to experience its affordances and capabilities and thus they considered it as a candidate modeling tool for the purposes of reconstructing an existing unit from the national curriculum.

The last but the most frequent criterion that was evident in almost every teacher's report, pertains to the *appreciation of modeling as an instructional approach* that could be followed for reconstructing their units. It is important to state that none of the teaching units in the national curriculum used MSCI as the instructional approach, and the units that use models as instructional means are sparse. Hence, teachers' statements in their reports, through which they underscored the added value of modeling towards offering important learning experiences to their students (e.g., help students to interpreting the phenomena they are studying, using their own models to formulate and testing predictions) or stimulating students' interest and engagement for science lesson, indicate that, by the end of the PDC, indicate that they came to understand that modeling as an instructional approach has multiple benefits for both the teacher and the students (Harlow, 2010; Louca et al., 2011; Schwarz & White, 2005; Shen & Confrey, 2007).

#### **5.4. What are the characteristics of teachers' modeling-centered curriculum designs?**

In answering this research question, a thorough examination of teachers' MCSI curriculum materials<sup>5</sup> that were prepared by the end of Phase 2 of the PDC was performed. The initial focus during the analysis of these curriculum materials was on the *content* and the *structure* of the activities that teachers designed in reconstructing the unit they selected, while at the same time a serious attempt was made to identify possible links between the activities and the modeling ability framework the teachers had already been familiar with during Phase 2 of the PDC. After several iterations of curriculum examination, the focus of the analysis became broader, and finally seven dimensions were considered as critical to guide the identification of the characteristics of teachers' curriculum materials. The

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<sup>5</sup> The terms "curriculum materials" or "curriculum designs that are used interchangeably relate to all products that teachers created for accomplishing the requirements of the project-based assignment (redesign of an existing unit from the National Curriculum) they were asked to prepare. These products entailed text-based materials submitted in electronic form [(i) selection of a teaching unit and describe the rationale behind this selection; (ii) formulation of learning objectives; (iii) mapping the activity sequence; (iv) design and detailed description of the activities proposed in the activity sequence section; (v) design of activity sheets; and (vi) design of assessment tasks], and computer-based models created in SC.



characteristics that emerged for each dimension were clustered along three levels of increased sophistication. The dimensions of analysis along with the levels of increased sophistication that illuminate teachers' MCSI curriculum characteristics were presented in Table 43 (see page 199).

While redesigning the selected teaching unit from the national curriculum, it was hypothesized that teachers would transform experiences, knowledge, and skills gained throughout the course, and these transformations would be illuminated within their curriculum materials. Therefore, teachers' modeling-based curriculum designs would serve as "transparent prisms" through which transformations of their evolved *modeling ability*, their *CK about models and modeling*, and their *CuK for MCSI* could be investigated. Indeed, in looking closely at the rich description of the characteristics that emerged for every level and for each of the seven dimensions of analysis that teachers' MCSI curriculum materials was grounded on (see section 4.4. in the chapter of Findings, p. 197 for details), the aforementioned assumption can be securely confirmed. Most importantly, teachers' MCSI curriculum characteristics that emerged not only provide in depth insights of the status of their modeling ability, CK for models and modeling, and CuK for MCSI, but the amalgamation of these three aspects that are assumed to have been transformed for the purposes of their curriculum designs portray teachers' *PCK* (pedagogical content knowledge) *for MCSI*. This argument departs from prior reports in the literature (Henze, Van Driel, & Verloop, 2007; Grossman, 1990; Justi & Van Driel, 2005; Magnusson et al., 1999; Davis, Nelson, & Bayer, 2008; Nelson & Davis, 2011; Treagust & Harrison, 2000) that PCK includes components such as knowledge of instructional strategies, instructional representations, classroom explanations, students' ideas, and curriculum. This special knowledge held by teachers requires what some refer to as a transformation of subject matter knowledge and pedagogical knowledge (e.g., Magnusson et al., 1999) but what could also be viewed as the well-integrated knowledge base of an effective teacher (Davis, Nelson, & Bayer, 2008). For instance, PCK for MCSI, according to Davis, Nelson, and Bayer, "requires meaningful integration of ideas about subject matter, models, modeling, learners, learning, and instruction. To develop this special knowledge, a teacher may need to (for example) add new meta-modeling knowledge about models and modeling, add a new specific idea about a specific instructional approach, connect these to an existing idea about learners, and so forth" (p. 3). While I concur with how Davis, Nelson, and Bayer delineate PCK for MCSI, I would like to expand their definition by suggesting *knowledge about learners' modeling ability* as an additional important component that the present

study has highlighted. Adding up this component in the existing definitions of PCK for MCSI (see for other related definitions Henze, Van Driel, & Verloop, 2007; Justi & Van Driel, 2005; Nelson & Davis, 2011) is considered of pivotal importance, because learners' meaningful engagement in the act of scientific modeling is constrained by the development of the components of their modeling ability in unison.

Consequently, the characteristics of teachers' MCSI curriculum designs can be discussed in light of their PCK for scientific modeling, and inferences about their CK for models and modeling, CuK for MCSI, and knowledge about the modeling ability framework will be drawn. Additionally, instead of discussing each dimension of analysis with its corresponding emerged levels (because of the homogeneity that was found in the classification level for the majority of teachers' curriculum designs across the seven dimensions of analysis, see Table 50 for details), the three levels that emerged across the seven dimensions of analysis will be discussed as representing three different profiles of teachers' PCK for MCSI.

#### ***PCK for MCSI Profile A: The authoritarian modeler***

The teachers with this PCK profile adopt an "authoritarian" and teacher-directed orientation while designing their curriculum. The activities they design are permeated of strong *transmissive* pedagogies (Miller & Seller, 1990), since they appear to manage and control students' learning in a strong dominant manner, and expect from their students to act as "followers"<sup>6</sup> of the pieces of knowledge they diffuse throughout the lessons. The teaching materials they prepare for teaching a topic through modeling show little deviation from the existing activities of the national curriculum unit. The format, the structure, and the content of the activities of the national curriculum are maintained intact, while the few modeling activities that are designed are used as *add-ons* without truly being incorporated in the activity sequence. Because they develop materials of limited scope to supplement and enrich ready-made materials, they are considered as *consumer-developers* (Silberstein, 1984).

In attending to students' conceptual understanding, there are some rare instances in the curriculum that the teachers would attempt to elicit students' prior ideas about a phenomenon under study, but activities that relate to monitoring students' conceptual development throughout the curriculum are omitted. Additionally, the introduction of new

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<sup>6</sup> The term "followers" is used anecdotally to illustrate the analogy that comes from the online social networking service, namely Twitter, through which individuals follow (the "followers") a user's postings (or tweets). [Source: <http://en.wikipedia.org/wiki/Twitter>]

concepts in the curriculum is accomplished either through teacher lecturing or through content-delivery statements, without giving the opportunity to students to sense the need to develop operational definitions for the concepts they are experiencing.

The inquiry activities that they design or select from the textbooks are “closed-ended”, since students are neither allowed to investigate a phenomenon through hands on experimentation nor are given the opportunity to collect and interpret data from the experiments for answering a question or confirming/rejecting a hypothesis. Likewise, the few modeling activities that they propose do not depart from the need on behalf of the students to develop a model that would help them interpreting the phenomenon under study or use their model for hypothesis/prediction testing about certain aspects of the phenomenon being modeled. Instead, the way these activities are designed designate that modeling is used as a means for “mimicking” ready-made models that are presented by the teacher. Thus, the emphasis is on the transition of the content of certain models (Henze, Van Driel, & Verloop, 2007; Van Driel & Verloop, 2002), and because modeling appears in the eyes of the student as a straightforward, rational process, is congruent with the positivist perspective (Van Driel & Verloop, 1999). Additionally, in describing or creating the models they expect their students to create, they give mainly emphasis on the representation of only observable patterns from a phenomenon, and ignore the interpretive potential and predictive power of their models. Therefore, the models that result from this approach are *animation-like* in their format and nature.

Because the emphasis they devote during modeling is on the content and not on the process, they select a variety of related phenomena to be modeled through the activities they propose. For each phenomenon they incorporate in their curriculum, they suggest a new model that the students should create, and they do not make an attempt to help students unify all different but related models in a broader model that could apply to phenomena of the same class.

As far as the implementation of the modeling ability framework is concerned, this is done in a very superficial manner, since there is no strong coherence between the learning objectives they set and the corresponding modeling activities they design, and also, the students are not supported enough to develop a particular modeling ability component. On the other hand, and most importantly, it appears quite often the teachers to have “mutated” (or misunderstood) the content and rationale of a specific modeling ability component, and

thus, these “mutations” of the modeling ability framework are considered as *lethal* (Brown, 1992), because since they falsify the content and rationale of specific modeling ability components, students’ modeling ability would not only be distorted but fragmented as well.

Lastly, the evaluation of students’ learning gains is intended to be undertaken at the beginning and the end of the implementation of the curriculum, and the assessment tasks that are designed are mostly in the format of true/false statements or closed-ended questions. Even though the teachers aim to use modeling as the teaching approach through which the development of students’ conceptual understanding could be facilitated, they do not design any tasks to evaluate students’ possible development of their modeling ability.

### ***PCK for MCSI Profile B: The “play safe” coach***

The teachers with this PCK profile adopt a combination of *transmissive* and *transactive*<sup>7</sup> curriculum design orientations (Miller & Seller, 1990) while reconstructing a unit from the National Curriculum, as they switch between the two types of orientations during engaging their students in modeling, inquiry-oriented and conceptual development activities. In preparing their MCSI instruction, they proceed to a partial reconstruction of the format, the structure, and the content of the existing unit from the national curriculum, and the MCSI activities that they design are interconnected with the rest of the activities of the curriculum. Their curriculum designs entail fewer “didactic” activities and more “hands-on” activities that are used for verification or discovery purposes. These “hands-on” activities differentiate from the “didactic” activities in that the students are given authority over the use and manipulation of the materials and equipment that are provided by the teacher, when performing investigations. Nevertheless, the teachers still remain in the center of the learning process to control students’ learning pathways, as they appear to constantly telling students, either directly or through the curriculum, what they are supposed to see or learn (Magnusson et al., 1999).

As far as the modeling activities are concerned, the teachers design modeling activities through which the learners would create models to represent and interpret a phenomenon

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<sup>7</sup> A *transactive* teaching orientation, according to Miller and Seller (1990), assumes knowledge is constructed by learners through the process of learning, and the role of the teacher is to facilitate learning and to create environments which stimulate learners’ interests, recognizing that learning is social and at the same time individual.

under study. Although they pay a lot of attention to the representational complexity of models, their proposed modeling activities fell short in the interpretive aspect of models, as the main emphasis is on approaching the interpretive aspect of models only through a “mechanistic” perspective (e.g., *how* the phenomenon functions?), and not through a “causal” perspective (e.g., *why* the phenomenon functions the way it appears through the model?). Nonetheless, the cultivation of all components of the modeling ability framework components appears as moderate, because some components of the modeling ability framework are either superficially approached or the place of integration of the modeling activities within the curriculum that are aligned with specific modeling ability components is not appropriate. There are might be instances, for example, that a specific modeling ability component appears very early in the activity sequence, and thus, its cultivation cannot be promoted, because some other modeling ability components, which were considered as prerequisites for the effective development of this modeling ability component, should have been preceded. Likewise, there might be some other instances where the modeling activities that preceded have the potential to fertilize the ground for the development of a specific modeling ability component, but such an attempt is omitted from the activities that follow. Additionally, in some other cases the activities that are designed for the development of a specific modeling ability component are very sparse throughout the curriculum, and thus the development of this component cannot be granted. Consequently, combining the previous characteristics with the fact that some of the modeling activities make an insignificant contribution to learners’ modeling ability, it appears that teachers’ priority during designing their curriculum materials is to design modeling activities for the *sake of modeling* (the “modeling for modeling’s sake” effect), and not for the effective development of learners’ modeling ability.

As far as the models’ progression in the curriculum, the teachers choose the development of various independent models to illustrate different aspects of the phenomenon under study, but fail to come across with a way to merge all aspects from the different models into a unifying model that would illustrate, explain, and generate new predictions that can be tested at a later stage against data from the phenomenon it represents. The models they expect from their students to create are characterized as “simulation”-like models, because significant emphasis is placed on their representational complexity and predictive power, whereas their interpretive potential is based only on a *mechanistic* interpretation for the phenomenon they represent. More specifically, both the representational format of the models and the syntax of the rules that are created to control their behavior are constrained

to provide only an explanation that accounts to *how* the phenomenon functions the way it has been represented through the model. Thus, the models lack of another type of explanation, namely a “causal interpretation”, that would explain *why* the phenomenon behaves as it does. On the other hand, these models are robust enough to enable the formulation and testing of a variety of predictions, since they are not intended to be built on a fixed programmable routine.

Lastly, to evaluate their students learning gains, the teachers propose the evaluation of students’ development of both modeling skills and conceptual understanding in the context of the curriculum that they departed from. The administration of the assessment tasks, which are in the format of open-ended questions, is set at the beginning and the end of the implementation of the curriculum. Given the fact that teachers choose to design assessment tasks to evaluate students’ development of modeling skills and omit the evaluation of their meta-modeling knowledge and metacognitive knowledge about the modeling process, designates that they do not consider those two types of knowledge as important aspects of students’ modeling ability. Additionally, since they chose the context of their curriculum as the context for the design of the evaluation tasks, the development of students’ modeling skills might not be granted, because the evaluation of students’ development of modeling ability needs to be pursued in contexts other than the one of the instruction.

### ***PCK for MCSI Profile C: The constant modeling inquirer***

The teachers with this PCK profile adopt a combination of *transactive* and *transformative*<sup>8</sup> teaching orientations (Miller & Seller, 1990) while reconstructing a unit from the National Curriculum. Apart from the transactive activities through which the students are supported in constructing their own learning and the teacher acts as a facilitator during students’ learning development, the teachers usually design activities to foster students’ learning through self-reflection, self-awareness, and self-learning. Specifically, the teachers systematically intend to prompt their students to elicit their existing knowledge about a topic under study, then they proceed on helping students to confront their prior knowledge with knowledge that emerges through inquiry and modeling-oriented activities, and at the end they engage students in self-reflecting activities for reassessing the new knowledge in

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<sup>8</sup> A *transformative* teaching orientation, according to Miller and Seller (1990), refers to the case of instructional settings that learning is developed through self-reflection, self-awareness, and self-learning; the learner is offered opportunities to reassess new knowledge in relation to existing knowledge and reflect upon the underlying assumptions and biases that are the foundation of that existing knowledge.

relation to their existing knowledge. The curriculum materials they intend to use for the purposes of their instruction emerge through a total reconstruction of the national curriculum unit, and most importantly, the modeling activities that are interwoven within the curriculum reveal a strong priority to modeling as the approach through which students' conceptual scaffolding and enhancement can be achieved. Their curriculum designs encompass *guided-inquiry* and *modeling-centered scientific inquiry* activities (Schwarz & Gwekwerere, 2006) that both impact on promoting modeling as a vehicle through which students are supported in representing and interpreting phenomena under study, and using their models for testing of predictions. The *guided inquiry* activities are developed around a learning community-centered approach; "the teacher and students participate in defining and investigating problems, determining patterns, inventing and testing explanations, and evaluating the utility and validity of their data and the adequacy of their conclusions. The teacher scaffolds students' efforts to use the material and intellectual tools of science, toward their independent use of them" (Magnusson et al., 1999, p. 101). Likewise, *modeling-centered scientific inquiry* is "guided inquiry focused around creating and using models to predict and explain phenomena and then comparing those models with those from canonical science. These scientific models frequently embody patterns in data and have an explanatory component" (Schwarz & Gwekwerere, 2006, p. 184).

In attaining to the development of their students modeling ability, they efficiently transform the modeling ability framework into pedagogically potent modeling activities through which learners' modeling ability is enhanced. Each component of the modeling ability framework is fostered through productive modeling activities that are placed in a meaningful order in the activity sequence, and are also well interwoven with the rest of the activities in the curriculum. In accomplishing their modeling objectives, they engage their students in the development of a sequence of interrelated models with a gradual complexity and applicability to represent various aspects of a phenomenon under study. In doing this, they make serious attempts to engage their students in multiple iterative cycles of model development and deployment of a natural phenomenon or a system, and thus the resulting models' progression entails a series of models, each of which is an improved or a revised version of the previous model that was created. Consequently, the final models that are produced by the end of the implementation of their curriculum represent several aspects of the phenomenon under study in unison, entail a robust interpretive mechanism

for *how* and *why* the phenomenon functions, and enable the formulation and testing of predictions and hypotheses for a family of phenomena of the same class.

For evaluating their students learning achievements, the teachers design assessment tasks for initial, ongoing and final evaluation of the development of their modeling ability and conceptual understanding in new contexts. Besides designing pre- and post- assessment tasks to capture students' development of conceptual understanding and modeling ability, they also design intermediate tasks through which students' ongoing understandings and modeling ability are monitored and captured. These tasks are in the form of reflective diaries, concept maps, or asynchronous discussions in an online learning platform that the students enroll at certain instances in the curriculum. The teachers appear to be aware that in evaluating learners' development of modeling ability, one should aim to situate his/her evaluation in new contexts in order to assess if students are able to transfer their modeling ability in unfamiliar contexts.

Consequently, the teachers with the *PCK for MCSI Profile C* can be justifiably characterized as *autonomous developers* (Silberstein, 1984) who can plan, design, and develop an entire course of study.

In sum, the three different profiles with respect to teachers' PCK for MCSI demonstrate that teachers who were engaged in the same PDC for MCSI and followed the same learning pathways during developing and deploying models in the context of 1-D collisions have conceptualized in diverse ways the underlying principles of the MCSI approach. Thus, a critical question that emerges is "Can the level of development of teachers' modeling ability, CK about models and modeling, and CuK for MCSI be used to explain these differences?" Put differently, are these three different domain predictors of teachers' PCK for MCSI? These questions, albeit important, were not the focus of this study, but can be used as starting points for future research (see Recommendations for further research section below).



