EPISTEMIC PERSPECTIVE ON A CONCEPTUAL EVOLUTION IN PHYSICS AT THE SECONDARY LEVEL

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ABSTRACT
The research deals with qualitative understanding of physics notions at the secondary level. It attempts to identify and to label, in the verbalizations of 12 to 16 year-old students, the tendencies that guide their cognitive itineraries through the exploration of problem-situations. The hypotheses of work were about models, conceptions and p-prims. These last objects are seen, in DiSessa's epistemological perspective, as a type of habit that influences the determination of links between the parameters of a problem. In other words, they coordinate logically and mathematically. Methodology is based on explicitation interviews. Five students were invited to share their evocations as they explored the logics of a computerized microworld. This microworld is programmed on the *Interactive Physics*™ software and is made of five different situations that involve Newton's laws. An analysis of the five student's verbalizations shows the existence of elements that play a part in modelisation and qualitative construction of comprehension as well as in its qualitative/quantitative articulation. Results indicate the presence of easily discernible coordinative habits. P-prims appear to play an important part in the construction of models and in the determination of links between the variables of a problem. Implications of the research are, among others, at the praxic level; it becomes possible to imagine sequences of learning and teaching physics based on the consideration of p-prims despite the implicit nature of these objects. This is a truly constructivist practice which establishes bridges between novice and expert knowledge.

KEYWORDS
Science education, microworld, conceptions, conceptual change, p-prims, physics

INTRODUCTION

In science classes, mathematics constitute an important tool used to express models. They allow a description and an efficient treatment of the relations between the parameters inside models. We sometimes even hear that mathematical expression of problems is unavoidable to the point that *mathematic model* is often synonymous with *accomplished model*. (Orange, 1997) However, it happens that this formal expression of scientific knowledge often dramatically overshadows comprehension instead of helping it. This happens when problems are tackled, described, and solved in quantitative terms exclusively.

Undoubtedly, one can hardly admit that the mathematical expression of a model constitutes its explanation. One will rather accept that it is the qualitative comprehension of a problem that commands the choice of relevant variables as well as their articulation. It is the reason why, for many years now, experts in science didactics concentrate their efforts on qualitative aspects of comprehension. This brought them to develop an arsenal of means to make qualitative comprehensions evolve. These understandings, when expressed, appear as conceptions. When they are more or less in rupture with scientific conceptions, they are labeled of "erroneous", "primitive", "naïve" conceptions or simply "misconceptions". (Potvin, 1998; Novak, 1994). The challenge is clear: one has to make these conceptions evolve and reconcile with ideas recognized by the scientific community.

Different models of "conceptual change" have been proposed (Laplante, 1997). The elements of the problem on which these models insist are many: cognitive or sociocognitive conflicts, comparison of models on the basis of their validity or they capacity to explain or predict, conditions that favor conceptual change, etc. (Potvin, 1998) While some of these models think of conceptual change as a rupture, others think of it as a continuous process. However, despite a myriad of models, analogies and propositions and despite the enthusiasm produced by this multitude of models, their respective successes are questionable. When we examine the results of the pre- and post- tests, we don't see much evolution: those results are often comparable to what traditional teaching can do.

The 1990's, however, have seen a new conceptual framework appear which allows a new epistemic perspective on the conceptual problem: p-prims (phenomenological primitives). (DiSessa, 1993, 1998; Marton, 1993; Hammer, 1996). These objects are more similar to tools than to conceptions. They can be understood as interpretative habits that allow individuals who use them to coordinate parameters of the problems they approach. In fact, they are elementary objects that allow subjects to interpret certain phenomena and to give these phenomena meaning. One of the major interests of p-prims is that they are about understanding model construction as well as the origin of certain conceptions. Another advantage is that they exist in a smaller number than conceptions, so they are more easily approached.

In this research, we present mechanical problem-situations to secondary students. These situations are inscribed in a computerized microworld programmed within the *Interactive Physics*™ software. The subject's goal is to try to establish the logics of the situations by free exploration. The research questions asked during the analysis of the data were: 1) "Which are the models developed by the subjects to grasp the logics of the situations?", 2) "Which conceptions were evoked by the subjects during the explorations?" and 3) "Which p-prims are mobilized during explorations?".

METHOD

The interviews

Overall, 20 subjects from every secondary level were interviewed. We selected 5 of them for further analysis, one for each level. All of the subjects attended Jeanne-Mance secondary school in downtown Montreal. Each student subject was interviewed for a period of 5 to 6 hours.

