SYSTEMATIC ANALYSIS OF THE POTENTIAL CONTRIBUTION OF COMMUNICATION AND INFORMATION TOOLS TO THE DESIGN AND DEVELOPMENT OF RESEARCH-BASED SCIENCE CURRICULUM

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ABSTRACT

Computer technology has received much attention as a means of reforming educational practice in Physics. It is widely believed that technology could function as a medium for bringing about the necessary reform to improve learning standards and in particular to promote the conceptual understanding and reasoning skills that so many of our students lack after traditional instruction. The Learning in Physics Group has a coordinated program combining research with the development and validation of curriculum for secondary and high school grades. We have undertaken a systematic analysis of the capabilities of a range of computer-based tools that are conducive to improving the quality of the learning and teaching of Physics. This type of analysis leads to the detailed formulation of a series of competencies relevant to Physics that could be developed with appropriate use of these tools. In this paper, we concentrate on the development of modeling skills and we outline the methodology we have developed followed by typical results. We also demonstrate how our results could be used in the design and development of innovative learning environments. Finally, we discuss the constraints to the effective use of educational technology and implications for Physics teaching as well as for the preparation of teachers and the development of curricula.

1. INTRODUCTION

Learning in science can be analyzed into a number of constituent components: the acquisition of *experiences* with natural phenomena provides the basis for the subsequent development of *concepts*; the mental representation of the structure and organisation of scientific knowledge that is needed to avoid knowledge fragmentation and meaningless use of jargon comes with the development of *epistemological awareness*; *scientific and reasoning skills* provide the strategies and procedures for making operational use of one's conceptual understanding in order to analyse and understand everyday phenomena but also to undertake critical evaluation

of evidence in decision making situations. Finally, *positive attitudes* towards inquiry feed student motivation and safeguard sustainable engagement with the learning process.

Traditional instruction has failed to explicitly take into account many of these components. This has severely constrained the ability of traditional teaching approaches to promote real learning. Effective instructional programs need to promote all these components in unison in a manner that enhances situated learning and promotes awareness of the significance of coherent operational understanding and its power in shaping decisions, both public and personal. Computer based tools have received much attention in recent years as a means of reforming the structure and organization of the learning environment and as a medium for developing interdisciplinary connections. The available technological media present a challenge to the researcher and educator: how can one take advantage of the transition to a technologically richer educational environment in order to also upgrade the quality of the learning that takes place?

In this paper we present a systematic methodology for addressing this issue in the context of two types of tools: computer-based modeling environments and concept mapping software.

At the level of the individual student, modeling can provide a theme that runs through the whole of science learning and through appropriate instructional design can be used to continuously focus in on all the components mentioned above in a systematic and constructive way. The analytical methodology presented in this paper, provides a systematic approach to exploring the way modeling can shape the teaching and learning process in science and the extent to which computer-based modeling tools can support this process.

Concept – mapping can potentially be used as a tool in performance assessment and in knowledge organization and development. A concept map is a graphical representation consisting of nodes representing concepts and labeled lines denoting the relationship between a pair of concepts. A concept map is interpreted as representing important aspects of the student's organization of concepts and, indirectly, the student's construction of meaning. As we seek to demonstrate in this paper, when approached systematically it can be incorporated in research-based curricula as an important tool for promoting epistemological awareness and meta cognitive control of the development of one's own knowledge structures

2.1 MODELING AS A TEACHING AND LEARNING PROCESS

Meaningful learning in science can be thought of as a dynamic process of building, organizing and elaborating knowledge of the natural world. The cornerstones of this knowledge are conceptual models. Physical science can be characterized as a complex network of models interrelated by a system of theoretical principles. Models are units of structured knowledge used to represent observable patterns in physical phenomena. Accordingly, *physical understanding* can be perceived as a complex set of modeling skills, that is, cognitive skills for making and using models [3,6,14]. The development of modeling skills enables students to make sense of their own physical experiences and to evaluate information reported by others.