## Chapter 6: Conclusions and Implications

### 6.1. Introduction

Models and modeling have been the focus of many studies the past two decades, and as discussed in Chapter 2, most of the earlier studies sought to explore students' and teachers' epistemic understandings of the nature of models (Grosslight et al., 1991; Smit & Finegold, 1995), model attributes (Schwarz & White, 1998), types of representation (Van Driel & Verloop, 1999), and nature, entities, and purposes of models (Justi & Gilbert, 2002b). The findings of these studies revealed students' and teachers' consistent misconceptions about various epistemic elements and functions of models and the processes of modeling. Follow-up studies attempted to foster the development of students' and teachers' informed understandings about models and modeling through engaging them in the productive act of modeling natural phenomena with the use of computer-based tools (Ergazaki et al., 2005; Louca, 2004; Schwarz & White, 2005) or other modeling media (Acher, Arcà, & Sanmartí, 2007; Penner et al., 1997). The findings of these studies and other similar ones revealed also improvements in students' and teachers' conceptual understanding about concepts and phenomena they were investigating, and also epistemic changes with respect to the nature of science.

Despite the promising findings of the latter research attempts, modeling-centered scientific inquiry continues to hold the position of “Cinderella” in teachers' ordinary teaching practices repertoire (Crawford, 2005; Duschl, Schweingruber, & Shouse, 2007; Justi & van Driel, 2005), because of either “...a lack of existing information, frameworks, and structures for guiding teachers in engaging children in model-based inquiry practices” (Schwarz & Gwekwerere, 2006, p. 2) or because of the absence of activities from school textbooks that welcome students active construction, testing, or revision of their own models as part of the learning process (Barab et al., 2000). Consequently, current research (e.g., Nelson & Davis, 2011; Schwarz, 2009) place emphasis on how best to prepare teachers to design and enact science instruction through modeling, in an attempt to make teachers aware of the multiple learning benefits that can result from such an approach, both from the perspective of the teacher and the perspective of the learner.

In order to succeed in facilitating the professional development of teachers, we need to “...understand the process by which teachers grow professionally and the conditions that support and promote that growth” (Clarke & Hollingsworth, 2002, p. 947). At the same time, it is crucial to understand and value the personal knowledge and beliefs that teachers develop within their participation in PDCs, because teacher knowledge influences instructional practice (Clark & Peterson, 1986; Duffee & Aikenhead, 1992). Also, we need provide them with opportunities “...not only to learn about scientific modeling, but to also engage in scientific modeling in ways that are grounded in specific science content”. (Nelson & Davis, 2011, p.25). In doing so, there is an emergent need to identify the *role* of teachers within these courses in order to help them learn *how to do science* and *talk about science* (Crawford & Cullin, 2004; Windshittl & Thompson, 2006) in the context of MCSI.

The present study emerged as a response to the aforementioned critical question. It aimed to investigate whether situating teachers as *learners* and *curriculum designers* within the context of a strategically designed PDC can impact on the development of their modeling ability, CK about models and modeling, and CuK for MCSI. A second aim of this thesis was to identify and describe the characteristics of teachers’ designed MCSI curriculum materials to shed light on the types of transformations that were enacted by the participants in their effort to apply the theoretical perspectives of MCSI approach for the design of their own curriculum materials. I summarize below what is learnt from answering the research questions of this study, and discuss the implications of the study, both for research and practice. The chapter ends with references on the limitations of this study and suggestions for future research.

## **6.2. What is learnt about teachers’ modeling ability development?**

Both the qualitative and quantitative findings that emerged in addressing the first research question of the study (*How does teachers’ modeling ability compare prior to and after their participation in the PDC?*) designate that the PDC had a great impact on the development of all components of teachers’ modeling ability in unison. In addition, since the evaluation of teachers’ modeling ability, prior to and after the PDC, was accomplished in a variety of content areas that differed to the one experienced during the PDC (e.g., elastic collisions), the findings that were revealed from the analysis of their responses in the modeling ability assessment tasks indicate not only the development of their modeling ability, but also their capability to transfer all components of their modeling ability into

new contents. Consequently, the findings of the present thesis indicate that the teachers who engaged as *learners* in the strategically designed MCSI setting of the PDC developed modeling skills, metacognitive knowledge about the modeling process, and meta-modeling knowledge with respect to the nature and purpose or utility of scientific models, and succeeded on transferring all of these modeling performances across content areas.

Despite teachers' competence in transferring all components of their modeling ability in unfamiliar domains, it was found that teachers' model formulation skill differed significantly between the two contents of the assessment tasks at the end of Phase 1 of the PDC. This finding was attributed to the content of the assessment tasks and it was claimed that the teachers might have performed better in the assessment task whose content was closer to the one of the MCSCI curriculum that was used during the PDC. Hence, it is important to examine the validity of this claim in future research attempts, by designing and administering assessment tasks that are closer and farther to the content of the curriculum of the intervention, and study afterwards the differences that might emerge.

Another issue that merits attention concerns the modeling ability framework that was used for the purposes of this study. As it was documented in Chapter 2, the modeling ability framework developed for the purposes of this thesis emerged as a response to closing a gap in the literature of what constitutes learners' modeling ability, because some authors conceived modeling ability as a thinking tool that pertains on several types of knowledge about the nature and purpose of models (e.g., Duit & Treagust, 2003; Harrison and Treagust, 2000), and others thought of modeling ability as a procedural tool that involves several modeling practices (e.g., Van Driel & Verloop, 2002). Accordingly, the framework came out of a synthesis of disparate research literatures on learning and teaching science through modeling, and entailed five modeling skills, as well as, two types of knowledge (metacognitive knowledge and meta-modeling knowledge) that were considered as essential for an individual to effectively and successfully engage within MCSI instructional settings. The framework served as a guide for the design and implementation of a sequence of MCSI activities in the context of 1-D elastic collisions, and it was empirically tested through the analysis of the data collected from the several assessment tasks designed and administered at the beginning and the end of Phase 1 of the PDC.

Consequently, I acknowledge that, at the culmination of this work, the groundings of this modeling ability framework can advance from the theoretical considerations its

conceptualization was based on at the outset of this thesis, to a more robust empirical documentation of the content and the connections among its constituent components, because the levels that emerged for each of the modeling ability components can potentially inform, enrich, and help in revising its foundations. To support this claim, I discuss below instances of two modeling ability components that their initial description needs revisions, due to the findings that emerged, and another case where its initial delineation appeared to be consistent with the findings.

To begin with, my understanding when defining the *model formulation skill* was that this skill pertains to a learner's ability to create an external representation of a phenomenon under study, and this representation would be comprehensive, if it entailed all four different types of model constituent components (e.g., objects, variables, processes, interactions). The analysis of teachers' created models in the two assessment tasks, through which their model formulation skill was evaluated, revealed that model's *representational comprehensiveness* was one out of the three aspects that teachers paid attention during creating their model. *Interpretive potential* and *predictive power* were the other two important aspects that characterized teachers' models, and consequently the definition of the model formulation skill should be revised to include not only the model's representational comprehensiveness, but also its interpretive potential and predictive power.

Likewise, the *comparing and contrasting models of the same phenomenon skill* was defined as the skill that learners apply to select the most appropriate model that represents a phenomenon under study based on certain criteria. These criteria referred to: (a) plausibility (e.g., the model represents parts of the phenomenon); (b) accuracy (e.g., the model represents the way the phenomenon functions in real life); and (c) allowance of the model to formulate and test predictions (Fortus et al., 2006; Lehrer & Shauble, 2000; Penner et al., 1997). However, the analysis of teachers' responses on the two tasks that were designed to evaluate this skill revealed that the teachers used an additional criterion to support the selection of the best (or the worst) model to represent a specific phenomenon. This criterion pertained to the model's *interpretive potential*, and was extracted from teachers' statements when made references of the presence or absence of a mechanism that illustrated how and why the model functions the way it did. Additionally, the first two criteria (e.g., model's plausibility and accuracy) that were used in defining the modeling skill under discussion were not examined individually and meticulously by the teachers;

instead model's *representational comprehensiveness* was used as a broader criterion that took into account both aforementioned criteria. Consequently, this is another instance that the findings that emerged point to specific modifications to the conceptualization of the comparing and contrasting models of the same phenomenon skill.

On the other hand, the conceptualization of the model evaluation and formulating ideas for improvement skill was found to be in line with the empirical evidence derived from teachers' responses in the two assessment tasks that were designed to evaluate this skill. Specifically, the most superior level that emerged from the analysis of teachers' responses in the aforementioned modeling skill entailed all three predefined criteria for evaluation (representation, interpretation, prediction).

In summary, the aforementioned considerations suggest the need for reframing the content of the modeling ability framework components on the basis of findings that emerged from the phenomenographic analysis of teachers' responses. The new version of the modeling ability framework that entails an updated description for each of its components based on the most superior level that emerged across the eight components is presented in Table 51.

A major outcome that comes out from the discussion of the findings related to the first research question, and can be spotted also in the updated description of the modeling ability components presented in Table 51, concerns the relationship and the degree of correlation among the various modeling ability components. It follows that all modeling ability components relate with each other to some extent, but most importantly, it appears that *meta-modeling knowledge with respect to nature of models* is at the heart of the development of all components. For instance, in examining teachers' created models as a means to get insight to the development of their model formulation skill, it emerged that the creation of their models was influenced and constrained by their meta-modeling knowledge about the nature of models, as their main focus at the end of Phase 1 of the PDC was on models' *representational complexity, interpretive potential, and predictive power*. Likewise, the teachers appeared to have used the abovementioned aspects of their meta-modeling knowledge, when comparing and contrasting candidate models of the same phenomenon to select the one that best described and interpreted the phenomenon it related with, or when evaluating a given model and formulated ideas for improvement. Based on this evidence, it can be argued that meta-modeling knowledge about the nature of models appears to guide the effective development and application of each individual component

of the modeling ability framework, and thus future attempts in enhancing teachers or students modeling ability should place significant emphasis on this aspect of meta-modeling knowledge. This claim concurs with Schwarz's and White's (2005) statement that without meta-modeling knowledge learners "...cannot fully understand the nature of science, and their ability to use and develop scientific models will be impeded" (p. 166).

To illustrate the relationships and interconnections among the components of the modeling ability framework identified from the findings, and to highlight the centrality of meta-modeling knowledge about the nature of models within these associations, a representation was created and is presented in Figure 45. The metacognitive knowledge about the modeling process appears in the surroundings of the modeling ability components, because it was found to entail an overall reflection of the modeling practices and knowledge that are enacted during learners' application of modeling skills and meta-modeling knowledge.

In conclusion, the modeling ability framework, as is shown in Figure 45, is important because it can be used by other researchers and teacher professional development trainers to track the changes of teachers' or students' modeling ability. Additionally, the identification of levels of increased sophistication that emerged for every component of the modeling ability framework provide a useful guide that educators can use to better understand and even predict many of their students' learning difficulties, when trying to develop their modeling ability. It can also assist in the design and organization of learning experiences and assessment tools that recognize and take advantage of the most likely trajectories towards expertise (learning progressions) followed by many students. Because textbooks rarely include modeling assignments that invite students to actively construct or test models (Erduran, 2001), the clarification of each constituent component of the modeling ability framework can inform science educators and curriculum designers on how to design assessment tasks to evaluate students' mastery of the skills or knowledge that relate to their modeling ability.

Table 51. Reframing the content of the modeling ability framework components on the basis of the most superior level that emerged from the qualitative analysis of the collected data

Component	Description
<u>I. Modeling skills</u>	
• <i>Model formulation</i>	The model (i) provides a <i>comprehensive representation</i> of the phenomenon (e.g., all types of the components of the phenomenon are represented), (ii) encompasses both a <i>mechanistic interpretation</i> for how the phenomenon functions and a <i>causal interpretation</i> that explains why the phenomenon functions the way it does; (iii) has a <i>strong predictive power</i>
• <i>Identification of model components</i>	Identification of examples of <i>objects, variables, interactions</i> and <i>processes</i> and <i>explicit</i> reference on the names of the identified model components.
• <i>Comparing and contrasting models of the same phenomenon</i>	Detection of the best or worst model based on model's (i) <i>representational comprehensiveness</i> , (ii) <i>interpretive potential</i> , and (iii) <i>predictive power</i>
• <i>Model evaluation and formulating ideas for improvement</i>	Evaluation of a model based on the identification of limitations of (i) the representational completeness of the model, e.g., absence of objects, or variables, or processes, or interactions among the components of the model (ii) the interpretive potential of the model (e.g, a mechanism that explains how and why the phenomenon functions is missing) (iii) the predictive power of the model
• <i>Model validation through comparison with phenomena in the same class</i>	Validation of a model through application of the model in a total new case of a phenomenon (e.g., a phenomenon of the same class) and study if the model fits in this new case
<u>II. Metacognitive knowledge about the modeling process</u>	
	The process of modeling involves (i) collecting information about the phenomenon (e.g., performing observations, identification of the objects, variables, processes and interactions of the phenomenon), (ii) selection of the best appropriate means for building the model, (iii) building a model based on the data collected, (iv) comparing the model and the real phenomenon or the model with other models, (v) evaluation of the model according to its representational completeness, interpretive potential and predictive power, (vi) improving the model, (vii) testing the validity of the model, (viii) repetition of the steps (iv) through (vii).
<u>III. Meta-modeling knowledge</u>	
▪ <i>Nature of models</i>	A model describes, represents and explains a phenomenon under study (e.g., provides a possible mechanism of how the phenomenon functions) and can be used to test predictions about specific aspects of the phenomenon
▪ <i>Purpose or utility of models</i>	The models serve as (i) instructional aids; (ii) simulations; (iii) facilitators of our conceptual understanding about a phenomenon under study; (iv) communication tools; (v) external representations for a phenomenon under study; and (vi) vehicles for formulating and testing of predictions

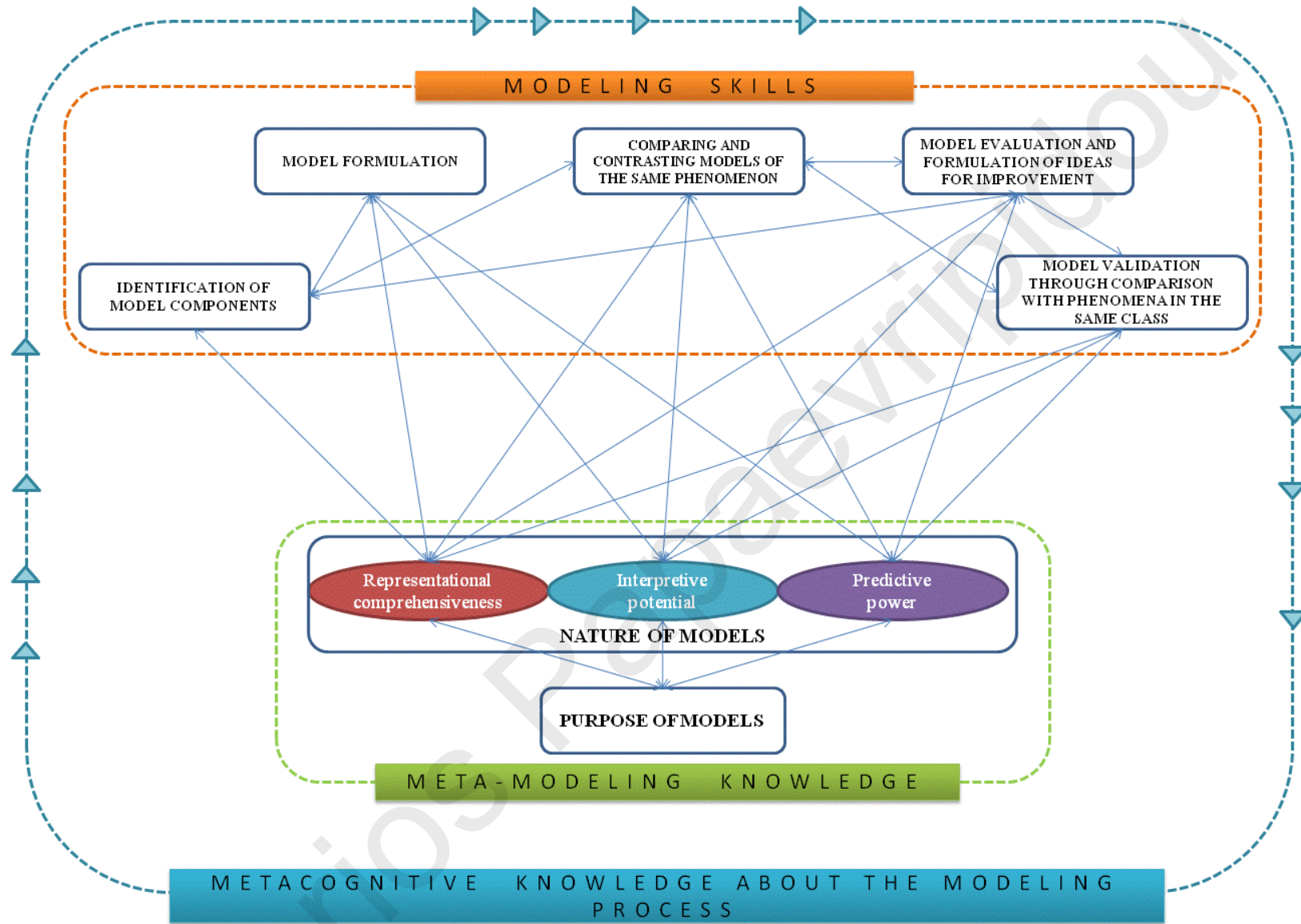


Figure 45. Representation of the emerged interconnections among the components of the modeling ability framework



### **6.3. What is learnt about teachers' CK about models and modeling and CuK for MCSI?**

As far as the second research question that this study aimed to address is concerned (*How do teachers' CK about models and modeling, and CuK for MCSI change as a result of their participation in the PDC?*), both findings pertaining to teachers' examination of CK about models and modeling, and CuK for MCSI revealed significant changes as teachers transitioned from the beginning to the end of the PDC. These changes can be attributed to several designed elements of the PDC that appeared to influence teachers' knowledge bases in several ways. Beginning with teachers' CK about models and modeling, it appeared in the discussion of the findings that the elements of the PDC that fostered the development of their epistemic understandings about the nature of models and modeling were as follows: (i) the design and implementation of the 1-D elastic collisions activity sequence within the MCSI curriculum; (ii) teachers' collaborative model building of the five 1-D elastic collision phenomena; (iii) the modeling tool, namely SC, that facilitated the dynamic model development and deployment of elastic collision phenomena; (iv) teachers' reflective journals that were completed after the end of each session of the PDC through which they were prompted to reflect on their modeling experiences and the "lessons learned" after each session; (v) peer evaluation of the models emerged from collaborative building during the sessions; and (vi) asynchronous discussions in the BeEP on topics emerged from teachers' reflective journals.