The type of interview used for this purpose was the *explicitation interview* type. (Vermersh, 1994) This is a powerful means to obtain information about exploration paths followed by individuals. Among other things, explicitation interviews forbid the use of the question « why? », because the answers given to these questions usually deviate from what the subjects really believes. It is therefore preferable to ask them to verbally produce descriptions of the exploration steps they choose to follow. It is through these descriptions that the researcher gets some further insight as to what the subject thinks.

The situations

The situations presented to our subjects were elaborated on the *Interactive Physics*™ program. *Interactive Physics*™ is a software designed at the origin for modelisation in mechanical engineering, but it is so easy to learn that it can also be used in lower levels. There are five situations, numbered with increasing levels of difficulty, all of which have been programmed from the virgin matrix of the software. They all involve a moving ball and neglect gravity and friction with air. These movements, from situation 01 to situation 05, are consistent with Newton's laws of mechanics. The situations as a whole constitute a microworld. As Legendre (1993) suggests, a microworld of movements, like ours, is a learning environment that insists on the functional and experimental components of knowledge in physics.

The situations can be considered as more elaborate versions of Legendre's (1993, 1997). They were designed from the "Dynaturtle" program and were characterized by the possibility to give impulsions, or "kicks" of different intensities in different directions.

In our situations, the subject must also decide about a certain number of parameters that can influence the behavior of the ball (*mass*, *force*, *direction*, etc.). When the choice of parameters is made, the subject can discuss them with the interviewer, and enter them in boxes appearing on the screen. Then, he is ready to launch his trial. The subject can press the "run" button to initiate the test and than follow the path of the ball on the screen. The ball will behave according to the choice of parameters. Certain information about this behavior can be obtained by the simple observation of the ball (relative estimation of speed, position or of its "photo", trajectory, etc.), while others can be obtained by reading instruments (chronometer, velocimeter). It is with this information that the subjects can learn about the effect of their choices, draw conclusions, adjust his models, and anticipate the next trial. To help the subject evaluate certain parameters, a ruler is sometimes present on the back of the screen. Other iconic objects such as hearts, flowers or snowflakes are also occasionally present. Though they do not have a mechanical part to play, they can be used as targets, or references. Despite the fact that they were omnipresent, all subjects understood rapidly that they did not have anything to do except to provide spatial references. No subject ever thought that the ball could bounce on those objects.

In each one of the situations, we asked the subjects to explore economic ways to efficiently predict the behavior of the ball. They had, in fact, the duty to try to respond to the challenges proposed by the interviewer. For example, to cover a target, to make the ball bounce, to increase its speed from 1m/s to 3m/s, etc.

Because situations 01 and 02 can be considered like software familiarizing exercises, we will insist more on the following two: situations 03 and 04. Situation 05 will also not be explored in details as much as 03 and 04 due to the fact that subjects could not explore situation 05 equally because of their unequal rate of progression.

Situation 03
Situation 03 asked the subjects to coordinate the *mass* (M), *force of the kick* [or simply *force*] (F) and the *photo* (p) parameters. The ball then accelerated from rest proportionally to the *force of the kick* and inversely to the *mass*. The ball was not accelerated during all of the trial. It reached its maximum speed in a glimpse, a relatively short interval of time. After this acceleration, the speed of the ball remains constant. As for the *photo*, it is the delay at the end of which the ball will leave a black print (like a shadow on the screen). It's a very useful tool when one needs to know the exact position of the ball at a given moment and so the distance (D) gone over by the ball before the photo-delay. Finally, the ball comes out of the screen towards the right after a more or less long duration of time.

The subjects were then presented with the same starting situation. Then, the interviewer indicated that when the value of all parameters is one (1), the photo of the ball will be "taken on the green star (D=4)". When the subject launched a trial with those values of *mass*, *force* and *photo*, the ball behaved according to what appears in figure 1. This information is the starting point (the reference) from which one can justify modifications made to the parameters for the purpose or reaching other targets. Following which the interviewer proposed new challenges to the subjects by comparison of the results obtained. For instance: "Knowing that those values will make the photo cover the yellow star (D=2), can you change the *mass* in order to cover the red star instead? (D=4)".