Modeling can potentially provide a backbone structure for constructing meaning in physical science. In this approach, students are guided to develop a set of generic modeling skills in one domain and to transfer those same skills in other domains, further elaborating and developing them with experience and practice. 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 behaviour of the system.

A model is a surrogate system, a conceptual representation of structure in a physical system or process. The system may consist of one or more material objects or massless entities such as light. Unlike a theory, a model refers to an individual system, though that individual may be an exemplar for a whole class of systems. In Physics research, models have a very central role: they are continuously created through applications of scientific theory to physical systems. Models that are subsequently validated, when their predictions are found to correlate well with experiment, in turn influence the design principles that constitute the scientific theory which originally gave rise to their formulation. Modeling skills also have a very central role to play in Physics learning. For instance, the *complete* solution to every Physics problem is actually a model, not, as often supposed, a mere number, the value of some quantity required in the problem. More importantly, modeling can provide the underpinnings and basic structure of a learning strategy that is student-centered, inquiry-based and effective.
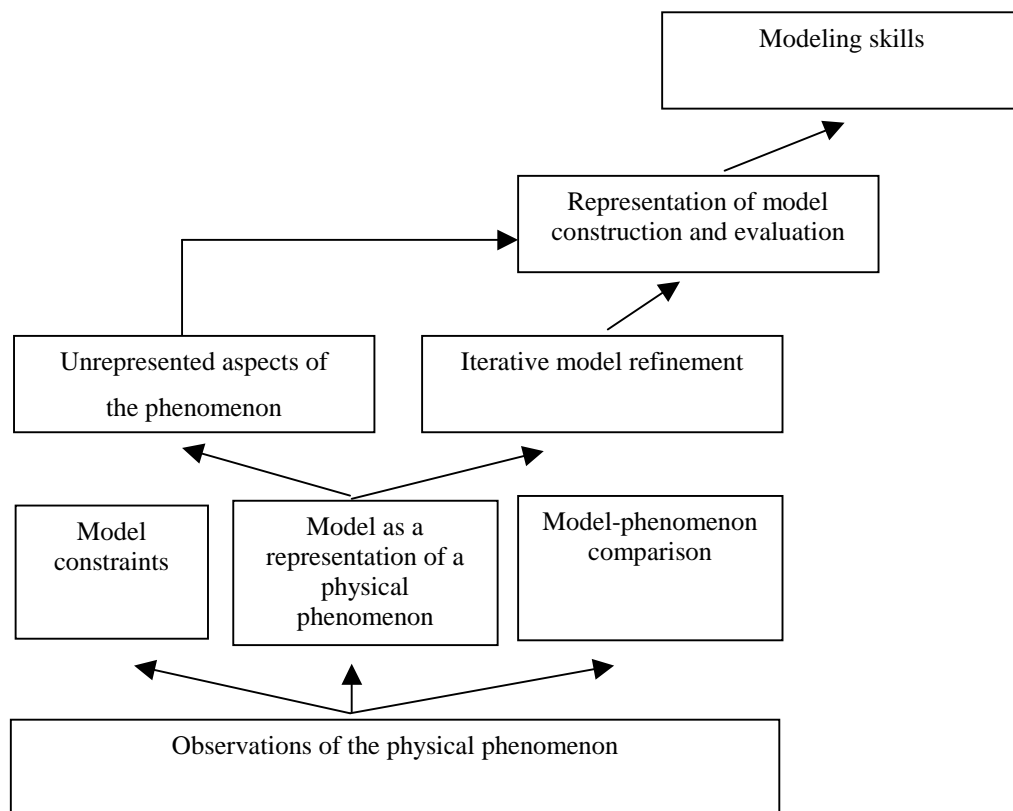
Figure 1
Epistemological analysis of learnable skills related to modeling

2.2 COMPUTER BASED MODELING TOOLS

Educational software has become increasingly powerful, interactive and hence more likely to contribute to the learning environment in an effective manner. Dynamic modeling constitutes one of the capabilities that have only become a possible part of the learning process as a result of the advent of computers in the classroom.