As far as teachers' CuK for MCSI is concerned, it appeared that the theoretical paper that focused on the presentation of the modeling ability framework and the analysis of its constituent components had a great impact on filling the gaps in teachers' evolved CuK, as they transitioned from Phase 1 to Phase 2 of the PDC, and helped them transform their modeling experiences into sophisticated CuK for MCSI. Consequently, I argue that active reflection and explicit support underlie successful transfer of knowledge and skills to new situations (Schwartz, Lederman, & Crawford, 2004).

All the elements that navigated the design and implementation of the PDC, not only served as productive scaffolds for the development of teachers' CK about models and modeling and CuK for MCSI, but also contributed in the collection of rich data through which teachers' CK and CuK progressions were constantly monitored and evaluated. Therefore, the use of these multiple data sources was essential in order to be able to analyze the teachers' knowledge changes (Magnusson et al. 1999). Also, the collection of data during

different phases of this study also contributed to ensure its internal validity. This methodological perspective was also underscored by Crawford & Cullin (2005) who demonstrated that the use of a single assessment instrument may give an inaccurate or an incomplete picture of a teacher's knowledge structure.

In sum, supporting teachers' understandings about models and modeling and how to enact science teaching through modeling, using modeling-based pedagogies, is demanding work, particularly for beginning teachers (Crawford & Cullin, 2004; De Jong, van Driel, & Verloop, 2005; Schwarz, 2009). MCSI was a totally new science pedagogy to teachers of this study, but – as the findings of this study indicate – with carefully designed PDCs, they can become more familiar with what scientific modeling and modeling-based pedagogies entail (Crawford & Cullin, 2004; Justi & van Driel, 2005; Kenyon et al., 2011; Schwarz, 2009; Windschitl & Thompson, 2006; Windschitl, Thompson, & Braaten, 2008b). Also, the modeling curriculum that shaped the design of such PDCs was of pivotal role, because it stressed the role of models explicitly and provided teachers with modeling tools in a way that teachers came to value this core practice and developed a level of facility in constructing and applying appropriate models (NRC, 2012).

#### **6.4. What is learnt about teachers' MCSI curriculum designs characteristics?**

The findings that emerged in response to the third research question of this study (*What are the characteristics of teachers' modeling-centered curriculum designs?*) indicate that teachers' curriculum designs can contribute to our understanding of how to better monitor teachers' knowledge bases that evolve as a result of their participation in PDC. I suggest that instead of using only questionnaires or interviews to capture teachers' views and understandings of a particular teaching approach, science educators might find it more productive to help teachers transform their acquired experiences and knowledge into designed artifacts (Papert, 1991). For instance, instead of just asking teachers to express what they have learned about MCSI after their participation in a PDC, an alternative and more productive approach that was used in this study is to ask them to design curriculum materials that would be grounded on the premises of MCSI. Teachers' curriculum designs serve as transparent prisms through which teacher educators can collect rich data about their understandings, their difficulties and their "genuine" CK, CuK, and PCK for MCSI.

Although this study did not attempt to examine explicitly teachers' development of PCK for MCSI, the findings that emerged in relation to the characteristics of teachers'

curriculum materials enabled the drawing of inferences about their PCK for MCSI, because the dimensions of analysis that emerged from open-coding of the data are compatible with the conceptualizations of PCK for MCSI reported in the literature (e.g., Davis et al., 2008; Henze et al., 2007; Justi & Van Driel, 2005; Nelson & Davis, 2011). The three different PCK for MCSI profiles that were portrayed in Chapter 5 provide insights of how teachers' PCK for MCSI has been influenced by the format, the content, and the context of the PDC. Consequently, this emergent finding is one of the contributions of the present study that merits to be addressed.

Following the recommendations of Nelson and Davis (2009), that for teachers to develop PCK for MCSI, “teacher educators may consider having preservice teachers work directly with curriculum materials they are likely to encounter in classrooms, and “model” for them the processes of analyzing and modifying a range of lesson plans (and/or unit plans) to infuse modeling” (p. 51), the findings of the present study demonstrate that engaging teachers as *learners* and *curriculum designers* in a strategically PDC, and supporting the development of their modeling ability, their CK for models and modeling, and their CuK for MCSI through productive scaffolds can create a gestalt shift in their philosophy of teaching science (Crawford, 2005a). Even though only nine participants appeared to have developed their PCK for MCSI consistent with Profile C and six others with Profile B, this is encouraging from the standpoint that during redesigning the unit they selected, they were working on their own without any guidance or feedback for the progress of their work. Hence, given that teachers quite often follow a “lonesome journey” during designing or adapting curricula for their own field of practice, it appears that the participants of this study left the PDC equipped with more articulate and robust ways to talk about scientific models and modeling, and with sufficient knowledge and skills necessary for changing radically their teaching and curriculum design orientations.

Reconsidering the dimensions of analysis through which teachers' characteristics of curriculum designs were elicited from, in conjunction with the description of the emerged levels for every dimension (see Table 43 for details), this matrix can alternatively be approached as a *framework* that provides a ground for examining teacher created curriculum materials from different perspectives, while at the same time inferences about the status of their CK, CuK, and PCK for MCSI can be abstracted. This framework informs and complements other PCK for MCSI frameworks reported in prior research (e.g., Henze et al., 2007; Justi and Gilbert, 2005; Nelson & Davis, 2011), as it entails descriptions for

aspects of teachers' CK, CuK, and PCK in a more analytical way. Furthermore, since the framework provides substantial information about the levels for each dimension of analysis, it can be used as a guide for the design of interventions that aim to impact on the development of teachers PCK for MCSI, and also, as a key for the analysis of teachers MCSI curriculum designs. Interested scholars are welcomed to use and implement this framework in their own field of research and share their findings with the scientific community.

### **6.5. Are there any connections between teachers modeling ability, CK about models and modeling, and CuK for MCSI?**

Looking at the findings that emerged, that provide insights about teachers' modeling ability, CK about models and modeling, and CuK for MCSI, it appears that these three domains overlap to some extent, indicating that interconnections among the three might exist. For instance, the evaluation criteria that were revealed from examining teachers' *model evaluation and formulating ideas for improvements skill* appear to be a subset of the criteria that teachers' suggested in a corresponding question in the CK test. Also, teachers' definitions for scientific models that were provided at the end of Phase 1 of the PDC concur with teachers' post-meta-modeling knowledge with respect to the nature of models. Furthermore, teachers' CuK with respect to the types of activities a MCSI curriculum should entail was found to encompass references that resemble to the components of the modeling ability framework. Therefore, it can be assumed that both three domains interact during their development in a way that elements from one domain inform elements of the other (e.g., CK about the evaluation criteria for scientific models inform the model formulation skill) or elements from one domain are transformed for the needs of the other (e.g., the modeling ability components are transformed to pieces of knowledge for the needs of the corresponding CuK for MCSI). Although these are mere assumptions that this thesis did not aim to investigate, they contribute, however, to our understanding of the types of knowledge or skills that might affect the development of other knowledge or skills during teachers' engagement in PDCs in the context of MCSI.

On the other hand, evidence from teachers' curriculum designs indicates that both three domains might influence or navigate the ways they are designing their curriculum. For instance, the models in SC that teachers created to illustrate the types of models they anticipated from their students to develop in a future implementation of their curriculum provide insights to both their model formulation skill (modeling ability domain), their

knowledge about the nature of models (CK about models and modeling domain), and the modeling activity through which they intend to implement the formulation of that particular model (CuK for MCSI domain).

The abovementioned relationships that depart from the findings of this study, in conjunction with the claim that teachers' PCK for MCSI can be inferred from their curriculum designs, are portrayed in Figure 46. Nevertheless, further systematic analysis of the data is needed to depict the kind of relationship among these domains.

In closing, I hope that this work will inform future studies interested on impacting on the development of teachers' modeling ability, CK about models and modeling, CuK for MCSI, and PCK for MCSI. As the findings of this thesis suggest, these four domains are areas ripe for further study.

## **6.6. Limitations of the study**

The limitations of the present study can be grouped in two areas: (i) assessment of teachers' modeling ability, CK about models and modeling, and CuK for MCSI; and (ii) the context of implementation of the PDC.

With respect to the first area of limitations, teachers' modeling ability was evaluated through text-based assessment tasks, and only in the post-test the model formulation skill was evaluated both within the text-based assessment tasks and the use of SC<sup>9</sup>. Given that modeling ability entails five modeling skills, as described and presented in Chapter 2, these modeling skills would be preferable to be evaluated during their application for completing the assessment tasks (e.g., through observation with the use of video recording equipment). Although this suggestion would provide more authentic data about the actual ways and the type of reasoning that is used during their application, it was a difficult task to be accomplished because of the number of the participants and the context within which the PDC was implemented (more of this factor are discussed below). Hence, in interpreting the findings this limitation should be explicitly stated.

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<sup>9</sup> The rationale behind this methodological decision was based on the fact that we wanted to examine if the modeling medium constrains teachers' model formulation skill. Comparing the models they created both in paper and in SC for the same phenomenon, it was found that these models differed only dynamically, as the information that was needed to make inferences about the status of their model formulation skill was identical in both cases.

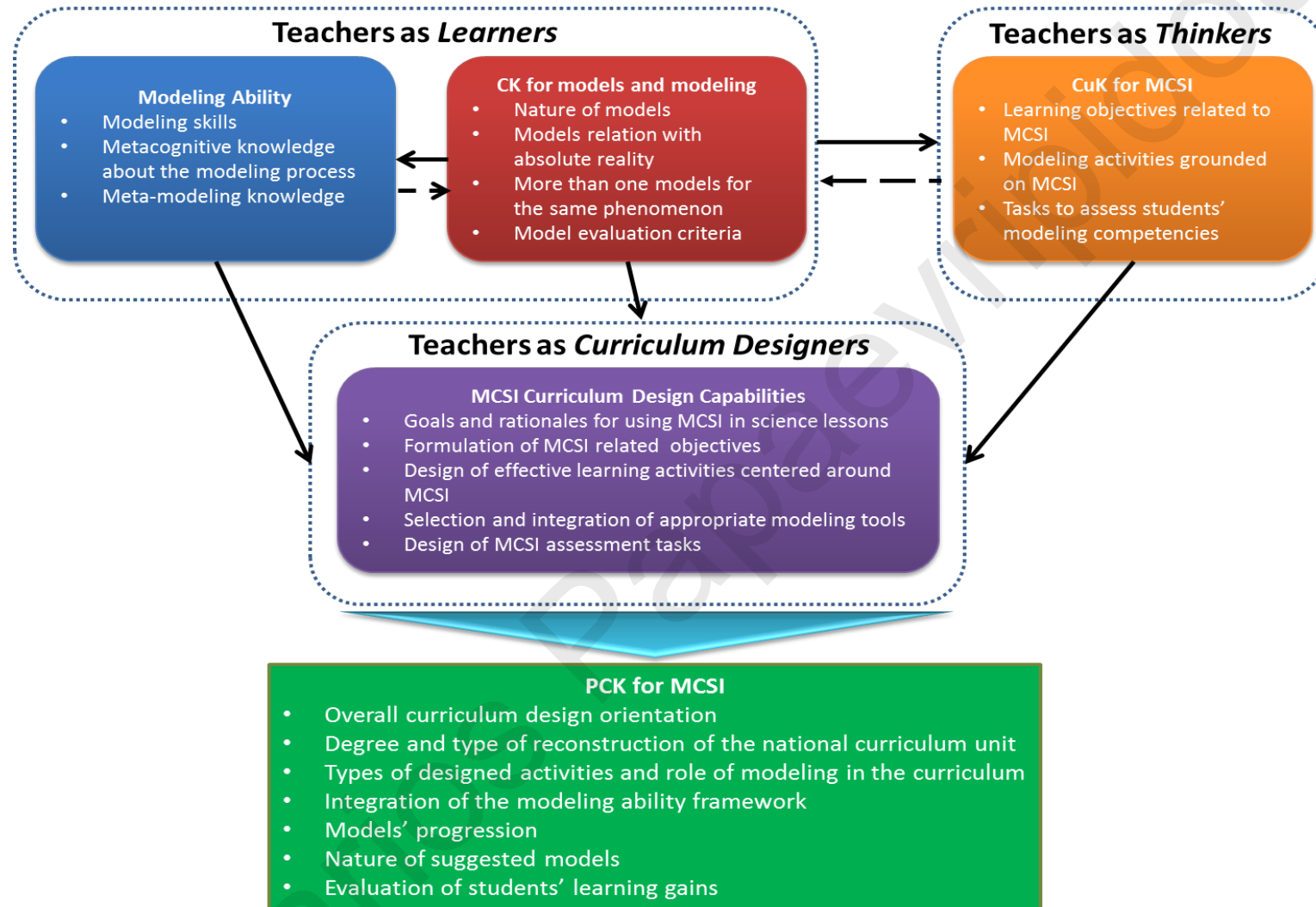


Figure 46. Plausible interconnections among teachers' modeling ability, CK about models and modeling, and CuK for MCSI

Likewise, teachers' CK and CuK were evaluated only through text-based tests, because of time limitations on behalf of the participants of the study. Although interviews as a research tool enable the collection of rich data, especially when the aim of the study is to elicit teachers' knowledge and understandings about a particular topic, the present study made use of other data collection instruments (e.g., assignments, reflective diaries, asynchronous discussions, peer evaluation of models, completed activity sheets) for analyzing and monitoring teachers' knowledge and their change. Thus, these multiple data sources used during different phases of the present research ensured its interval validity.

The second area of limitations concerns the context within which the PDC was implemented. As it was stated in Chapter 3, a selective master's science education course was used for implementing the PDC, and thus, the teachers who participated in the present study were the twenty graduate students who were attending the course at the time. Because all requirements of the PDC were simultaneously translated as compulsory requirements for the master's course, and given that the participants wished to receive a good grade after finishing the course, the data collected for the purposes of the design of this study were constrained by the abovementioned considerations. Hence, the data, the findings and the implications of this study might have been different if the PDC was implemented within another context (e.g., as part of the volunteer-based courses that are organized by the Pedagogical Institute in Cyprus and are attended by teachers from primary and secondary education).

### **6.7. Suggestions for future research**

In light of the findings and conclusions of this study, important questions and recommendations for future research are raised. For instance, given the finding that differences were yielded between teachers' model formulation skill after Phase 1 of the PDC, and the assumption made that the degree of proximity of content of the assessment tasks with to the content of the PDC curriculum might be used to explain the differences, it is important to examine the validity of this claim in future research attempts, by designing and administering assessment tasks that are closer and farther to the content of the curriculum of the intervention, and study afterwards the differences that might emerge.

Also, in light of the findings relating to the first research question (*How does teachers' modeling ability compare prior to and after their participation in the PDC?*) that

demonstrate teachers' significant development of all components of their modeling ability, a question that emerges is "*How does teachers' (or learners') modeling ability change as a result of their participation in a strategically designed instructional setting?*". The answer to this question would shed light on the cognitive processes taking place during learners' active engagement with the several modeling practices (e.g., model construction, model evaluation, model revision, model validation, and so on) and inform the modeling ability framework about *how* learners progress from a lower to an upper level of a specific modeling ability component. This question is also important because it will provide empirical documentation of the nature and types of relationships and interconnections between the components of the modeling ability framework that their existence was conjectured in this study (see Figure 45).

Lastly, in order to examine if there exist relationships among teachers' modeling ability, CK about models and modeling, and CuK for MCSI (an assumption made in an earlier section) and how these affect their curriculum design capabilities, future research is needed to depict the kind of relationships (if any) among these domains. A possible way to examine this is to find ways for capturing teachers' active reflections and pedagogical decisions at the instant time they are designing their curriculum materials.



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Marios Papaevripidou



## Appendix I

### “Modeling 1-D Elastic Collision Phenomena” Curriculum

Marios Papaevripidou

  Παρατηρήστε προσεκτικά το video1 που βρίσκεται στο folder «videos».  

[Τα δύο καρότσια είναι πανομοιότυπα και έχουν ίσες μάζες ( $m_1=m_2=50\text{ gr}$ ). Τα καρότσια κινούνται **χωρίς τριβή** στον αεροδιάδρομο. ]

1. Σχεδιάστε ένα διάγραμμα του οπτικογραφημένου Πειράματος 1 που παρακολουθήσατε και στη συνέχεια περιγράψτε τι παρουσιάζει το σχέδιό σας. Στο διάγραμμά σας να περιλάβετε όλα τα απαραίτητα στοιχεία, τα οποία θα βοηθήσουν κάποιον που δεν παρακολούθησε το βίντεο να καταλάβει τι είδατε να συμβαίνει.

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Περιγραφή του διαγράμματός μου



Το σχέδιο που δημιουργήσατε είναι ένα «**μ ο ν τ έ λ ο**» του φαινομένου που παρακολουθήσατε στο βίντεο, δηλαδή της σύγκρουσης δύο καρτσιών. Στις Φυσικές Επιστήμες προτιμούμε να φτιάχνουμε **απλά** μοντέλα για να αναπαραστήσουμε κάποιες από τις λειτουργίες ενός φαινομένου που παρατηρούμε.

👉 Πηγαίνετε πίσω στο σχέδιό σας και δώστε του το όνομα «Μοντέλο 1Α».

2. Ποιος από τους πιο κάτω αριθμούς μπορεί να αντιπροσωπεύει την ταχύτητα του **κινούμενου** καρτσιού **πριν από τη σύγκρουση**; (βάλτε σε κύκλο την επιλογή σας)

-50

0

50

Εξηγήστε γιατί διαλέξατε αυτό τον αριθμό.

3. Ποιος από τους πιο κάτω αριθμούς μπορεί να αντιπροσωπεύει την ταχύτητα του **ακίνητου** καρτσιού **πριν από τη σύγκρουση**; (βάλτε σε κύκλο την επιλογή σας)

-50

0

50

Εξηγήστε γιατί διαλέξατε αυτό τον αριθμό.

4. Ποιος από τους πιο κάτω αριθμούς μπορεί να αντιπροσωπεύει την ταχύτητα του **κινούμενου** καροτσιού **μετά τη σύγκρουση**;  
(βάλτε σε κύκλο την επιλογή σας)

-100      -50      -25      0      25      50      100

Εξηγήστε γιατί διαλέξατε αυτό τον αριθμό.