Overall, there are six targets (all different colored stars) located on integer values of D. These values are 1, 2, 3, 4, 6, and 8 for the black, yellow, red, green, orange and blue stars respectively. The particular choice of these values is determined because of the simple ratios we can establish between pairs of those values; double, triple, quadruple, octuple, half, third, forth... However, it is also possible to obtain pairs of values that give more simple ratios. For instance, from the red star (D=4) to the blue one (D=8), the ratio is 2,666… The interviewer will propose problems that involve those two types of ratios.

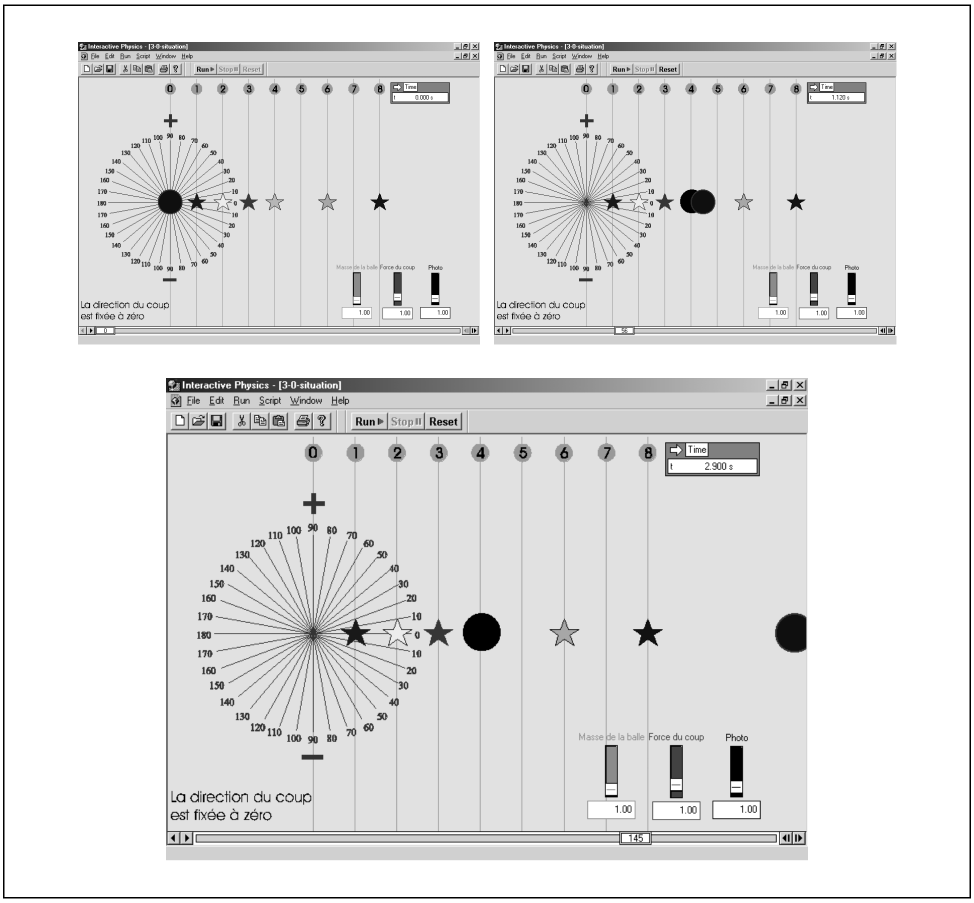

Figure 1. Situation 03 [Mass=1, Force of the kick=1, Photo=1]; Notice the shadow of the moving ball; it stopped on the red star [D=4] because the delay of the "photo"parameter was over when the ball went just over that star

From the knowledge of the results (D) obtained with a set of values, the interviewer asks the subjects to change one or more parameters to obtain the same results, or to cover another target.

It seems reasonable at this point to say that the goal of this situation consists essentially for the subjects to translate in mathematical terms the intuitions they developed in earlier situations (like situation 02) in which they were asked to aim targets without the use of calculus, by trial and error in mathematical terms. In situation 03 they were invited to elaborate logico-mathematic articulations of the variables, because they had to take explicit account of evaluations of D.

Situation 04

Situation 04 is in continuation of situation 03. It works the same, except that when the ball gets the kick, it is not at rest. However, it essentially consists of the same premise, with the exception of continuously moving at a constant speed of 1m/s. A new parameter can be modified: the *direction of kick* (d). This button allows only two possibilities: directions 0 and 180, so it is impossible to give kicks in other directions than right (0^o) or left (180^o). The ball cannot change the axis of its movement, but it can change direction, accelerate or decelerate. Consequently, for the same values of M, F and d, the ball behaved differently than in earlier situations, where there was no initial movement of the ball. Therefore, the subjects had to deal with the momentum of the ball in their explorations.