There is a wide range of software that can serve as powerful modeling tools [12]. However, the purpose of this section is not a thorough review of the entire collection. Rather, we simply seek to convey a sense of the wide diversity of modeling tools that is currently available, in terms of their complexity and capabilities. More importantly we will present an analysis of the capabilities of these tools and the potential use they can serve in the context of the physics learning environment.

Most probably, *Stagecast Creator* constitutes the simplest, but certainly not the most powerful, computer based modeling tool [7]. It contains a fully graphical development environment that facilitates the construction of models, through the insertion of objects (characters) and the definition of their behavior and their interrelationships with other objects. Its entirely graphical nature makes it fairly easy to develop graphical models for the emulation of physical phenomena and systems. In particular the facility to develop object behavioral rules without resorting to a single text command makes it possible to use *Stagecast Creator* in order to develop programming skills from a very young age. However, the great level of ease suggests important constraints with respect to its capabilities. For example, it is not possible to implement a mathematical description of a complex physical phenomenon or get *Stagecast Creator* to construct a graph in run time. Essentially, the evolution of every model is predefined, in the sense that its behavior has to be explicitly declared during design time. Putting aside these limitations, *Stagecast Creator* provides a simple graphical environment that can be used to construct and refine microworlds as models of dynamic physical systems. The ability to refine the rules that govern the model behavior makes it possible to develop most of the skills outlined in Figure 1.

Conceptually, computer programming languages lie at the other end of the modeling tools continuum as the most powerful paradigm. Evidently, it is the most flexible and at the same time, the most complex and cognitively demanding one. Developing models using a programming language posits, amongst others, adequate familiarity with programming concepts and techniques. Its robustness rests on the fact that it allows for building powerful models capable of mathematically, graphically, pictorially or otherwise, describing even the most complex physical phenomena and systems. The process of modeling begins from an empty microworld, both in terms of existing objects and also methods for specifying their behavior, and in this sense the implemented components do not need to inherit properties of a given, predefined, template. Moreover, unlike *Stagecast Creator*, it is possible to produce run time components, such as graphs, that were not explicitly designed before. The more specialized example is the *Unified Modeling Language* [2] that aims to provide an elaborate structured process for developing models without necessarily having from the beginning a complete overview of the system to be modeled.

Of course, between these two extremes, there are several other modeling tools. Perhaps, the software that is most widely used is *Stella* [9]. In the *Stella* framework, a model for a physical phenomenon is constructed by first specifying the parameters of the model, and then defining potential interrelationships between the objects with the use of mathematical expressions.

Stella provides an array of structures - blocks, connectors etc - each of them representing a specific modeling element (parameter, relationship and so forth). After designing the model, learners can run it and observe its dynamic behavior in a number of formats such as animations, graphs and tables. *Stella* is an excellent tool for dealing with time-dependent phenomena. Essentially, productive interaction within the *Stella* environment requires prior familiarity with its aforementioned structures. In addition to this, defining the relationships between the embedded parameters posits mathematical awareness with respect to the algebraic representation of the underlying laws. Finally, being able to understand the emulated behavior of the model also entails the attainment of mathematical understanding. Due to these requirements, it becomes apparent that Stella might not be a viable tool for all learners and would be developmentally inappropriate for use by young children.

Table 1 presents an analysis that seeks to identify the capabilities of modeling tools, and subsequently evaluate those capabilities in terms of their potential contribution to the Physics learning environment. The analysis leads to the formulation of a series of competencies relevant to Physics that could be developed by each capability of the software at hand. This analysis could significantly inform the design of effective curriculum by providing the necessary underpinnings that could be cross-referenced with Figure 1 to make decisions on the sequencing of activities. The process can lead to the development of effective curriculum that can on one hand make the most of these tools by emphasizing their educationally useful capabilities while on the other hand avoiding complete reliance on the tools for objectives that they cannot meet. It is in this light that the analytic perspective that pertains to computer-based modeling tools is presented in Table 1. Nonetheless, it is worth noticing that this methodology would also be suitable for the design of curriculum regarding the entire set of educational software.