5. Ποιος από τους πιο κάτω αριθμούς μπορεί να αντιπροσωπεύει την ταχύτητα του **ακίνητου** καροτσιού **μετά τη σύγκρουση**;  
(βάλτε σε κύκλο την επιλογή σας)

-100      -50      -25      0      25      50      100

Εξηγήστε γιατί διαλέξατε αυτό τον αριθμό.

6. Α. Το ακίνητο καρότσι μετά τη σύγκρουσή του με το κινούμενο καρότσι αρχίζει να κινείται. Τι παρατηρείτε σε σχέση με την ταχύτητά του; Πώς προέκυψε η συγκεκριμένη ταχύτητα;

6.Β. Διαβάστε την απάντηση που έδωσε ο Αντρέας στην πιο πάνω ερώτηση.



Το ακίνητο καρότσι απέκτησε την ταχύτητά του μετά τη σύγκρουση του κινούμενου καροτσιού σε αυτό. Επειδή η ταχύτητα του ακίνητου καροτσιού είναι ίση με την ταχύτητα που είχε το κινούμενο καρότσι πριν από τη σύγκρουση, τότε θα μπορούσα να υποθέσω ότι το κινούμενο καρότσι «μετέφερε» την ταχύτητά του στο ακίνητο καρότσι κατά τη σύγκρουση. Επειδή το κινούμενο καρότσι μετέφερε όλη του την ταχύτητα στο ακίνητο καρότσι, μετά τη σύγκρουση η ταχύτητά του έχει μηδενιστεί.

Θα μπορούσε η απάντηση που έδωσε ο Αντρέας να αποτελέσει μια πιθανή εξήγηση για τις τιμές των ταχυτήτων των δύο καροτσιών μετά τη σύγκρουση; Εξηγήστε το συλλογισμό σας.

7. Πηγαίνετε στο «Μοντέλο 1Α» που δημιουργήσατε. Στο μοντέλο σας φαίνεται ξεκάθαρα ποια είναι η ταχύτητα του κάθε καροτσιού πριν και μετά από τη σύγκρουσή; Αν όχι, να συζητήσετε με τα μέλη της ομάδας σας για το πώς θα συμπεριλάβετε αυτή την πληροφορία στο μοντέλο σας. Γράψτε πιο κάτω τις εισηγήσεις της ομάδας σας για το πώς θα συμπεριλάβετε αυτά τα καινούρια στοιχεία στο μοντέλο σας.

8. Δημιουργήστε εδώ ένα καινούριο μοντέλο μετά από τις βελτιώσεις που αποφασίσατε να κάνετε στο Μοντέλο 1Α.

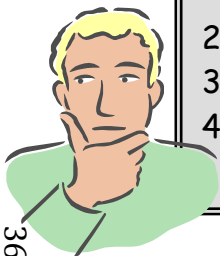


Στις Φυσικές Επιστήμες προσπαθούμε συνεχώς να τροποποιούμε τα μοντέλα μας, ώστε αυτά να **αναπαριστούν καλύτερα όλο και περισσότερες πτυχές του φαινομένου που μελετούμε** και επίσης να μπορούν να χρησιμοποιούνται για **διατύπωση και έλεγχο των προβλέψεών μας**. Η διαδικασία αυτή ονομάζεται «**βελτίωση του μοντέλου**».

☞ Ονομάστε το πιο πάνω μοντέλο «Μοντέλο 1Β».

Για να **βελτιώσουμε** ένα μοντέλο, κάνουμε τα εξής:

1. Πάμε πίσω στο φυσικό φαινόμενο που παρατηρούσαμε και εξετάζουμε αν το μοντέλο μας παρουσιάζει στοιχεία από το φυσικό φαινόμενο.
2. Βρίσκουμε καινούρια στοιχεία από το φυσικό φαινόμενο που θεωρούμε ότι είναι σημαντικά και λείπουν από το μοντέλο μας.
3. Βάζουμε τα καινούρια στοιχεία στο μοντέλο μας.
4. Εξετάζουμε αν το καινούριο μοντέλο μπορεί να **εξηγήσει** και να **περιγράψει** καλύτερα το φαινόμενο και κατά πόσο μπορεί να χρησιμοποιηθεί για τη **διατύπωση και εξέταση των προβλέψεών μας**.

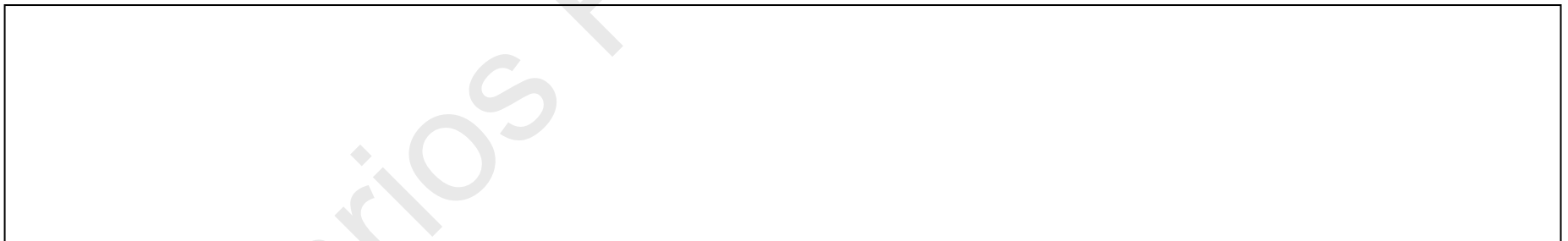


9. Για να δημιουργήσουμε τα μοντέλα 1A και 1B επιλέξαμε να κάνουμε ένα **σχέδιο** για να δείξουμε τι συμβαίνει πριν και μετά τη σύγκρουση των δύο καρτσιών.

A. Πιστεύετε ότι το σχέδιο είναι κατάλληλο για να δημιουργήσουμε ένα «καλό» μοντέλο για αυτό που είδαμε; Να εξηγήσετε πώς σκεφτήκατε την απάντησή σας. Αν η απάντησή σας είναι «όχι» να αναφέρετε κάποια μειονεκτήματα που παρουσιάζει το σχέδιο ως μέσο δημιουργίας ενός μοντέλου.



B. Αφού συζητήσετε με την ομάδα σας, να αναφέρετε με ποιο άλλο μέσο θα μπορούσατε να δημιουργήσετε το μοντέλο σας. Γράψτε πιο κάτω γιατί θεωρείτε το μέσο αυτό καλύτερο από το σχέδιο.





Το πρόγραμμα Stagecast Creator μας δίνει τη δυνατότητα να φτιάχνουμε **μοντέλα** για διάφορες καταστάσεις που παρατηρούμε στο φυσικό κόσμο. Στις Φυσικές Επιστήμες μας αρέσει να φτιάχνουμε **απλά** μοντέλα για να αναπαραστήσουμε κάποιες από τις λειτουργίες ενός φαινομένου που παρατηρούμε.

10. Περιγράψτε αναλυτικά πώς θα φτιάχνατε στο Stagecast Creator ένα μοντέλο που να παρουσιάζει ένα καρότσι να κινείται προς τα δεξιά και ακολούθως να συγκρούεται πάνω σε ένα ακίνητο καρότσι (βιντεοσκοπημένο πείραμα 1). Αναφερθείτε σε οποιαδήποτε εργαλεία ή εικόνες που θα χρησιμοποιήσετε για τη δημιουργία του μοντέλου σας.



Φτιάξτε το μοντέλο που περιγράψατε στο Α και ονομάστε το «Μοντέλο 1Γ».



**STOP!**

Ζητήστε ένα από τους διδάσκοντες να συζητήσει με την ομάδα σας !



11. Να συγκρίνετε αυτό το μοντέλο που δημιουργήσατε στο *Stagecast Creator* με μοντέλο που δημιουργήσατε στη σελίδα 4.

Ποιες ομοιότητες και ποιες διαφορές παρουσιάζουν τα δύο μοντέλα;

A. Ομοιότητες:

B. Διαφορές:

11. Στο «Μοντέλο 1Γ» το κινούμενο καρότσι κινείται με ταχύτητα 50 προς τα δεξιά και μετά τη σύγκρουσή του με το ακίνητο καρότσι, το ακίνητο καρότσι «αποκτά» ταχύτητα 50 προς τα δεξιά, ενώ η ταχύτητα του αρχικά κινούμενου καροτσιού μηδενίζεται.

**Π ρ ό β λ ε ψ η :**

A. Αν το κινούμενο καρότσι κινείται με ταχύτητα 100, ποια θα είναι η ταχύτητά του μετά τη σύγκρουση με το ακίνητο καρότσι;

B. Ποια θα είναι η ταχύτητα του ακίνητου καροτσιού μετά τη σύγκρουση;

Πράγματι, αν επαναλάβουμε το πείραμα που παρακολουθήσατε στο βίντεο 1 και το κινούμενο καρότσι κινείται με ταχύτητα 100 προς τα δεξιά, θα παρατηρήσουμε (μέσα από μετρήσεις που θα κάνουμε στις ταχύτητες των καροτσιών μετά τη σύγκρουση) ότι η ταχύτητα του κινούμενου καροτσιού μετά τη σύγκρουση γίνεται 0, ενώ το ακίνητο καρότσι αποκτά ταχύτητα 100 προς τα δεξιά μετά τη σύγκρουση.

12. Αν δεν ήταν δυνατό να επαναλάβετε το πιο πάνω πείραμα για να είστε σε θέση να μετρήσετε τις ταχύτητες των καροτσιών μετά τη σύγκρουση, με ποιο τρόπο θα μπορούσατε να εξετάσετε αν η πρόβλεψή σας είναι ορθή ή λανθασμένη;



Ένα από τα χαρακτηριστικά που πρέπει να πληροί ένα **μοντέλο** που κατασκευάζουμε είναι να μας παρέχει τη δυνατότητα να **διατυπώνουμε και να εξετάζουμε προβλέψεις** για διάφορες καταστάσεις που σχετίζονται με το υπό μελέτη φαινόμενο.

13.A. Με βάση το πώς σχεδιάσατε και κατασκευάσατε το Μοντέλο 1Γ στο Stagecast Creator, θα μπορούσε κάποιος να χρησιμοποιήσει αυτό το μοντέλο για να **προβλέψει** και να **εξετάσει** στη συνέχεια ποια θα είναι η ταχύτητα των δύο καρτσιών μετά τη σύγκρουση, αν οι αρχικές τους ταχύτητες ήταν: Ταχύτητα αριστερού καρτσιού= 150, Ταχύτητα δεξιού καρτσιού= 0 ;

B. Αν η απάντησή σας στο A είναι ΝΑΙ, προβλέψτε ποιες θα είναι οι ταχύτητες των καρτσιών μετά την κρούση και ακολούθως να εξετάσετε αν η πρόβλεψή σας είναι ορθή ή λανθασμένη χρησιμοποιώντας το μοντέλο σας.

<b>Πρόβλεψη</b>	
Μετά τη σύγκρουση	
Ταχύτητα αριστερού καρτσιού=	Ταχύτητα δεξιού καρτσιού=

Γ. Αν η απάντησή σας στο A είναι ΟΧΙ, να συζητήσετε στην ομάδα σας και να αποφασίσετε τι είδους βελτιώσεις πρέπει να κάνετε στο μοντέλο σας, ώστε να σας επιτρέψει να εξετάζετε προβλέψεις παρόμοιες με αυτή που διατυπώθηκε στο 13.A. Γράψτε εδώ τις βελτιώσεις που θα κάνετε στο μοντέλο σας.

Εφόσον προβείτε στις βελτιώσεις που εισηγηθήκατε πιο πάνω, να προβλέψτε ποιες θα είναι οι ταχύτητες των καρτσιών μετά την κρούση και ακολούθως να εξετάσετε αν η πρόβλεψή σας είναι ορθή ή λανθασμένη χρησιμοποιώντας το μοντέλο σας.

<b>Πρόβλεψη:</b> Μετά τη σύγκρουση → Ταχύτητα αριστερού καρτσιού= Ταχύτητα δεξιού καρτσιού=
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Δ. Ξαναγράψτε όλα τα βήματα που ακολουθήσατε για να κατασκευάσετε το Μοντέλο 1Γ στο *Stagecast Creator*, λαμβάνοντας υπόψη τις αλλαγές που κάνατε καθώς κατασκευάζατε το μοντέλο. Προσοχή! Αν ακολουθήσει κάποιος την περιγραφή του μοντέλου που δημιουργήσατε στο *Stagecast Creator*, θα πρέπει να καταλήξει στο μοντέλο που μόλις έχετε κατασκευάσει.



**STOP!**

Ζητήστε ένα από τους διδάσκοντες να συζητήσει με την ομάδα σας !

14. Α. Με βάση το μοντέλο που έχετε κατασκευάσει στο Stagecast Creator, ποια είναι η επίδραση-συνεισφορά του κινούμενου καροτσιού προς το ακίνητο καρότσι;

.....  
.....

Β. Ποια είναι η επίδραση του ακίνητου καροτσιού προς το κινούμενο καρότσι;

.....  
.....

Γ. Με βάση τα πιο πάνω, πώς θα ονομάζατε το «Μοντέλο 1Γ»;

Μοντέλο .....

Δ. Συζητήστε στην ολομέλεια της τάξης για το όνομα που δώσατε στο μοντέλο σας. Στη συζήτηση θα ήταν καλό να καταλήξετε σε ένα κοινό όνομα για το μοντέλο που κατασκευάσατε.

Ποιο όνομα αποφασίστηκε από όλη την τάξη;

Μοντέλο .....

15. Συγκρίνετε το τελικό σας μοντέλο με το πραγματικό φαινόμενο. Ποιες ομοιότητες και ποιες διαφορές παρουσιάζουν;

A. Ομοιότητες:

B. Διαφορές:







**STOP!**

Ζητήστε ένα από τους διδάσκοντες να συζητήσει με την ομάδα σας !



Ανεβάστε (upload) το τελικό σας μοντέλο που δημιουργήσατε στο Stagecast Creator στο Blackboard και περιγράψτε τι κάνει το μοντέλο σας. Επισκεφτείτε τα μοντέλα που ανέβασαν οι υπόλοιπες ομάδες και κάντε σχόλια-κριτική σε αυτά.

  Παρατηρήστε προσεκτικά το video2 που βρίσκεται στο folder «videos».  

[Τα δύο καρότσια είναι πανομοιότυπα και έχουν ίσες μάζες ( $m_1=m_2=50\text{ gr}$ ). Τα καρότσια κινούνται **χωρίς τριβή** στον αεροδιάδρομο. ]

1. Δημιουργήστε πιο κάτω στο χαρτί ένα μοντέλο για το Πείραμα 2 που παρακολουθήσατε και στη συνέχεια περιγράψτε τι παρουσιάζει το μοντέλο σας. Στο διάγραμμά σας να περιλάβετε όλα τα απαραίτητα στοιχεία, τα οποία θα βοηθήσουν κάποιον που δεν παρακολούθησε το βίντεο να καταλάβει τι είδατε να συμβαίνει.

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Περιγραφή του διαγράμματός μου

2. Ποιος από τους πιο κάτω αριθμούς μπορεί να αντιπροσωπεύει την ταχύτητα του καροτσιού 1 (αριστερά) πριν από τη σύγκρουση; (βάλτε σε κύκλο την επιλογή σας)

-100      -50      -25      0      25      100      50

3. Ποιος από τους πιο κάτω αριθμούς μπορεί να αντιπροσωπεύει την ταχύτητα του καροτσιού 2 (δεξιά) πριν από τη σύγκρουση; (βάλτε σε κύκλο την επιλογή σας)

-100      -50      -25      0      25      100      50

4. Ποιος από τους πιο κάτω αριθμούς μπορεί να αντιπροσωπεύει την ταχύτητα του καροτσιού 1 (αριστερά) μετά τη σύγκρουση; (βάλτε σε κύκλο την επιλογή σας)

-100      -50      -25      0      25      100      50

5. Ποιος από τους πιο κάτω αριθμούς μπορεί να αντιπροσωπεύει την ταχύτητα του καροτσιού 2 (δεξιά) μετά τη σύγκρουση; (βάλτε σε κύκλο την επιλογή σας)

-100      -50      -25      0      25      100      50

Εξηγήστε γιατί διαλέξατε τους συγκεκριμένους αριθμούς στις πιο πάνω τέσσερις περιπτώσεις.



6. Θα μπορούσατε να χρησιμοποιήσετε το "μοντέλο μεταφοράς της ταχύτητας" που κατασκευάσατε στο προηγούμενο μάθημα για να δείξετε τι συμβαίνει στο βίντεο του σημερινού μαθήματος; Εξηγήστε πώς σκεφτήκατε την απάντησή σας.



Ανοίξτε το αρχείο στο οποίο σώσατε το "μοντέλο μεταφοράς της ταχύτητας".

Δώστε τιμές στις ταχύτητες των δύο καρτσιών, ώστε να ανταποκρίνονται στις ταχύτητες πριν από την κρούση που είδατε στο οπτικογραφημένο πείραμα.

7. Εξετάστε αν το μοντέλο αυτό λειτουργεί σύμφωνα με το πείραμα που παρακολουθήσατε στο βίντεο.

Γράψτε τις παρατηρήσεις και τα σχόλιά σας.

8. Θα προσπαθήσουμε τώρα να δημιουργήσουμε ένα καινούριο μοντέλο που να αναπαριστά αυτό το πείραμα.

A. Ας επικεντρωθούμε πρώτα στο καροτσάκι 1.

Πριν και μετά τη σύγκρουση, ποιες αλλαγές παρατηρείτε:

i) στην τιμή της ταχύτητας του καροτσιού;

ii) στη φορά της ταχύτητας του καροτσιού;

B. Ας δούμε τώρα το καροτσάκι 2.

Πριν και μετά τη σύγκρουση, ποιες αλλαγές παρατηρείτε:

i) στην τιμή της ταχύτητας του καροτσιού;

ii) στη φορά της ταχύτητας του καροτσιού;

9. Με βάση τις διαπιστώσεις που κάνατε πιο πάνω, τι θα μπορούσε το νέο μοντέλο σας να κάνει όταν τα δύο καρότσια συγκρούονται;

10. Α. Διαβάστε την απάντηση που έδωσε ο Αντρέας στην πιο πάνω ερώτηση.