In this situation, the interviewer bases his questions on the apparent trajectory of the ball and on its speed as read on the velocimeter. For example, he can ask the subject to make the ball "bounce toward the left part of the screen at a speed of 2m/s". In figure 2, we can see, in three steps, the behavior of the *mass*=1 ball when it is kicked by a F=1 force toward *direction* 0. Please note that the speed on the velocimeter increases from 1m/s to 2m/s because of the kick given at the center of the protractor.

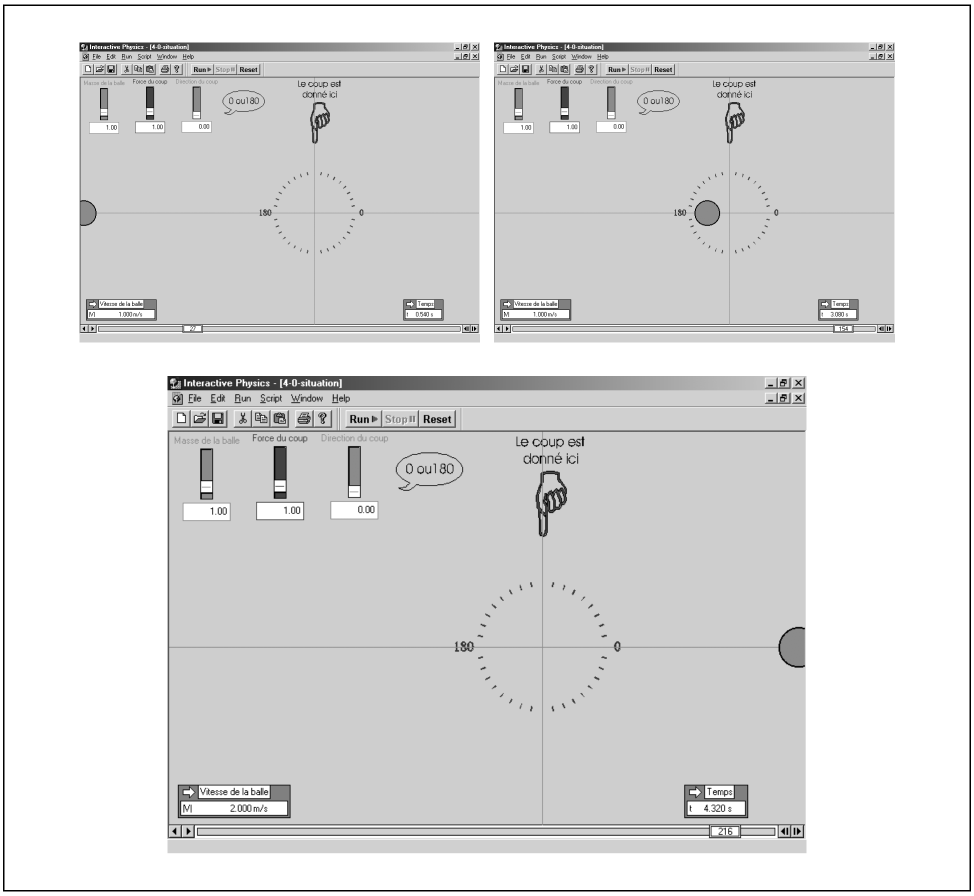

Figure 2. Situation 04; Ball accelerates after the kick

RESULTS AND INTERPRETATION

Results and interpretations are here presented according to the three initial questions of research. We propose a section for each specific questions. The first is about the models as developed by our subjects, the second has to do with the conceptions evoked and the third analyzes the p-prims which have been recognized in the explicitations.