2.3 THE DESIGN OF MODELING CURRICULUM

The design and development of effective curriculum that integrates computer based learning tools, is a stage of paramount importance in our effort to achieve their productive integration with instruction. Evidently, though, such process needs to be guided by methodical and systematic research.
At this point we should clarify that the purpose of this section is not to explicitly present a specific curriculum concerning computer based modeling tools. We simply aim to propose a methodology for its design. Finally, it should become apparent that the following discussion might not apply to all the currently available modeling software even though the resulting capabilities are provided by at least some of them and the methodology should pertain to most.

A major capability provided by modeling tools concerns the implementation of dynamic, in other words time dependent, models for physical phenomena. This makes it feasible for learners to explicitly compare their models with corresponding physical phenomena which in turn allows for effectively testing hypotheses, theories and predictions. In this way, it is possible for them to gradually improve their models so that they are more closely aligned with the related physical system.

Furthermore, engagement in computer-based modeling could help students develop a sense for some systematic processes that are very fundamental to physics learning [5]. Particularly, learners engage in constructing, analyzing, validating and employing models and in this way, they might develop an epistemological awareness with respect to physics learning per se [6].

During the design of a computerized model, learners need to select the appropriate objects they should implement, in terms of properties, and also the variables that should be taken into consideration. Finally, they also need to explore potential relationships, identify causal factors as well as irrelevant parameters. In this way, there is a strong possibility for them to develop a sense for the coherence that characterizes physics in general and also identify the causal and irrelevant parameters that apply to the specific model.

Another capability provided by modeling software relates to representational synthesis. In other words, learners can use multiple depictions, such as algebraic, diagrammatic and pictorial, in order to describe a model [1]. Potentially, students are provided with the ability to compare alternative representations with respect to their efficacy in communicating specific kinds of information. For this reason, they are very likely to develop the sense that there are multiple representations, which can often function complementary to each other, in terms of conveying information. In addition to this, it is possible that they become aware of the fact that specific information can be described best in particular representations.

Computer based modeling makes it probable for learners to use similar patterns for the description of entirely different phenomena or systems. The importance of this capability becomes obvious in light of the fact that students fail to recognize that physics encompasses a coherent conceptual framework and tend to believe that it constitutes a loose collection of unrelated concepts and theories. In this way, it appears apparent that they are likely to develop increased awareness with respect to the coherence that characterizes physics, which might in turn beneficially affect their performance.

Furthermore, computer based modeling tools allow for offloading the responsibility for performing complex algebraic calculations to the software itself. This might facilitate physics learning for a broad range of reasons. For instance, learners might develop a sense for their erroneous belief that physics is about memorizing mathematical formulae and applying them for solving quantitative problems. Engaging in computer-based modeling might shift the focus from quantitative to qualitative reasoning. This, in turn, can facilitate the development of useful meta-cognitive skills such as the realization that solving quantitative problems is one thing and understanding the underlying concepts and tenets is quite another.

The design of modeling curriculum needs to satisfy two constraints: it should satisfy the epistemological structure of the learning skills associated with modeling (Figure 1); it should also take into advantage the capabilities offered by available teaching and learning tools such as modeling software (Table 1) while at the same time seeking to fill in the conceptual gaps and realign any reasoning discrepancies that emerge. This approach outlines an analytical methodology for sequencing learning activities in a way that explicitly addresses the conceptual, reasoning and other demands placed on the learner. In implementing this approach the *Learning in Physics Group* typically exposes the initial curriculum design to classroom testing and evaluation. The evaluation always takes the form of research into student understanding and its development. It usually takes us a number of iterative cycles of curriculum – teaching – research before we can claim that our curriculum is refined to the point where it can be used effectively following suitable preparation by a wide range of teachers.

However, when we have tried to rely on intuition rather than systematic epistemological analysis and good understanding of the available tools, the resulting curriculum has always failed to converge to a version that we considered effective, even after repeated iterations of testing and modifying. In this sense the design board is an important pre-requisite to the curriculum development process and we find that it should always include epistemological analysis of the curriculum objectives along with detailed analysis of the capabilities of available tools. Both of these are necessary requirements for sequencing activities that, after refinement, will be expected to promote real learning.