Όταν παρακολούθησα το βίντεο 2 και προσπάθησα να σκεφτώ ένα μοντέλο που να αναπαριστά αυτή την περίπτωση κρούσης, κατέληξα στο εξής: τη στιγμή της σύγκρουσης θα διατηρείται η τιμή της ταχύτητας των δύο καροτσιών, αλλά θα αλλάζει η φορά της ταχύτητας του καθενός. Έτσι το αριστερά κινούμενο καρότσι θα συνεχίσει να κινείται με την ίδια τιμή στην ταχύτητά του που κινούνταν και πριν από τη σύγκρουση και θα αλλάξει απλά φορά η ταχύτητά του τη στιγμή της σύγκρουσης. Το ίδιο θα συμβαίνει και με το δεξιά κινούμενο καρότσι.

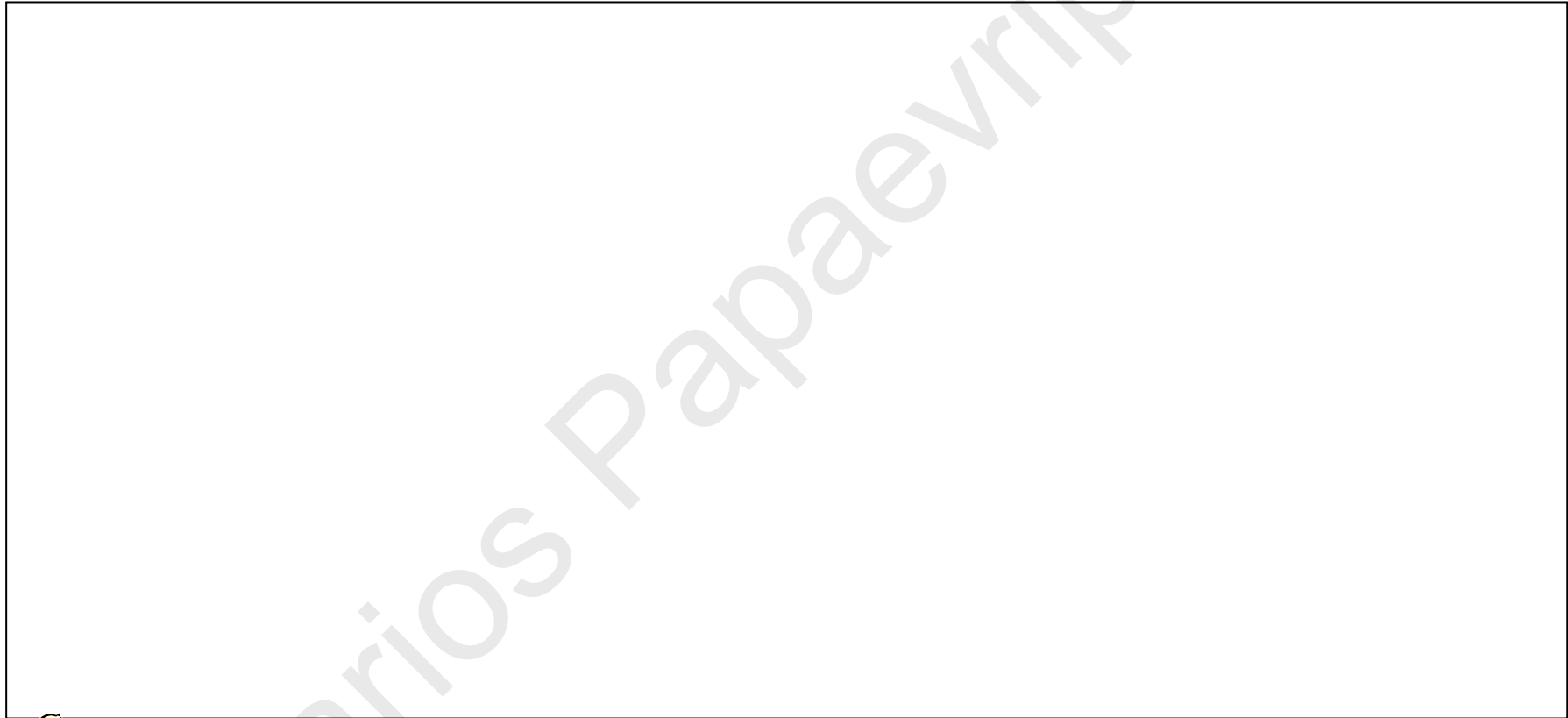
Θα μπορούσε η απάντηση που έδωσε ο Αντρέας να αποτελέσει μια πιθανή εξήγηση για τις ταχύτητες των δύο καροτσιών μετά τη σύγκρουση; Εξηγήστε το συλλογισμό σας.



**STOP!**

Ζητήστε ένα από τους διδάσκοντες να συζητήσει με την ομάδα σας!

11. Με βάση τις απαντήσεις που δώσατε στο 9 και 10 πιο πάνω να περιγράψετε τα βήματα δημιουργίας ενός μοντέλου στο Stagecast Creator το οποίο να αναπαριστά την περίπτωση κρούσης που παρακολουθήσατε στο βίντεο 2. Αναφερθείτε σε οποιαδήποτε εργαλεία, χαρακτήρες, μεταβλητές, κανόνες που θα χρησιμοποιήσετε ή θα δημιουργήσετε για την κατασκευή του μοντέλου σας.



Δημιουργήστε το μοντέλο που περιγράψατε πιο πάνω στο Stagecast Creator. Αν το μοντέλο που περιγράψατε πιο πάνω δεν λειτουργεί όπως θα περιμένατε, σκεφτείτε ποιες αλλαγές πρέπει να κάνετε.

12. Συγκρίνετε το μοντέλο που μόλις κατασκευάσατε με το πείραμα 2 που παρακολουθήσατε στο βίντεο. Ποιες ομοιότητες και ποιες διαφορές παρουσιάζουν;

Ομοιότητες:

Διαφορές:

13. Ποια είναι τα συστατικά στοιχεία του μοντέλου που δημιουργήσατε στο Stagecast Creator;



**STOP!**

Ζητήστε ένα από τους διδάσκοντες να συζητήσει με την ομάδα σας !



Στις Φυσικές Επιστήμες ένα μοντέλο θεωρείται ικανοποιητικό, αν περιλαμβάνει τα πιο κάτω συστατικά στοιχεία:

1. αντικείμενα
2. μεταβλητές
3. διαδικασίες
4. αλληλεπιδράσεις μεταξύ αντικειμένων, μεταβλητών και διαδικασιών

14. Να πάτε πίσω στο μοντέλο που δημιουργήσατε στο Stagecast Creator και να εντοπίσετε παραδείγματα για το κάθε συστατικό στοιχείο που αναφέρεται πιο πάνω.

Να γράψετε τα αποτελέσματά σας στον ακόλουθο πίνακα.

Συστατικά στοιχεία	Παραδείγματα από το μοντέλο σας
1. αντικείμενα	
2. μεταβλητές	
3. διαδικασίες	
4. αλληλεπιδράσεις μεταξύ αντικειμένων, μεταβλητών, διαδικασιών	



**STOP!**

Ζητήστε ένα από τους διδάσκοντες να συζητήσει με την ομάδα σας !

15. Στο προηγούμενο μάθημα μάθατε ότι ένα από τα χαρακτηριστικά που πρέπει να πληροί ένα **μοντέλο** που κατασκευάζουμε είναι να μας παρέχει τη δυνατότητα να **διατυπώνουμε και να εξετάζουμε προβλέψεις** για διάφορες καταστάσεις που σχετίζονται με το υπό μελέτη φαινόμενο.

Τι θα κάνατε για να διαπιστώσετε κατά πόσο το μοντέλο που δημιουργήσατε στο Stagecast Creator πληροί το πιο πάνω κριτήριο; Εξηγήστε την απάντησή σας και εφαρμόστε αυτό που εισηγήσατε στην απάντησή σας για να διαπιστώσετε αν το μοντέλο σας πληροί αυτό το κριτήριο.

16. Ονομάστε το μοντέλο σας με βάση τον τρόπο λειτουργίας του (*Θυμηθείτε ότι το προηγούμενο μοντέλο το ονομάσατε "μοντέλο μεταφοράς της ταχύτητας"*, γιατί κάνατε το κινούμενο καρότσι να μεταφέρει την ταχύτητά του στο ακίνητο καρότσι). Εξηγήστε γιατί επιλέξατε αυτό το όνομα.



**STOP!**

Ζητήστε ένα από τους διδάσκοντες να συζητήσει με την ομάδα σας!



17. Ελέγξτε αν το καινούριο μοντέλο που κατασκευάσατε με βάση το Πείραμα 2 μπορεί να εφαρμοστεί στο οπτικογραφημένο Πείραμα 1 που είδατε την προηγούμενη φορά. Για το σκοπό αυτό δώστε στα καρτσάκια τις τιμές της ταχύτητας που είχαν στο προηγούμενο πείραμα και τρέξτε το μοντέλο σας.

Γράψτε τα αποτελέσματα εφαρμογής του καινούριου σας μοντέλου στο Πείραμα 1. Προσπαθήστε να εξηγήσετε τις παρατηρήσεις σας.

Στις Φυσικές Επιστήμες όταν ένα μοντέλο που κατασκευάσαμε με βάση ένα φαινόμενο δεν λειτουργεί σε ένα φαινόμενο της ίδιας κλάσης, προσπαθούμε να προσδιορίσουμε τους λόγους που δεν λειτουργεί το μοντέλο μας και δημιουργούμε ένα καινούριο μοντέλο που να έχει τη δυνατότητα να εφαρμόζει και στα δύο φαινόμενα της ίδιας κλάσης. Η διαδικασία αυτή ονομάζεται **εγκυροποίηση του μοντέλου**.







Στο επόμενο μάθημα θα ασχοληθούμε πρακτικά με την εγκυροποίηση των μοντέλων που δημιουργήσατε μέχρι τώρα στο *Stagecast Creator*.





Ανεβάστε (upload) το τελικό σας μοντέλο που δημιουργήσατε στο Stagecast Creator στο Blackboard και περιγράψτε τι κάνει το μοντέλο σας. Επισκεφτείτε τα μοντέλα που ανέβασαν οι υπόλοιπες ομάδες και κάντε σχόλια-κριτική σε αυτά.

Marios Papaevripiou

  Παρατηρήστε προσεκτικά το video3 που βρίσκεται στο folder «videos».  

[Τα δύο καρότσια είναι πανομοιότυπα και έχουν ίσες μάζες ( $m_1=m_2=50\text{ gr}$ ). Τα καρότσια κινούνται χωρίς τριβή στον αεροδιάδρομο. ]

1. Δημιουργήστε πιο κάτω στο χαρτί ένα μοντέλο για το Πείραμα 3 που παρακολουθήσατε και στη συνέχεια περιγράψτε τι παρουσιάζει το μοντέλο σας. Στο διάγραμμά σας να περιλάβετε όλα τα απαραίτητα στοιχεία, τα οποία θα βοηθήσουν κάποιον που δεν παρακολούθησε το βίντεο να καταλάβει τι είδατε να συμβαίνει.

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Περιγραφή του διαγράμματός μου

2. Ποιος από τους πιο κάτω αριθμούς μπορεί να αντιπροσωπεύει την ταχύτητα του καροτσιού 1 (αριστερά) πριν από τη σύγκρουση; *(βάλτε σε κύκλο την επιλογή σας)*

-90      -50      -25      0      25      50      90

3. Ποιος από τους πιο κάτω αριθμούς μπορεί να αντιπροσωπεύει την ταχύτητα του καροτσιού 2 (δεξιά) πριν από τη σύγκρουση; *(βάλτε σε κύκλο την επιλογή σας)*

-90      -50      -25      0      25      50      90

4. Ποιος από τους πιο κάτω αριθμούς μπορεί να αντιπροσωπεύει την ταχύτητα του καροτσιού 1 μετά τη σύγκρουση; *(βάλτε σε κύκλο την επιλογή σας)*

-90      -50      -25      0      25      50      90

5. Ποιος από τους πιο κάτω αριθμούς μπορεί να αντιπροσωπεύει την ταχύτητα του καροτσιού 2 μετά τη σύγκρουση; *(βάλτε σε κύκλο την επιλογή σας)*

-90      -50      -25      0      25      50      90

Εξηγήστε γιατί διαλέξατε τους συγκεκριμένους αριθμούς στις πιο πάνω τέσσερις περιπτώσεις.

6. Θα μπορούσατε να χρησιμοποιήσετε το "μοντέλο αλλαγής κατεύθυνσης της ταχύτητας" που κατασκευάσατε στο προηγούμενο μάθημα για να δείξετε τι συμβαίνει στο βίντεο του σημερινού μαθήματος; Εξηγήστε πώς σκεφτήκατε την απάντησή σας.



Ανοίξτε το αρχείο στο οποίο σώσατε το "μοντέλο αλλαγής κατεύθυνσης της ταχύτητας".

Δώστε τιμές στις ταχύτητες των δύο καρτσιών, ώστε να ανταποκρίνονται στις ταχύτητες των δύο καρτσιών πριν από την κρούση που είδατε στο οπτικογραφημένο Πείραμα 3.

7. Εξετάστε αν το μοντέλο αυτό λειτουργεί σύμφωνα με το πείραμα που παρακολουθήσατε στο βίντεο.

Γράψτε τις παρατηρήσεις και τα σχόλιά σας.

8. Βάλτε σε κύκλο την ορθή απάντηση

Το μοντέλο "αλλαγής κατεύθυνσης της ταχύτητας" εφαρμόζει/δεν εφαρμόζει στο Πείραμα 3.

9. Θα μπορούσατε να χρησιμοποιήσετε το "μοντέλο μεταφοράς της ταχύτητας" που κατασκευάσατε με βάση το Πείραμα 1 για να δείξετε τι συμβαίνει στο Πείραμα 3; Εξηγήστε πώς σκεφτήκατε την απάντησή σας.



Ανοίξτε το αρχείο στο οποίο σώσατε το "μοντέλο μεταφοράς της ταχύτητας".

Δώστε τιμές στις ταχύτητες των δύο καρτσιών, ώστε να ανταποκρίνονται στις ταχύτητες των δύο καρτσιών πριν από την κρούση που είδατε στο βιντεοσκοπημένο Πείραμα 3.

Εξετάστε αν το μοντέλο αυτό λειτουργεί σύμφωνα με το Πείραμα 3 που παρακολουθήσατε στο βίντεο.

Γράψτε τις παρατηρήσεις και τα σχόλιά σας εδώ.

Βάλτε σε κύκλο την ορθή απάντηση

Το "μοντέλο μεταφοράς της ταχύτητας" εφαρμόζει / δεν εφαρμόζει στο Πείραμα 3;

10. Θυμηθείτε ότι στις Φυσικές Επιστήμες, όταν ένα μοντέλο που κατασκευάσαμε δεν λειτουργεί σε μια καινούρια κατάσταση, προσπαθούμε να προσδιορίσουμε τους λόγους που δεν λειτουργεί το μοντέλο μας και δημιουργούμε ένα καινούριο μοντέλο που να αναπαριστά την καινούρια κατάσταση. Πώς ονομάζεται αυτή η διαδικασία;

11. Θα προσπαθήσουμε τώρα να δημιουργήσουμε ένα καινούριο μοντέλο που να αναπαριστά το τι είδατε να συμβαίνει στο Πείραμα 3.

A. Ας επικεντρωθούμε πρώτα στο καροτσάκι 1.

Πριν και μετά τη σύγκρουση, ποιες αλλαγές παρατηρείτε:

i) στην τιμή της ταχύτητας του καροτσιού;

ii) στη φορά της ταχύτητας του καροτσιού;

B. Ας δούμε τώρα το καροτσάκι 2.

Πριν και μετά τη σύγκρουση, ποιες αλλαγές παρατηρείτε:

i) στην τιμή της ταχύτητας του καροτσιού;

ii) στη φορά της ταχύτητας του καροτσιού;

12. Με βάση τις διαπιστώσεις που κάνατε πιο πάνω, τι θα μπορούσε το νέο μοντέλο σας να κάνει όταν τα δύο καρότσια συγκρούονται;



13. Με βάση τις απαντήσεις που δώσατε στο 11 και 12 πιο πάνω να περιγράψετε τα βήματα δημιουργίας ενός μοντέλου στο Stagecast Creator το οποίο να αναπαριστά την περίπτωση κρούσης που παρακολουθήσατε στο βίντεο 3. Αναφερθείτε σε οποιαδήποτε εργαλεία, χαρακτήρες, μεταβλητές, κανόνες που θα χρησιμοποιήσετε ή θα δημιουργήσετε για την κατασκευή του μοντέλου σας.





Δημιουργήστε το μοντέλο που περιγράψατε πιο πάνω στο Stagecast Creator. Αν το μοντέλο που περιγράψατε πιο πάνω δεν λειτουργεί όπως θα περιμένατε, σκεφτείτε ποιες αλλαγές πρέπει να κάνετε.

14. Θα μπορούσε κάποιος να χρησιμοποιήσει το μοντέλο που μόλις δημιουργήσατε για να υπολογίσει τις ταχύτητες δύο καροτσιών ίσης μάζας που κινούνται με αρχικές ταχύτητες  $U_1 = 92$  και  $U_2 = -27$ ; Εξηγήστε πώς σκεφτήκατε την απάντησή σας και ακολούθως δοκιμάστε να δώσετε τις πιο πάνω ταχύτητες στα καρότσια του μοντέλου σας για να εξετάσετε κατά πόσο το μοντέλο σας μπορεί να εφαρμοστεί σε αυτή την περίπτωση κρούσης. Αν το μοντέλο σας δεν εφαρμόζει σε αυτή την περίπτωση κρούσης, να εξηγήσετε πιο κάτω τους λόγους που καθιστούν αδύνατη την εφαρμογή του μοντέλου σας σε αυτή την περίπτωση και να περιγράψετε πώς θα βελτιώσετε το μοντέλο σας, ώστε να είναι ικανό να ανταποκριθεί σε οποιαδήποτε περίπτωση κρούσης δύο καροτσιών ίσων μαζών που κινούνται το ένα προς το άλλο με οποιαδήποτε τιμή στην ταχύτητά τους.

15. Συγκρίνετε το μοντέλο που μόλις κατασκευάσατε με το πείραμα 2 που παρακολουθήσατε στο βίντεο. Ποιες ομοιότητες και ποιες διαφορές παρουσιάζουν;

Ομοιότητες:

Διαφορές:



16. Είναι χρήσιμο να συγκρίνουμε ένα μοντέλο που δημιουργούμε με το αντίστοιχο φυσικό φαινόμενο που αναπαριστά; Εξηγήστε πώς σκεφτήκατε την απάντησή σας.