1. Models

Situation 03

At the start of each situation, subjects almost always began their exploration by proceeding by trial and error. After a while, step by step, they improved their predictions and then proposed certain models. Most of them rapidly developed a rather good idea of the proportional nature of the relation between the *force* (F) and the covered distance (D). They understood, for instance, that when they double the first, the second is taken twice as far. For all integer ratios between F and D, all subjects, with the exception of the youngest ones, felt quite comfortable: to double, triple, quadruple, divide by 2,3,4, etc. It is to be noted, however, that only the oldest students established the right *force of kick* to give to the ball for non-integer ratios. For example, where it was necessary to displace the photo from the green star (D=4) to the orange star (D=6), the subjects had to multiply F by 1,5. Most of them preferred using the « center point » model. Whereas, if I knew that F=3 gives the green star (D=4) ant that F=6 gives the blue star (D=8), then the intermediate value of F between 3 and 6 [F=4,5] should give access to the star that we find between D=4 and D=8 (the orange star [D=6]). This model was widely employed, especially when the subjects looked for a way to get closer to the origin, as in when the ratio is less than

1 (ex: to displace the photo from the orange star to the green one). Despite all this, we still remarked that certain individuals were quite comfortable with those ratios. For example, to displace the photo from the green star (D=4) to the red one (D=3), F has to be multiplied by ¾.

The exploration of the effect of the *mass of the ball* (M) on D has been much more difficult. The relation between M and D is inversely proportional. If it is quite obvious for our subjects that when you double M, D is half what it was in the earlier trial, it is not at all so obvious that if you double M again, the displacement of D will be much smaller. Subjects had great difficulties to recognize the asymptotic nature of the relation. For example, if one reduces the *mass* by a factor 10, like changing M from 2 to 0,2 (both little values), the distance covered will multiply ten-fold (it goes, for instance, from 3 to 30!). Subjects really didn't make sense of these results. They all remained very surprised. In order to accommodate their beliefs, they sometimes used quite unexpected explanations, such as one of the subjects, for instance, insisted that there had to be an invisible inclined plane on which the ball rolled, because otherwise, it was impossible to make sense of that much speed.

Subjects also had a hard time to admit that there was no value of M big enough to immobilize the ball when it was kicked (D=0). In fact, each subject had a hard time with this asymptotic character. For example, most of them tried with great stubbornness to apply the "center point" model to the relation between M and D, but the relation between them is not linear, as is the relation between F and D. We can then hypothesize that they thought of this relation as a linear negative proportional [type y=(-)x+b], which it is not.

Subjects who were the most successful were the ones who developed a model that we'll call "2 jumps in 1". When the interviewer asked the subject to displace the photo at a non-integer ratio of D values or near the axis, the subject imagined an easy jump (from one star to another) combined to another easy jump (that can reach the target), and then he made one single operation out of it. For instance, to displace the photo from the orange star (D=6) to the green star (D=4), by changing M, he imagines a first jump to the yellow star (D=2) by tripling M, and another one from the yellow to the green star (D=4), by dividing M by 2. Thus, the unique operation to do on M became: "M times 3 divided by 2".

Situation 04
Recalling that in situation 04, the ball is not initially at rest (S_i=1m/s), the interviewer insisted not so much on the final location of the photo as on the final speed of the ball.

In preliminary explorations, the youngest subjects were the ones who had the most difficult time to recognize the effects of the initial momentum. These subject's hypothesis and predictions were quite interesting: "A zero force kick should stop the ball", "We can't stop a ball by giving it a kick", "If we increase the force, it will necessarily produce a [positive] acceleration", "A kick given toward left has to make the ball bounce", or "a reduction of the *force of the kick* will produce a proportional reduction of speed". Most of these propositions would work in cases where the ball is initially at rest, but not in situation 04. Subjects did not let go easily and they succeeded only after many sterile trials, indicating a certain resistance to develop an idea of inertia.

Of course, not all exploration initiatives are sustained by qualitative considerations. Certain subjects will develop models based only on mathematical terms. Those subjects are looking for the "right numbers" in order to make successful predictions. Many of them will even look for superficial resemblances into F or S: "If there's two five (ex: 3,55) in the decimals, then, it'll work". Others will even accuse the computer to reject certain values: "the computer does not like numbers that end with 667 (ex: 3,667), it hates them".

Other subjects also developed models that worked quite well, but seemed to originate from accident, or chance. For example one of them developed the "(F-M)/M" model. It allows its user to determine S knowing F and M when the *direction of kick* is 180, i.e. when this direction if opposed to the momentum, but it only had a local worth (it is inefficient when the *direction of kick* and the direction of momentum are opposed), and the subject was unable to physically explain it.

Other and more efficient models have been developed by our oldest subjects. We will examine them more closely because they are based on more qualitative understanding. We will also see that they are more efficient.