Table 1. Capabilities provided by modelling software and potential contribution to the physics learning environment

What capabilities do they provide?	Why are they useful to the Physics learning environment?
Create animated/dynamic models of physical phenomena	Comparison with corresponding physical phenomena in order to (a) effectively test hypotheses, theories and predictions; (b) refine the model gradually, aiming for closer alignment with the physical system.
Develop mental models for interpreting the world	Identify Physics as a process of model construction
• Select appropriate objects to be included in the model • Identify variable quantities • Explore interactions between objects	• Identify causal relationships and irrelevant parameters
Direct and systematic implementation of mental models	• Testing the validity of ideas • Self – regulation in developing and applying mental models
Carry out complex calculations thus allowing learners to focus on qualitative conceptual reasoning.	Identify Physics learning with the development of conceptual understanding rather than rote memorization or derivation of numerical answers.
Provision of generic routines and procedures for model construction.	Appreciate that Physics is characterized by only a small number of fundamental principles.
Facility to synthesize diverse representations.	• Develop communication skills in multiple representation formats • Foster the ability to choose optimal representations for specific ideas.
Correlate models from various branches of Physics.	Develop a sense for the coherence that characterizes Physics.

3.1 CONCEPT MAPPING AS AN INSTRUCTIONAL TOOL

A concept map represents some important aspects of students' knowledge structure in a given subject domain. It consists of nodes and labeled lines. The nodes correspond to terms that are

deemed significant and indicate the student's appreciation of concepts. The lines denote a relation between a pair of concepts (nodes) and the label on each line denotes how two concepts are related. Concept mapping is grounded on theories postulating a networked or hierarchical structure of knowledge organization in memory.

There is evidence suggesting that concept mapping can function as an efficient didactical tool that supports learning in Physics [11]. Its contribution to the construction of meaning rests on the premise that when students elaborate on the development of conceptual networks with respect to a particular domain, they are likely to enrich and foster their knowledge structures by constructing more connections among existing nodes and will meaningfully integrate new concepts by establishing new links. Many students lack the epistemological awareness required for appreciating the coherence that characterizes Physics. Elaborating on conceptual mapping might also contribute towards meeting this need by helping them develop the sense that Physics presents a coherent body of knowledge containing conceptually interrelated ideas and concepts. These issues are further discussed through the presentation of the most important capabilities of concept mapping software and their linkage to the relevant Physics competencies that they can develop.

3.2 COMPUTER–BASED CONCEPT MAPPING TOOLS

Concept mapping has been traditionally carried out in paper and pencil format. However, Information Technology has contributed important tools that have significantly enhanced this process. Even though there is a wide range of concept mapping software, it is worth noticing that the cognitive demands they place on learners do not vary significantly and the different software often share the same structural characteristics. For this reason, unlike modeling software, the notion of continuum is not suitable for the description of concept mapping tools.

Concept mapping software provide a user-friendly graphical environment that includes powerful tools which significantly advance, facilitate and systematize the process of constructing and modifying concept maps. Amongst others, they allow students to easily insert (or remove) nodes and synapses, embed graphics and attach notes in the form of hypertext. The cognitive load that is associated with their use does not suggest important developmental constraints or cognitive prerequisites and it would make sense to argue that concept mapping software are suitable even for young learners beginning with the upper elementary school grades.

As was outlined earlier, the meaningful integration of computer-based tools with instruction should be based on methodical research. Systematic analysis of their capabilities has to be undertaken in order to identify the competencies in Physics that these tools can be used to develop. This analysis can reveal the rationale that pertains to the implementation of the tools since it enables us to infer the Physics learning objectives that they can promote. We have carried out a capability analysis of concept mapping software. The results are presented in table 2.

Concept mapping software facilitates and enhances the process of constructing and modifying multi-level hierarchical networks of concepts. It provides a working framework that contains predefined structure elements (nodes, synapses, labeling and linking procedures) which can be used by students to quickly and easily draw maps. In this way, students are likely to pay less attention to the inauthentic labor of merely drawing graphical representations and focus on the intellectual processes that are involved in concept mapping.