17. Ποια είναι τα συστατικά στοιχεία του μοντέλου που δημιουργήσατε στο Stagecast Creator;



**STOP!**

Ζητήστε ένα από τους διδάσκοντες να συζητήσει με την ομάδα σας !

18. Ονομάστε το μοντέλο σας με βάση τον τρόπο λειτουργίας του (*Θυμηθείτε ότι το προηγούμενο μοντέλο το ονομάσατε "μοντέλο αλλαγής κατεύθυνσης της ταχύτητας"*, γιατί η ταχύτητα των κινούμενων καρτσιών αλλάζει κατεύθυνση, όταν συγκρουστούν). Εξηγήστε γιατί επιλέξατε αυτό το όνομα.

Όνομα:

Γιατί δώσαμε αυτό το όνομα στο μοντέλο μας;

19. Να συνοψίσετε στον πιο κάτω πίνακα τα 3 μοντέλα που έχετε κατασκευάσει μέχρι τώρα στο Stagecast Creator για να αναπαραστήσετε τις 3 διαφορετικές περιπτώσεις κρούσεων που παρακολουθήσατε στα βίντεο 1, 2 και 3.

Οπτικογραφημένο Πείραμα	Όνομα μοντέλου	Περιγραφή μοντέλου
1		
2		
3		

20. Ποιες είναι οι δυνατότητες και ποιοι οι περιορισμοί του κάθε μοντέλου σας;

Μοντέλο	Δυνατότητες	Περιορισμοί
1		
2		
3		

21. Είναι κάποιο από τα τρία σας μοντέλα καλύτερο ή χειρότερο από τα υπόλοιπα; Εξηγήστε πώς σκεφτήκατε την απάντησή σας.



**STOP!**

Ζητήστε ένα από τους διδάσκοντες να συζητήσει με την ομάδα σας !



Στις Φυσικές Επιστήμες ένα μοντέλο μπορεί να δημιουργηθεί με διάφορους τρόπους ανάλογα, π.χ. λεκτική περιγραφή, σχέδιο-διάγραμμα, μαθηματική σχέση, γραφική παράσταση, χρήση λογισμικού μοντελοποίησης, χρήση πραγματικών υλικών, κτλ. Έτσι, ανάλογα με το μέσο που χρησιμοποιείται για την αναπαράσταση ενός φυσικού φαινομένου, ένα μοντέλο μπορεί να είναι *λεκτικό, γραφικό, μαθηματικό, υπολογιστικό*, κτλ.

22. Μέχρι τώρα έχετε δημιουργήσει μοντέλα στο χαρτί (γραφικό μοντέλο) και στο λογισμικό Stagecast Creator (υπολογιστικό μοντέλο). Θα προσπαθήσουμε τώρα να αναπαραστήσουμε το μοντέλο «ανταλλαγής ταχυτήτων» που δημιουργήσατε σε αυτό το μάθημα με τη χρήση άλλων μέσων.

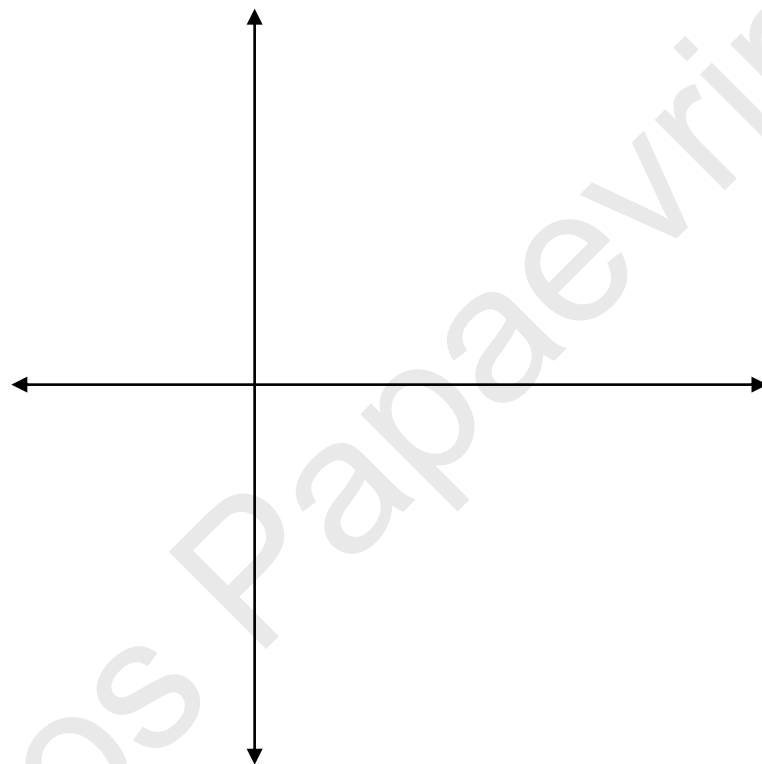
A. Δημιουργία λεκτικού μοντέλου ανταλλαγής ταχυτήτων. Περιγράψτε με λόγια το μοντέλο ανταλλαγής ταχυτήτων.



B. Δημιουργία μαθηματικού μοντέλου ανταλλαγής ταχυτήτων. Διατυπώστε μια μαθηματική σχέση που να αναπαριστά το μοντέλο ανταλλαγής ταχυτήτων.



Γ. Δημιουργία μοντέλου ανταλλαγής ταχυτήτων σε γραφική παράσταση. Δημιουργήστε μια γραφική παράσταση που να αναπαριστά το μοντέλο ανταλλαγής ταχυτήτων



23. Να συγκρίνετε τα πέντε μοντέλα (1. γραφικό, 2. υπολογιστικό, 3. λεκτικό, 4. μαθηματικό, 5, γραφική παράσταση) που έχετε δημιουργήσει για να αναπαραστήσετε την περίπτωση κρούσης στο Πείραμα 3.

A. Ποιο από αυτά είναι περισσότερο κατάλληλο για να αναπαρασταθεί το πείραμα 3; Εξηγήστε πώς σκεφτήκατε την απάντησή σας.

B. Ποιο από αυτά είναι λιγότερο κατάλληλο για να αναπαρασταθεί το πείραμα 3; Εξηγήστε πώς σκεφτήκατε την απάντησή σας.



**STOP!**

Ζητήστε ένα από τους διδάσκοντες να συζητήσει με την ομάδα σας !

Στο σημερινό μάθημα θα εξετάσουμε αν το μοντέλο «ανταλλαγής ταχυτήτων» που κατασκευάσαμε στο προηγούμενο μάθημα εφαρμόζει και σε κάποιες άλλες περιπτώσεις κρούσεων. Ας παρακολουθήσουμε το οπτικογραφημένο Πείραμα 4 που υπάρχει στο φάκελο videos. [Τα δύο καρότσια είναι πανομοιότυπα και έχουν ίσες μάζες ( $m_1=m_2=50\text{ gr}$ ). Τα καρότσια κινούνται **χωρίς τριβή** στον αεροδιάδρομο. ]

Πριν από την κρούση η ταχύτητα του αριστερού καροτσιού είναι 80, ενώ του δεξιού καροτσιού είναι 30.

Μετά την κρούση η ταχύτητα του αριστερού καροτσιού είναι , ενώ του δεξιού καροτσιού είναι .



Βάλτε τις τιμές των ταχυτήτων των καροτσιών πριν από την κρούση στο μοντέλο «ανταλλαγής ταχυτήτων» και τρέξτε το μοντέλο.

Το μοντέλο σας εφαρμόζει σε αυτή την περίπτωση; Εξηγήστε πώς σκεφτήκατε την απάντησή σας.

Αν το μοντέλο σας δεν εφαρμόζει σε αυτή την περίπτωση, να κάνετε τις απαραίτητες τροποποιήσεις ώστε το μοντέλο σας να μπορεί να εφαρμοστεί και σε αυτή την καινούρια περίπτωση ελαστικής κρούσης.



Δοκιμάστε το μοντέλο «ανταλλαγής ταχυτήτων» στα Πειράματα 1 και 2.

Το μοντέλο σας εφαρμόζει στο πρώτο πείραμα; Εξηγήστε πώς σκεφτήκατε την απάντησή σας.

Το μοντέλο σας εφαρμόζει στο δεύτερο πείραμα; Εξηγήστε πώς σκεφτήκατε την απάντησή σας.





Όταν ένα μοντέλο ταιριάζει σε περισσότερες από μια περιπτώσεις, θεωρούμε ότι το μοντέλο αυτό είναι περισσότερο κατάλληλο σε σύγκριση με τα άλλα μοντέλα τα οποία δεν εφαρμόζουν σε όλες τις περιπτώσεις των πειραμάτων.



Πώς ονομάζεται η διαδικασία εφαρμογής ενός μοντέλου σε φαινόμενα της ίδιας κλάσης και η διαπίστωση της επιτυχίας εφαρμογής του σε αυτά τα φαινόμενα;

Πώς ονομάζεται η διαδικασία καλύτερευσης ενός μοντέλου με την προσθήκη καινούριων στοιχείων που συλλέξαμε συγκρίνοντας το μοντέλο μας με το πραγματικό φαινόμενο;

Στον επόμενο πίνακα να συνοψίσετε τα αποτελέσματά σας όσον αφορά στα τρία μοντέλα που κατασκευάσατε και στις περιπτώσεις των πειραμάτων στις οποίες *ισχύουν* ή *δεν ισχύουν* (γράψτε κάτω από κάθε πείραμα αν ισχύει ή δεν ισχύει το κάθε μοντέλο).

	Πείραμα 1	Πείραμα 2	Πείραμα 3	Πείραμα 4
Μοντέλο				

Ποια είναι τα συμπεράσματά σας με βάση τον πιο πάνω πίνακα;

Ποια είναι τα κριτήρια με βάση τα οποία αξιολογούμε την «καταλληλότητα» ενός μοντέλου σε σχέση με το φαινόμενο που αντιπροσωπεύει; Απαριθμήστε αυτά τα κριτήρια.



**STOP !**

Ζητήστε ένα από τους διδάσκοντες να συζητήσει με την ομάδα σας !



Στις Φυσικές Επιστήμες ένα μοντέλο αξιολογείται με βάση συγκεκριμένα κριτήρια που μας βοηθούν να αποφασίσουμε κατά πόσο ένα μοντέλο είναι αντιπροσωπευτικό του φαινομένου με το οποίο σχετίζεται. Τρία βασικά κριτήρια αξιολόγησης ενός μοντέλου είναι τα ακόλουθα:

1. Το μοντέλο **ΑΝΑΠΑΡΙΣΤΑ** το υπό μελέτη φαινόμενο; Δηλ. το μοντέλο αναπαριστά τα βασικά χαρακτηριστικά-συστατικά του φαινομένου ή μιας πτυχής του φαινομένου
2. Το μοντέλο **ΕΡΜΗΝΕΥΕΙ/ΕΠΕΞΗΓΕΙ** το υπό μελέτη φαινόμενο; Δηλ. το μοντέλο προσφέρει μηχανισμό εξήγησης της λειτουργίας ή των λειτουργιών του φαινομένου;
3. Το μοντέλο επιτρέπει τη **ΔΥΝΑΤΟΤΗΤΑ ΔΙΑΤΥΠΩΣΗΣ και ΕΛΕΓΧΟΥ ΠΡΟΒΛΕΨΕΩΝ** για το υπό μελέτη φαινόμενο; Δηλ. το μοντέλο μπορεί να χρησιμοποιηθεί για τη διατύπωση και έλεγχο προβλέψεων για αλλαγές που παρατηρούνται σε διάφορες πτυχές του φαινομένου;

Να χρησιμοποιήσετε τα πιο πάνω κριτήρια για να αξιολογήσετε το μοντέλο «ανταλλαγής ταχυτήτων». Να περιγράψετε πώς το κάθε κριτήριο εφαρμόζει ή δεν εφαρμόζει σε αυτό το μοντέλο.

**Κριτήρια:**

- 1.
- 2.
- 3.



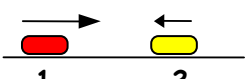
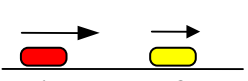


**STOP!**

Ζητήστε ένα από τους διδάσκοντες να συζητήσει με την ομάδα σας!

Συμπληρώστε στον ακόλουθο πίνακα τις τιμές των ταχυτήτων των καρτσιών πριν και μετά την κρούση για το κάθε πείραμα που παρακολουθήσατε.

**Πίνακας 1**

Πείραμα	Ταχύτητα του 1 πριν από την κρούση	Ταχύτητα του 2 πριν από την κρούση	Ταχύτητα του 1 μετά από την κρούση	Ταχύτητα του 2 μετά από την κρούση	Άθροισμα των ταχυτήτων πριν από την κρούση	Άθροισμα των ταχυτήτων μετά από την κρούση
						
						
						
						

Τι συμπέρασμα προκύπτει από τον πιο πάνω πίνακα ως προς το άθροισμα των ταχυτήτων των καρτσιών πριν και μετά την κρούση;

Η πιο πάνω διαπίστωση προέκυψε μετά από τη μελέτη μιας ή περισσότερων περιπτώσεων;



Στις Φυσικές Επιστήμες είναι χρήσιμο να εντοπίζουμε μεγέθη τα οποία δεν αλλάζουν, ασχέτως του τι μπορεί να συμβαίνει σε ένα φαινόμενο (π.χ. μια κρούση) ή μια μεταβολή (π.χ. αλλαγές καιρικών συνθηκών). Όταν εντοπίσουμε ένα τέτοιο μέγεθος, λέμε ότι έχουμε *ένα κανόνα διατήρησης*.

Να προβλέψετε τις ταχύτητες των καρτσιών σε κάθε μια από τις πιο κάτω περιπτώσεις. Στη συνέχεια να χρησιμοποιήσετε το μοντέλο «ανταλλαγής ταχυτήτων» στο Stagecast Creator για να εξετάσετε αν οι προβλέψεις σας είναι ορθές.

**Πίνακας 2**

Πείραμα	Ταχύτητα του 1 πριν από την κρούση	Ταχύτητα του 2 πριν από την κρούση	Ταχύτητα του 1 μετά από την κρούση	Ταχύτητα του 2 μετά από την κρούση	Άθροισμα των ταχυτήτων πριν από την κρούση	Άθροισμα των ταχυτήτων μετά από την κρούση
 1      2					-75	
 1      2			-80			
 1      2		-10			50	
 1      2	100					125

Ένα άλλο φυσικό μέγεθος που σχετίζεται με την κίνηση των καρτσιών είναι η **Κινητική Ενέργεια**. Κινητική ενέργεια έχει οποιοδήποτε σώμα το οποίο κινείται με κάποια ταχύτητα. Η Κινητική Ενέργεια συμβολίζεται με το γράμμα  $K$  και μπορεί να υπολογιστεί με την ακόλουθη σχέση

$$K = \frac{1}{2} m u^2, \text{ όπου } m \text{ είναι η μάζα του σώματος και } U \text{ είναι η ταχύτητα του σώματος}$$

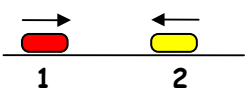
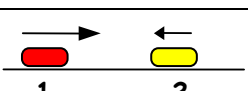
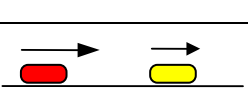
Η Κινητική Ενέργεια ενός συστήματος (συνόλου) σωμάτων σε κάποια χρονική στιγμή είναι το άθροισμα της κινητικής ενέργειας του κάθε σώματος. Έτσι, στις περιπτώσεις των κρούσεων που μας έχουν απασχολήσει, η κινητική ενέργεια του συστήματος των καρτσιών πριν ή μετά από την κρούση τους μπορεί να υπολογιστεί ως εξής:

$$K = \frac{1}{2} m_1 u_1^2 + \frac{1}{2} m_2 u_2^2$$

**Η Κινητική Ενέργεια του συστήματος των καρτσιών διατηρείται μετά την κρούση τους;**

Για να απαντήσουμε σε αυτό το ερώτημα, αρκεί να υπολογίσουμε την κινητική ενέργεια του κάθε καρτσιού πριν από την κρούση και μετά την κρούση και να εξετάσουμε αν το άθροισμά τους διατηρείται σταθερό.

Συμπληρώστε τον πιο κάτω πίνακα, αφού κάνετε τους απαραίτητους υπολογισμούς (χρησιμοποιήστε τις τιμές των ταχυτήτων από τον πίνακα 1).

Πείραμα	Κινητική Ενέργεια του 1 πριν από την κρούση	Κινητική Ενέργεια του 2 πριν από την κρούση	Κινητική Ενέργεια του 1 μετά από την κρούση	Κινητική Ενέργεια του 2 μετά από την κρούση	Άθροισμα της Κινητικής Ενέργειας του συστήματος των καροτσιών πριν από την κρούση	Άθροισμα της Κινητικής Ενέργειας του συστήματος των καροτσιών μετά από την κρούση
						
						
						
						

Τι συμπέρασμα προκύπτει από τον πιο πάνω πίνακα ως προς το άθροισμα της Κινητικής Ενέργειας του συστήματος των καροτσιών πριν και μετά την κρούση;

Χρησιμοποιήστε το πιο πάνω συμπέρασμα για να διατυπώσετε ένα κανόνα σε σχέση με την Κινητική Ενέργεια δύο σωμάτων.

Ονομάστε τον κανόνα που διατυπώσατε:

Σε ποιες περιπτώσεις ισχύει ο πιο πάνω κανόνας που διατυπώσατε;




**STOP!**

Ζητήστε ένα από τους διδάσκοντες να συζητήσει με την ομάδα σας!



Οι ακόλουθες ερωτήσεις απαιτούν μια σύνθεση των γνώσεων που αποκτήσατε μέχρι σήμερα,

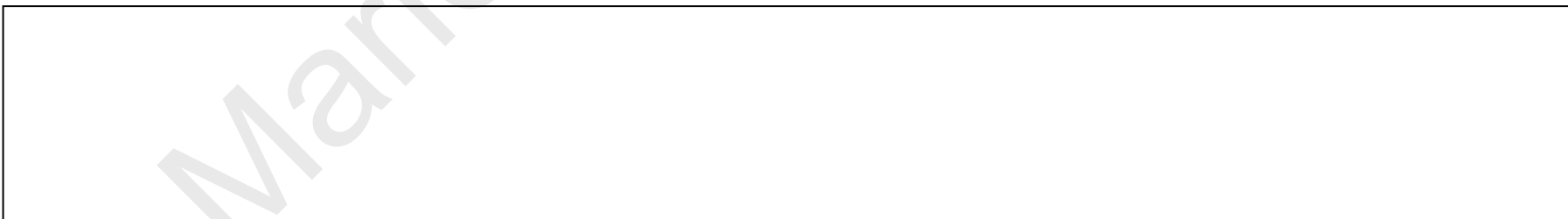
Ποια πορεία ακολουθούμε για να κατασκευάσουμε ένα μοντέλο; Απαριθμήστε τα στάδια αυτής της πορείας.