The "equilibrium + gap" model
This model is based on the idea that any movement of a ball must pass through a phase of immobilization. The essential work of someone using this model is to first find which set of values will imply a kick that can "balance", "neutralize" or "cancel" the initial speed. When this is done, the subject has to look for the value of final speed that corresponds to one (1) gap of F (that's what we call the "gap" in "*equilibrium + gap"*). Once the subject had found this, he added or withdrew [depending on what the ball has to do; bounce (toward left), accelerate (toward right)] F as many times he needed to get the right speed. This model has two important disadvantages: 1) It can't describe what happens when speed has to go over 1 toward right, in which case the subjects has to add a complementary model and 2) the user must find, generally by trial and error, the new value of the "gap" every time that *mass* changes.

The "*effect of kick +1-1*" model
This model is probably the closest one to the Newtonian perspective. It takes account of the initial speed, but only at the end of the calculation. The model consists in inventing an additional variable, which is not present in the situation itself. Since F cannot by itself determine the variation of speed (because the mass is also implied in the problem), the subject had to find something more like "*effect of the kick*". Certain subjects would rather talk about the "boost" or the "speed after kick". This "*effect of kick*" is, in fact, nothing else than the acceleration. All the subjects who felt the need to involve this new variable found easily and rapidly the right calculations: F/M (like in F=MA or here, A=F/M). After this, subjects added or withdrew 1, which is the initial speed, according to the *direction of the kick*. It is clear that subjects who developed this model are the ones who were the most comfortable with qualitative reasoning during the explorations.

2. Conceptions
A certain number of conceptions have been evoked by the subjects during the explorations. These conceptions are considered here as verbalized justifications on which subjects based their explanations or made a prediction. Even though they had not been deliberately provoked by the interviewer, they still appeared and were consistently used on two occasions in the interviews: 1) at the beginning of explorations like a basis for first predictions and 2) when the subjects discovered new fertile coordinations and were looking for ways to interpret them.

Here are a few examples. Note that these conceptions can be easily associated with conceptions already identified in similar circumstances by other authors. (Thouin, 1997)

Marco (sec. 2): "The more the ball is heavy, the more it'll stop near [the origin], because when you throw something heavy, like a <..?..>, if you throw it hard enough, it'll stop somewhere, and if you throw it feebly, with the same mass, it'll stop before because it's heavier (sic)."

Emmanuel (sec. 4): "If you push the ping-pong ball, the force you put in it should not be felt, maybe, as long, but if you take the golf ball and if you throw it, it'll roll longer, because it's heavier… So maybe it'll maintain the force longer, the force we put in it. It might roll longer."

Marie (sec. 5): "Yes, because if it's lighter, it'll go…well… with the same force… when it's lighter, it goes faster."

One observation we can make about conceptions in the particular context of this research is that they were quite rare. Even though they were present, they were rather anecdotal during the explorations. Also, they do not seem to be as solid as the conceptual change literature might suggest. In fact, not only were they quickly abandoned by the subjects when predictions based on them failed, but they were rapidly replaced by new models. The majority of interview time had been invested on the exploration of the relations between the parameters of the situations. It can then seem doubtful to think, seeing the results of this inquiry, that it is through conceptions that subjects developed their comprehension of the microworld.

3. P-prims

We now turn our attention to the analysis essentially based on the discovery by our subjects of the simple relations that exist between the variables of our situations. The exploration of these relations, or coordinations, is so important, in terms of interview time invested, that it was possible to determine what were the "coordinative habits" of our subjects and to associate them with certain p-prims identified by DiSessa (1993).

P-prim "symmetry"

In the most diverse circumstances, subjects had sometimes a very strong and spontaneous tendency to look for symmetries. We saw subjects systematically looking for symmetries and using related findings in a broad range of situations. Sometimes efficiently, as in cases where the *direction of kick* could be changed (situations 1 & 2), and sometimes inefficiently, for example, within attempts to reproduce at the right "what happens left". The secondary 5 subject proposed that, in situation 03, calculations that could predict what happened at the right of the green star (by measuring the distances from the initial starting location of ball) could be "reversed" (by measuring them from the blue ball [which is at the same distance from the green star than the origin]). The situation does not follow this logic because all values of D must be measured from the origin, otherwise they have no physical meaning. Many observations of this nature had been made over the transcriptions. Subjects from 3rd and 4th year of the secondary (grades 9 & 10) course also showed this propensity. We must note that subjects used this p-prim more often when they lacked qualitative explanations.