Table 2. Capabilities provided by concept mapping software and potential contribution to the physics learning environment

What capabilities do they provide?	Why is this useful to the Physics learning environment?
Construct multi-level hierarchical networks of concepts	• Develop effective and operational knowledge structures • Enhance problem solving skills through problem mapping and/or procedure outlines. • Meaningfully interrelate prior with new knowledge • Develop epistemological awareness with respect to the coherence that characterizes physical science.
Integrate notes and hyperlinks	• Readily available student-constructed operational definitions. • Linking across phenomena and domains.

Concept mapping software contribute to learning in physical science mainly in three ways. Firstly, students are likely to be engaged in productive and analytic processes like the systematic selection of the concepts that should be incorporated in a concept map, the identification of irrelevant concepts that should be excluded and the appreciation of how the embedded concepts should interrelate. It can be argued that this elaboration might be of great benefit to students since they are likely to reshape and enhance their knowledge structures in physical science. This becomes essential in view of the findings reported in experts-novices research. Experts, tend to form rich knowledge structures in the sense that they include more concepts and they link them in multiple ways to other concepts and relevant procedures. On the other hand, novices' knowledge structures, tend to be poor in the sense that they include significantly fewer concepts and many important links are absent while many of the existing ones are often inappropriate [8]. This difference can be used to interpret the higher grade of effectiveness with which experts approach and address problems. In this light, it would make sense to argue that the intellectual engagement of students with the software enables them to elaborate on and optimize their knowledge structures which might, in turn, enhance their problem solving abilities. This, in turn, increases the likelihood of students developing operational aspects of their knowledge thereby exploring potentially productive ways of retrieving from the impasse of rote memorization that so often undermines their ability to analyze unfamiliar phenomena and make viable predictions. Apart from this, students are also more likely to interrelate their preexisting knowledge, which plays an important role in learning, with new ideas and hence find further support for the process of meaningful learning to take place.

The second aspect of the potential contribution of concept mapping software pertains to the development of epistemological awareness. Physical science constitutes a coherent body of knowledge encompassing ideas and concepts that are meaningfully interrelated. Nonetheless, many students fail to appreciate this coherence and tend to consider physical science as a loosely structured collection of formulae, concepts and theories. This misinterpretation is highly detrimental to the process of learning in that it encourages knowledge fragmentations, rote memorization and a general lack of tendency to make any use of acquired knowledge outside the classroom context. In this light, it would make sense to seek methods for the

development of the epistemological awareness needed for students to avoid this. Student ability to represent and visualize knowledge structure in a diagrammatical format, such as is provided by concept mapping software, contributes greatly in this direction by making the links explicit and encouraging the student to elaborate on various forms of interconnections and the meaning that they might convey. In this way, students better appreciate the rigorous structure of a domain and that concept maps in a particular domain might extend and become relevant to other branches of physical science. In addition to this, students become acquainted with the opportunity to appreciate the systematic and consistent implementation of the tight linkages among concepts in physical science that underpin and establish its coherence.

The third aspect of concept mapping tools that contributes to the physics learning environment is the capability to incorporate notes and hypermedia features. This enables use of the concept mapping learning environment as a forum for tracking the distilled important aspects of ones learning process and as a useful tool for summary and review. For instance, in our work, students have often found it useful to summarize in transparent notes behind each concept its operational definition and in notes behind link labels specific working rules that have been developed in class based on direct observations and inference.

4. CONCLUDING REMARKS

In this paper we have outlined a methodology for sequencing learning activities in a way that explicitly addresses the conceptual, reasoning, epistemological and other demands placed on the learner. We have elaborated on this methodology in the context of developing modeling skills as a means of providing scaffolding structure transferable across topics to the whole of physics learning. As has been repeatedly proven by physics education research, learners cannot be expected to fill in the cognitive gaps for themselves, nor can they be expected to identify implicit pre-requisite knowledge. An analytical approach to the design of science curriculum, of the kind outlined here, can provide a breakthrough to the seemingly intractable quality problem we are faced with in physics teaching and learning.

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