Η πορεία κατασκευής μοντέλου που περιγράψατε πιο πάνω έχει γραμμική ή κυκλική μορφή; Να δικαιολογήσετε την επιλογή σας κάνοντας αναφορά σε ποιο ή ποια σημεία της πορείας που διατυπώσατε πιο πάνω φαίνεται η γραμμικότητα ή η κυκλικότητα αυτής της πορείας.



Γιατί είναι σημαντικό να κατασκευάζουμε μοντέλα στις Φυσικές Επιστήμες;



Τι έχετε μάθει εσείς μέσω της διαδικασίας κατασκευής μοντέλων για διάφορες περιπτώσεις κρούσεων της ίδιας κλάσης;

Να αναφέρετε περιπτώσεις όπου η κατασκευή μοντέλου θα μας βοηθούσε να κατανοήσουμε καλύτερα έννοιες των Φυσικών Επιστημών.

Γιατί είναι χρήσιμοι οι κανόνες διατήρησης στις Φυσικές Επιστήμες;



**STOP!**

Ζητήστε ένα από τους διδάσκοντες να συζητήσει με την ομάδα σας !

📺📺 Παρατηρήστε προσεκτικά το video5 που βρίσκεται στο folder «videos». 📺📺

Σχεδιάστε ένα διάγραμμα του Πειράματος 5 που παρακολουθήσατε και στη συνέχεια περιγράψτε τι παρουσιάζει το σχέδιό σας.

1. Σχεδιάστε ένα διάγραμμα του οπτικογραφημένου Πειράματος 5 που παρακολουθήσατε και στη συνέχεια περιγράψτε τι παρουσιάζει το σχέδιό σας. Στο διάγραμμά σας να περιλάβετε όλα τα απαραίτητα στοιχεία, τα οποία θα βοηθήσουν κάποιον που δεν παρακολούθησε το βίντεο να καταλάβει τι είδατε να συμβαίνει

Θεωρήστε ότι τα δύο ενωμένα καροτσάκια αποτελούν το ΑΝΤΙΚΕΙΜΕΝΟ 1 και το ακίνητο καροτσάκι το ΑΝΤΙΚΕΙΜΕΝΟ 2.

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Περιγραφή του διαγράμματός μου

2. Ποιες διαφορές παρουσιάζουν τα δύο ΑΝΤΙΚΕΙΜΕΝΑ του πειράματος;

3. Ποιος παράγοντας δεν διατηρείται σταθερός και για τα δύο αντικείμενα σε αυτό το πείραμα, ο οποίος διατηρούνταν σταθερός σε όλα τα προηγούμενα πειράματα;

**Η ταχύτητα του αντικειμένου 1 είναι 90 και η ταχύτητα του αντικειμένου 2 είναι 0.  
Η μάζα του αντικειμένου 1 είναι 100 και η μάζα του αντικειμένου 2 είναι 50.**

4. Ποιος από τους πιο κάτω αριθμούς μπορεί να αντιπροσωπεύει την ταχύτητα του αντικειμένου 1 μετά τη σύγκρουση; *(βάλτε σε κύκλο την επιλογή σας)*

-120      -30      0      30      120

Εξηγήστε γιατί διαλέξατε αυτό τον αριθμό.

5. Ποιος από τους πιο κάτω αριθμούς μπορεί να αντιπροσωπεύει την ταχύτητα του αντικειμένου 2 μετά τη σύγκρουση; (βάλτε σε κύκλο την επιλογή σας)

-120                      -30                      0                      30                      120

Εξηγήστε γιατί διαλέξατε αυτό τον αριθμό.



Βάλτε τις τιμές των ταχυτήτων των αντικειμένων πριν από την κρούση στο μοντέλο «ανταλλαγής ταχυτήτων» και τρέξτε το μοντέλο.

6. Το μοντέλο σας εφαρμόζει σε αυτή την περίπτωση; Εξηγήστε πώς σκεφθήκατε την απάντησή σας.

7. Το μοντέλο «ανταλλαγής ταχυτήτων» εφαρμόζε σε όλες τις προηγούμενες περιπτώσεις κρούσεων. Γιατί νομίζετε δεν μπορεί να εφαρμοστεί και σε αυτή την περίπτωση κρούσης;

8. Ποιος παράγοντας πιστεύετε ότι επηρεάζει την ταχύτητα του κάθε αντικειμένου μετά από την κρούση και θα θέλατε να συμπεριλαμβανόταν στο μοντέλο που ήδη κατασκευάσατε;

9.A. Εξετάστε αν ο κανόνας διατήρησης της ταχύτητας εφαρμόζει σε αυτό το πείραμα. Κάντε τους υπολογισμούς σας πιο κάτω και περιγράψτε τα αποτελέσματά σας.

Συμπέρασμα: *(βάλτε σε κύκλο την ορθή απάντηση)* Ο κανόνας διατήρησης της ταχύτητας ισχύει / δεν ισχύει στο πείραμα 5.

9.B. Εξετάστε αν ο κανόνας διατήρησης της Κινητικής Ενέργειας εφαρμόζει σε αυτό το πείραμα. Κάντε τους υπολογισμούς σας πιο κάτω και περιγράψτε τα αποτελέσματά σας.

Συμπέρασμα: (βάλτε σε κύκλο την ορθή απάντηση) Ο κανόνας διατήρησης της κινητικής ενέργειας ισχύει / δεν ισχύει στο πείραμα 5.



Στις Φυσικές Επιστήμες είναι πάντοτε χρήσιμο να έχουμε κανόνες που να ισχύουν όσο το δυνατό σε περισσότερες περιπτώσεις, αν είναι δυνατό σε όλες. Όπως και στα μοντέλα, όταν δούμε ότι ένα μοντέλο που κατασκευάσαμε δεν εφαρμόζει σε μια καινούρια κατάσταση, το **βελτιώνουμε** ώστε να εφαρμόζει και σε αυτή την κατάσταση.

Αφού είδαμε ότι το μοντέλο ανταλλαγής ταχυτήτων και ο κανόνας διατήρησης της ταχύτητας δεν ισχύουν στο πείραμα που μελετούμε, θα πρέπει να προσπαθήσουμε να τροποποιήσουμε το μοντέλο μας και τον κανόνα που διατυπώσαμε ώστε να εφαρμόζουν σε όλες τις περιπτώσεις των κρούσεων που παρατηρήσαμε στο βίντεο.

Συμπληρώστε τον ακόλουθο Πίνακα.

Πείραμα	Ταχύτητα του 1 πριν από την κρούση	Ταχύτητα του 2 πριν από την κρούση	Ταχύτητα του 1 μετά από την κρούση	Ταχύτητα του 2 μετά από την κρούση	Γινόμενο μάζα * ταχύτητα αντικειμένου 1 πριν από την κρούση	Γινόμενο μάζα * ταχύτητα αντικειμένου 2 πριν από την κρούση	Γινόμενο μάζα * ταχύτητα αντικειμένου 1 μετά από την κρούση	Γινόμενο μάζα * ταχύτητα αντικειμένου 2 μετά από την κρούση	Άθροισμα των γινομένων μάζα*ταχύτητα των αντικειμένων 1 & 2 πριν από την κρούση	Άθροισμα των γινομένων μάζα*ταχύτητα των αντικειμένων 1 & 2 μετά από την κρούση
 $m_1 = 100$ $m_2 = 50$										

10. Τι συμπεραίνετε για το «γινόμενο μάζα \* ταχύτητα του αντικειμένου 1» πριν και μετά από την κρούση;

11. Τι συμπεραίνετε για το «γινόμενο μάζα \* ταχύτητα του αντικειμένου 2» πριν και μετά από την κρούση;

12. Τι συμπεραίνετε για το «Άθροισμα των γινομένων μάζα \* ταχύτητα των αντικειμένων 1 & 2 πριν από την κρούση» και «Άθροισμα των γινομένων μάζα \* ταχύτητα των αντικειμένων 1 & 2 πριν από την κρούση»;



Το γινόμενο μάζα \* ταχύτητα είναι αρκετά χρήσιμο, ώστε να το ονομάσουμε ως χωριστό φυσικό μέγεθος.

Το γινόμενο «μάζα \* ταχύτητα» ενός αντικειμένου ονομάζεται ορμή του αντικειμένου και συμβολίζεται με το γράμμα P.

13. Με βάση την απάντησή σας στο 3, τι μπορείτε να πείτε για το άθροισμα της ορμής των αντικειμένων πριν και μετά από την κρούση; Διατυπώστε μια μαθηματική σχέση με βάση το συμπέρασμα σας.



**STOP!**

Ζητήστε ένα από τους διδάσκοντες να συζητήσει με την ομάδα σας !



Όπως έχετε ήδη διαπιστώσει από τις προηγούμενες δραστηριότητες, το μοντέλο «ανταλλαγής ταχυτήτων» δεν μπορεί να εφαρμοστεί στην περίπτωση του Πειράματος 5. Θα προσπαθήσουμε πιο κάτω να σκεφτούμε και να δημιουργήσουμε ένα μοντέλο το οποίο να εφαρμόζει τόσο στο Πείραμα 5 όσο και στα προηγούμενα πειράματα.

14. Εξετάστε αν ο κανόνας διατήρησης της ορμής εφαρμόζει στα Πειράματα 1-4. Συμπληρώστε τον ακόλουθο πίνακα για να εξετάσετε αυτή την υπόθεση.

Πείραμα	Μάζα αντικειμένου 1	Μάζα αντικειμένου 2	Ταχύτητα του 1 πριν από την κρούση	Ταχύτητα του 2 πριν από την κρούση	Ταχύτητα του 1 μετά από την κρούση	Ταχύτητα του 2 μετά από την κρούση	Ορμή του αντικειμένου 1 πριν από την κρούση	Ορμή του αντικειμένου 2 πριν από την κρούση	Ορμή του αντικειμένου 1 μετά από την κρούση	Ορμή του αντικειμένου 2 μετά από την κρούση
1	50	50	100	0	0	100				
2	50	50	30	-30	-30	30				
3	50	50	90	-30	-30	90				
4	50	50	90	30	30	90				

Συμπέρασμα: (βάλτε σε κύκλο την ορθή απάντηση) Ο κανόνας διατήρησης της ορμής ισχύει / δεν ισχύει στα Πειράματα 1-4.

15. Με βάση την πιο πάνω διαπίστωσή σας, τι θα θέλατε να συμβαίνει στο μοντέλο που θα δημιουργήσετε; Ποιος θα είναι ο μηχανισμός με βάση τον οποίο θα λειτουργεί το μοντέλο σας; Ποια μεγέθη θα διατηρούνται σταθερά στο μοντέλο σας;

16. Έχετε καταλήξει σε κάποια μέθοδο υπολογισμού της ταχύτητας του κάθε καροτσιού μετά την κρούση; Αν ναι, ποια είναι αυτή;

17. Θα μπορούσε το μοντέλο σας να λειτουργεί **μόνο** με τον κανόνα διατήρησης της ορμής; Εξηγήστε πώς σκεφτήκατε την απάντησή σας. (Hint: γράψτε τον κανόνα διατήρησης της ορμής και δείτε αν με αυτόν μπορείτε να υπολογίσετε την ταχύτητα του κάθε καροτσιού μετά την κρούση).

18. Θα μπορούσε το μοντέλο σας να λειτουργεί **μόνο** με τον κανόνα διατήρησης της κινητικής ενέργειας; Εξηγήστε πώς σκεφτήκατε την απάντησή σας. (Hint: γράψτε τον κανόνα διατήρησης της ορμής και δείτε αν με αυτόν μπορείτε να υπολογίσετε την ταχύτητα του κάθε καροτσιού μετά την κρούση).



**STOP!**

Ζητήστε ένα από τους διδάσκοντες να συζητήσει με την ομάδα σας !

Όπως θα έχετε διαπιστώσει, για να μπορέσουμε να υπολογίσουμε την ταχύτητα του κάθε καροτσιού μετά την κρούση δεν μπορούμε να στηριχτούμε ούτε μόνο στον κανόνα διατήρησης της ορμής ούτε μόνο στον κανόνα διατήρησης της κινητικής ενέργειας. Θα δοκιμάσουμε πιο κάτω να συνδυάσουμε τους δύο κανόνες για τον υπολογισμό της ταχύτητας του κάθε καροτσιού μετά την κρούση.

Κανόνας διατήρησης της ορμής:  $\vec{P}_{ολ(αρχ)} = \vec{P}_{ολ(τελ)} \Rightarrow \vec{P}_1 + \vec{P}_2 = \vec{P}'_1 + \vec{P}'_2 \Rightarrow m_1 v_1 + m_2 v_2 = m_1 v'_1 + m_2 v'_2$   
(1)

Κανόνας διατήρησης της Κινητικής Ενέργειας:

$$K_{ολ(αρχ)} = K_{ολ(τελ)} \Rightarrow K_1 + K_2 = K'_1 + K'_2 \Rightarrow \frac{1}{2} m_1 v_1^2 + \frac{1}{2} m_2 v_2^2 = \frac{1}{2} m_1 v_1'^2 + \frac{1}{2} m_2 v_2'^2 \Rightarrow$$

$$m_1 (v_1^2 - v_1'^2) = m_2 (v_2'^2 - v_2^2) \Rightarrow m_1 (v_1 + v_1') (v_1 - v_1') = m_2 (v_2' + v_2) (v_2' - v_2) \quad (2)$$

Διαιρώντας κατά μέλη τις (1) και (2) προκύπτει η σχέση:  $v_1 + v_1' = v_2 + v_2'$  (3)

Λύνοντας το γραμμικό σύστημα των (1) και (3) έχουμε:

$$v_1' = \frac{(m_1 - m_2)v_1 + 2m_2 v_2}{m_1 + m_2} \quad (\text{A}) \quad \text{και} \quad v_2' = \frac{(m_2 - m_1)v_2 + 2m_1 v_1}{m_1 + m_2} \quad (\text{B})$$

19. Με βάση τους πιο πάνω υπολογισμούς να περιγράψετε τα βήματα δημιουργίας ενός μοντέλου στο *Stagecast Creator* το οποίο να αναπαριστά την περίπτωση κρούσης που παρακολουθήσατε στο βίντεο 2. Αναφερθείτε σε οποιαδήποτε εργαλεία, χαρακτήρες, μεταβλητές, κανόνες που θα χρησιμοποιήσετε ή θα δημιουργήσετε για την κατασκευή του μοντέλου σας.



Δημιουργήστε το μοντέλο που περιγράψατε πιο πάνω στο *Stagecast Creator*. Αν το μοντέλο που περιγράψατε πιο πάνω δεν λειτουργεί όπως θα περιμένατε, σκεφτείτε ποιες αλλαγές πρέπει να κάνετε.

20. Δώστε ένα όνομα για το μοντέλο που μόλις δημιουργήσατε. Εξηγήστε γιατί επιλέξατε αυτό το όνομα.




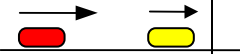
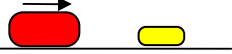
21. Χρησιμοποιήστε το μοντέλο αυτό για να βρείτε τις τιμές των ταχυτήτων που λείπουν στον πιο κάτω πίνακα.



Πείραμα	Μάζα αντικειμένου 1	Μάζα αντικειμένου 2	Ταχύτητα του 1 πριν από την κρούση	Ταχύτητα του 2 πριν από την κρούση	Ταχύτητα του 1 μετά από την κρούση	Ταχύτητα του 2 μετά από την κρούση
1	2	1	60	0		
2	8	4	20	5		
3	6	3	50	-10		
4	5	10	15	0		
5	6	12	50	20		
6	3	6	50	-40		

22. Επιλέξτε 3 από τα πειράματα του πίνακα και εξετάστε αν εφαρμόζει ο κανόνας διατήρησης της ορμής που διατυπώσατε στη σελίδα 41 του διδακτικού υλικού. Γράψτε τα αποτελέσματα και το συμπέρασμά σας πιο κάτω.

23. Στον επόμενο πίνακα να συνοψίσετε τα αποτελέσματά σας όσον αφορά στα 4 μοντέλα που κατασκευάσατε και στις περιπτώσεις των πειραμάτων στις οποίες ισχύουν ή δεν ισχύουν.

	Πείραμα 1	Πείραμα 2	Πείραμα 3	Πείραμα 4	Πείραμα 5
<b>Μοντέλο</b>					

Ποια είναι τα συμπεράσματά σας με βάση τον πιο πάνω πίνακα;

## **Appendix II**

### **Modeling ability Test A**

Marios Papaevripidou





Όνοματεπώνυμο: \_\_\_\_\_ Ημερομηνία: \_\_\_\_\_

### Model Formulation A1

Παρακολουθήστε προσεκτικά το video 1 που παρουσιάζει δύο περιπτώσεις βολών. Η αριστερή μπάλα εκτελεί ελεύθερη πτώση, ενώ η δεξιά μπάλα βάλλεται με ταχύτητα προς τα δεξιά.

1. Να κάνετε ένα σχέδιο-μοντέλο που να παρουσιάζει τις βολές που παρακολουθήσατε στο βίντεο. Προσπαθήστε να περιλάβετε συστατικά στοιχεία των βολών που παρακολουθήσατε στο σχέδιό σας. Μπορείτε, αν το θεωρείτε αναγκαίο, να περιλάβετε και λόγια στο σχέδιό σας.



2. Να εντοπίσετε και να ονομάσετε τα βασικά συστατικά στοιχεία του μοντέλου που δημιουργήσατε στο σχέδιό σας. Για κάθε διαφορετικό στοιχείο να αναφέρετε τουλάχιστον δύο παραδείγματα από το σχέδιό σας.

Απάντηση



Όνοματεπώνυμο: \_\_\_\_\_ Ημερομηνία: \_\_\_\_\_

### Model Formulation A1

3. Να δημιουργήσετε ένα μοντέλο στο Stagecast Creator, το οποίο να αναπαριστά αυτό που παρακολουθήσατε στο video 1. Όταν τελειώσετε αυτό το μοντέλο, να περιγράψετε πιο κάτω πώς εργαστήκατε για την κατασκευή του (π.χ. αναφορά σε κανόνες που δημιουργήσατε) και να γράψετε (αν χρειάζεται) οδηγίες για το πώς θα το χρησιμοποιήσει κάποιος (π.χ. αν πρέπει να θέσει τιμές σε κάποιες μεταβλητές, αν πρέπει να μετακινήσει κάποιο χαρακτήρα στην οθόνη, κτλ).