P-prim "cancelling"

The idea that certain physical agents or influences can literally neutralize others is a very current p-prim in physics and particularly in mechanics. Notwithstanding if it is consistent or not with canonic physics, it is striking to see how frequent and ever-present it was during verbalizations, as every subject touched upon it during the interviews. The p-prim was at the origin of a number of modelisations. The actual core of the "equilibrium + gap" model consists first in a "neutralization", an "extinction" or a "canceling". After that, the rest of the model can be constructed around this idea. Subjects have, currently used expressions such as: "compensate the force", "neutralize speed", "find the equilibrium-force" or even "cancel the kilograms"! (sic)

P-prim "force as a mover"

This p-prim, more specific than the others because of the circumstances in which it applies, is exclusively and directly about the physical nature of phenomena. It is about the force and its effects. Far from teaching that a force produces an acceleration, like the Newtonian law indicates, the "*force as a mover*" p-prim supposes that a *force* (direction X, intensity Y) always implies a movement at a constant speed proportional to its intensity (for a F_Y force, a S_Y proportional speed) and in the same direction than the application of the *force* (direction X → trajectory X) notwithstanding the initial movement of the ball. This p-prim could be used efficiently until situation 04 and even without it ever coming to light, it remains implicit. It is only by introducing an initial movement (situation 04) that the p-prim, in conflict, will manifest its existence explicitly. These manifestations were many. For example, subjects will very often express their surprise to see the ball going in a different direction than the kick (when it is weak) or be amazed that a kick might stop a moving ball or that a zero force kick will not stop the ball. Of course, by definition, "*force as a mover*" in an obstacle for the consideration of inertia, but it becomes empirically clear with our analysis of the data.

"Ohm's" p-prim

This p-prim was omnipresent in all interviews. Usually, subjects who used it involved an *agent* that is the cause of a *result*. This *result* is proportional to the intensity of the *agent*, but it also responds inversely to a *resistance*. Therefore, the more important is the *agent* is, and the more weakened *resistance*, the more favorable the *result*. Disessa (1993) calls it "Ohm's" p-prim because of its resemblance to Ohm's law in electricity, where the voltage (U) is the *agent*, the current (I) is the *result*, and where we can also find a *resistance* (R). However, these three roles, in the p-prim, can be played not only by these three variables, but also by any parameter of a scientific phenomenon that the individual chooses to coordinate.

It is clear that our subjects wanted to associate the *agent* with F. They also generally held as the *result* the parameter on which the interviewer bases his challenges (i.e. D or S). Finally, they associated the *resistance* with M. The choice of parameters and the way the p-prim articulated them were sometimes fertile and sometimes sterile, but it is clear that the subjects, in every one of our five situations, tried to use this p-prim to efficiently coordinate the variables. We can also easily associate the p-prim with certain models: "*center point*", "*2 jumps in 1*", "*effect of kick +1-1*" (where the *result* is the "*effect of kick*"), etc. Indeed, it is possible in all these models to find coordinations with an *agent*, a *result* and a *resistance*.

CONCLUSION

In light of what has been presented here, a certain number of conclusions can be drawn. First, it is clear that understandings of the situations which were based on qualitative considerations were the most promising and reliable. The models produced on this basis were the ones who could address the greatest number of particular cases (they are more universal). They were also the ones that were the most readily adaptable to all sorts of varied situations. We can also note that they are the ones that most resemble scientific knowledge. Conversely, understandings based only on superficial numeral considerations rarely approach science. This research clearly supports qualitative comprehension for construction of personal models.

A second conclusion, this one for the benefit of the researcher, is that p-prims constitute, in the present exercise, an interpretative framework much more interesting than conceptions do. P-prims occupied much more interview time than conceptions, they were more stable and allowed us to follow much more closely the cognitive itineraries of our subjects. It seems here that they provide a very promising universe of didactic knowledge.

Finally, we have to conclude that the microworld, programmed on *Interactive Physics*™, provided the subjects with powerful mechanical contexts of learning, full of "objects-to-think-with" (Papert, 1980). These objects are an excellent basis on which meaningful cognitive conflicts can be triggered and from which new efficient models can be invented and tested. As for the researcher interested in cognitive itineraries, it is not impertinent to suggest that the microworld provided very interesting "objects-to-do-research-with".

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