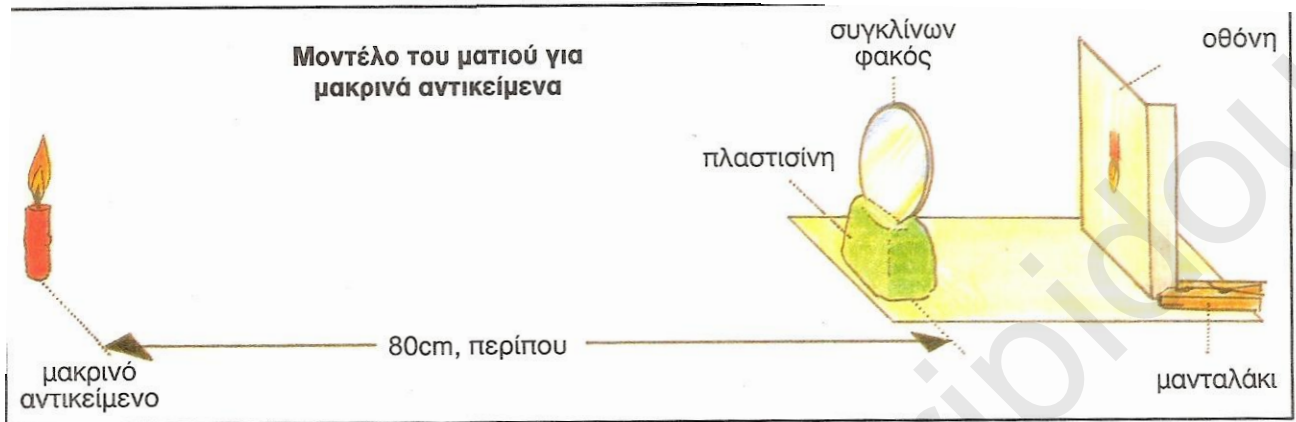
Περιγραφή πορείας κατασκευής μοντέλου

Τι αξιολογεί αυτό το διαγνωστικό δοκίμιο; (Σημ. Το διαγνωστικό δοκίμιο αποτελείται από 3 μέρη!)

Απάντηση

### Identification of Model Components B1

Παρατηρήστε πιο κάτω ένα μοντέλο που αναπαριστά το μηχανισμό της όρασης.



Να ονομάσετε τα βασικά συστατικά στοιχεία του πιο πάνω μοντέλου σε σχέση με το φαινόμενο που αναπαριστά. Δώστε 2 παραδείγματα για κάθε στοιχείο που εντοπίσατε.

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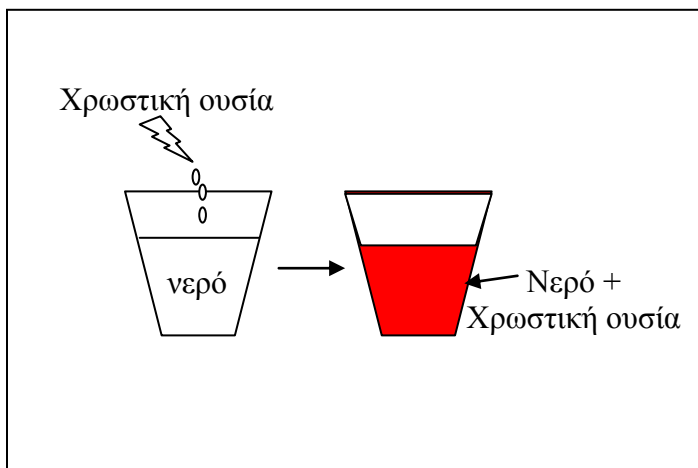


Όνοματεπώνυμο: \_\_\_\_\_ Ημερομηνία: \_\_\_\_\_

### Comparing Models D1

Ένας από τους διδάσκοντες θα κάνει επίδειξη της **διάλυσης** μιας χρωστικής υγρής ουσίας στο νερό.

Στη συνέχεια παρατηρήστε 4 διαφορετικούς τρόπους παρουσίασης του φαινομένου της διάλυσης της χρωστικής ουσίας στο νερό: (α) ένα σχέδιο (β) ένα δοχείο με χρωματιστούς κύβους (γ) ένα πρόγραμμα στο Stagecast Creator και (δ) μία λεκτική περιγραφή.



(α) σχέδιο

*Όταν υδροθέσουμε στο νερό λίγες σταγόνες χρωστικής ουσίας, τότε το άχρωμο νερό σιγά σιγά παίρνει το χρώμα της χρωστικής ουσίας, ειδικά τα μόρια της ουσίας αναμειγνύονται με τα μόρια του νερού.*

(δ) λεκτική περιγραφή

Ποιος από τους 4 τρόπους είναι ο **πιο κατάλληλος** για την αναπαράσταση και εξήγηση του φαινομένου της διάλυσης της χρωστικής ουσίας στο νερό; Να εξηγήσετε τον τρόπο που σκεφτήκατε την απάντησή σας.

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Όνοματεπώνυμο: \_\_\_\_\_ Ημερομηνία: \_\_\_\_\_

**Comparing Models D1**

Ποιος από τους 4 τρόπους είναι ο **λιγότερο κατάλληλος** για την αναπαράσταση και εξήγηση του φαινομένου της διάλυσης της χρωστικής ουσίας στο νερό; Να εξηγήσετε τον τρόπο που σκεφτήκατε την απάντησή σας.

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Marios Papaevripiδου











## **Appendix III**

### **Modeling ability Test B**

Marios Papaevripidou



Όνοματεπώνυμο: \_\_\_\_\_ Ημερομηνία: \_\_\_\_\_

### Model Formulation A2

Παρακολουθήστε προσεκτικά το video 2 που παρουσιάζει ένα φαινόμενο κυβικής διαστολής. Ακολούθως να κάνετε ένα σχέδιο-μοντέλο που να παρουσιάζει το φαινόμενο που παρακολουθήσατε στο βίντεο. Προσπαθήστε να περιλάβετε διάφορα συστατικά στοιχεία του φαινομένου που παρακολουθήσατε στο σχέδιό σας. Μπορείτε, αν το θεωρείτε αναγκαίο, να περιλάβετε και λόγια στο σχέδιό σας.



Να εντοπίσετε και να ονομάσετε τα βασικά συστατικά στοιχεία του μοντέλου που δημιουργήσατε στο σχέδιό σας. Για κάθε διαφορετική πτυχή να αναφέρετε τουλάχιστον δύο παραδείγματα από το σχέδιό σας.

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Όνοματεπώνυμο: \_\_\_\_\_ Ημερομηνία: \_\_\_\_\_

### Identification of model components B2

Παρακάτω φαίνεται ένα σχέδιο που παρουσιάζει πώς παίζεται το ποδόσφαιρο.



Να ονομάσετε τα βασικά συστατικά στοιχεία του πιο πάνω μοντέλου σε σχέση με το σύστημα που αναπαριστά. Δώστε 2 παραδείγματα για κάθε στοιχείο που εντοπίσατε.

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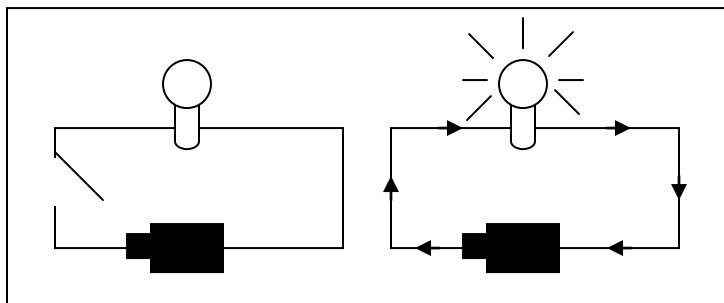


Όνοματεπώνυμο: \_\_\_\_\_ Ημερομηνία: \_\_\_\_\_

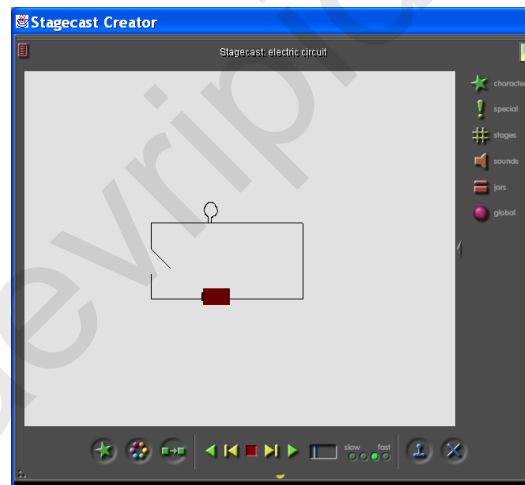
## Compare models D2

Ένας από τους διδάσκοντες θα κάνει επίδειξη της **συναρμολόγησης** ενός απλού ηλεκτρικού κυκλώματος.

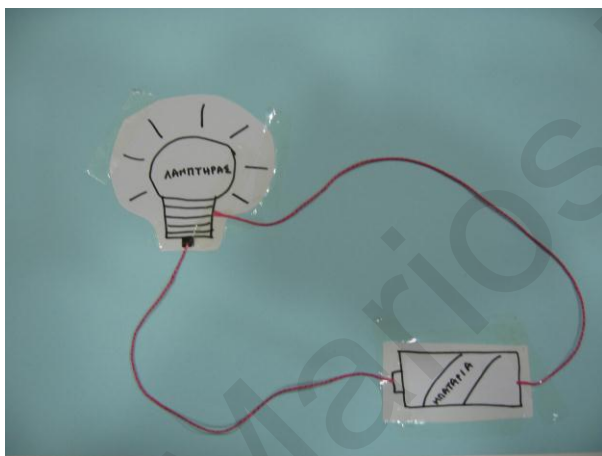
Στη συνέχεια παρατηρήστε 4 διαφορετικούς τρόπους που δίνουν μια εξήγηση του γιατί ο λαμπτήρας φωτοβολεί: (α) ένα σχέδιο, (β) μια κατασκευή με σχοινάκια και χαρτόνια, (γ) ένα πρόγραμμα στο Stagecast Creator και (δ) μία λεκτική περιγραφή.



(α) σχέδιο



(γ) πρόγραμμα στο Stagecast Creator



(β) κατασκευή με σχοινάκια και χαρτόνια

Όταν συνδέσουμε μια μπαταρία, ένα λαμπτήρα και ένα καλώδιο με τρόπο ώστε τα αγώγιμα μέρη του λαμπτήρα να συνδέονται με τα αγώγιμα άκρα της μπαταρίας με τη βοήθεια του καλωδίου, τότε δημιουργείται ένα κλειστό κύκλωμα και ο λαμπτήρας ανάβει. Μέσα στο κύκλωμα συμβαίνει «κάτω» το οποίο δεν μπορούμε να δούμε, αλλά μπορούμε να υποθέσουμε ότι αυτό το «κάτω» είναι ταυτόχρονο (συμβαίνει την ίδια χρονική στιγμή σε όλα τα σημεία του κυκλώματος), συνεχές (δεν διακόπτεται) και ομοιόμορφο (όλα τα σημεία του κυκλώματος υφίστανται την ίδια μεταβολή). Αυτή είναι η εξήγηση γιατί ο λαμπτήρας ανάβει.

(δ) λεκτική περιγραφή



Όνοματεπώνυμο: \_\_\_\_\_ Ημερομηνία: \_\_\_\_\_

**Compare models D2**

Ποιος από τους 4 τρόπους είναι ο **πιο κατάλληλος** για την αναπαράσταση και εξήγηση του γιατί ο λαμπτήρας ανάβει; Να εξηγήσετε τον τρόπο που σκεφτήκατε την απάντησή σας.

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Ποιος από τους 4 τρόπους είναι ο **λιγότερο κατάλληλος** για την αναπαράσταση και εξήγηση του γιατί ο λαμπτήρας ανάβει; Να εξηγήσετε τον τρόπο που σκεφτήκατε την απάντησή σας.

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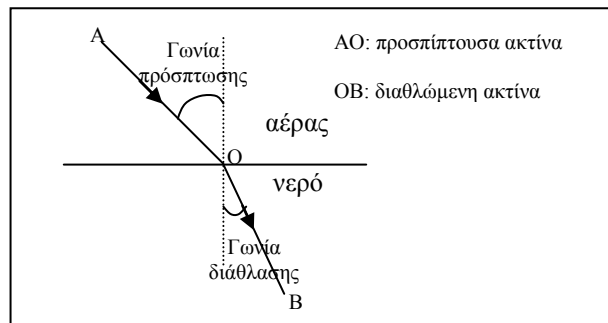
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Marios Papaeνριπίδου

Όνοματεπώνυμο: \_\_\_\_\_ Ημερομηνία: \_\_\_\_\_

### Model validation E2

Ο Αντώνης μελέτησε την πορεία μιας ακτίνας φωτός όταν αυτή εισέρχεται από τον αέρα στο νερό. Έκανε διάφορες δοκιμές και σε κάθε δοκιμή μετρούσε την γωνία πρόσπτωσης και την γωνία διάθλασης της ακτίνας φωτός (βλ. σχεδιάγραμμα).



Οι μετρήσεις του φαίνονται στον ακόλουθο Πίνακα.

Δοκιμή	Γωνία πρόσπτωσης	Γωνία διάθλασης
1	30°	14°
2	35°	18°
3	40°	25°
4	45°	29°

Στηριζόμενος στις μετρήσεις του δημιούργησε ένα μοντέλο στον ηλεκτρονικό υπολογιστή το οποίο στηριζόταν στις εξής ιδέες:

1. Όταν μια ακτίνα φωτός εισέρχεται από τον αέρα στο νερό, τότε πάντα διαθλάται.
2. Η γωνία διάθλασης είναι πάντοτε μικρότερη από τη γωνία πρόσπτωσης.

Τι χρειάζεται να κάνει ο Αντώνης για να αποφασίσει αν το μοντέλο που δημιούργησε στον υπολογιστή είναι έγκυρο;

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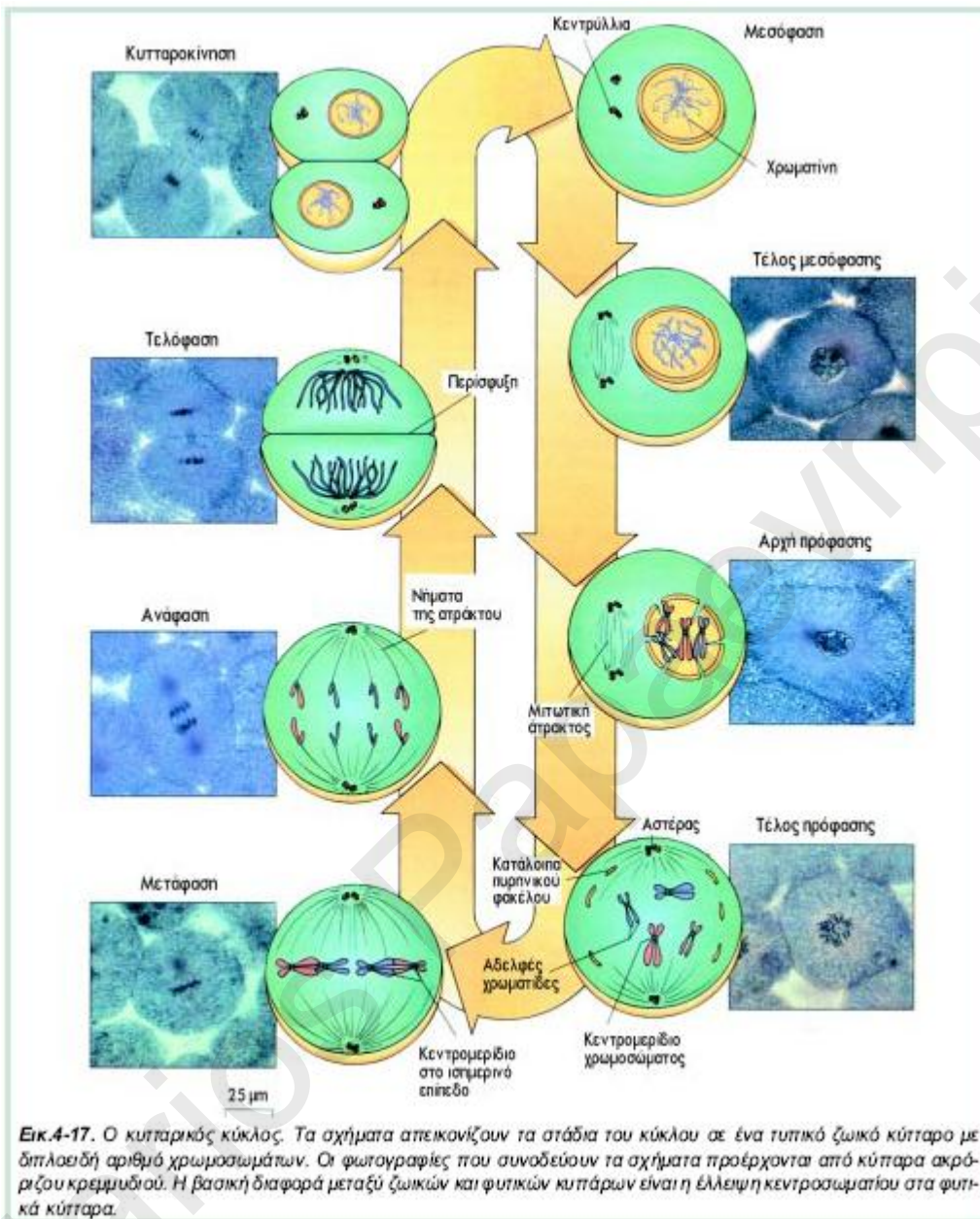
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**Nature of models G2 & Purpose of models H2**

Στο πιο κάτω διάγραμμα παρουσιάζεται μια αναπαράσταση του κυτταρικού κύκλου.



Να αναφέρετε τρεις τουλάχιστον λόγους για τους οποίους θεωρείτε ότι είναι χρήσιμο να φτιάχνουμε τέτοιες αναπαραστάσεις. Εξηγήστε το συλλογισμό σας.

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