A second order cybernetic model of scientific conceptual understanding with pedagogical applications to kinematics

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ABSTRACT

Even if difficulties of the students in sciences are diversified, most seem linked to deficiencies in their understanding of basic concepts. Since about twenty years, different researches tried to bring solutions in this problem, favouring the multiplication of directives that can be applied to science education. To integrate their results, we offer a second order cybernetic model of scientific conceptual understanding which allows, not only to describe all the paths learners took to understand, but also to choose instructional strategies of education appropriate to do so. We illustrate the application of this model to the teaching of the kinematical concepts of speed and acceleration. As a conclusion, we draw limits of the model and make suggestions for future research.

Keywords: Learning model; Conceptual understanding; Conceptual network; Science teaching; Kinematics

1. INTRODUCTION

At the dawn of the XXIth century, it has become essential for young people to undergo basic scientific training, either to favour their integration in a society more and more dominated by science and technology or as part of their studies in a scientific or technical domain. High schools, principally responsible for the acquisition of basic scientific learning and the training of new scientists, attains these purposes only partly as many young people leave school without completion of their high school diploma and others choose not to continue studying in a scientific or technical domain [1]. In this respect, difficulties students experience throughout their scientific studies seem to be connected to deficiencies in their understanding of basic concepts which remain, even after having completed several courses in a specific scientific domain [1,2]. In reference to these issues, a question arises: Is there a model of the process of understanding scientific concepts which would account of various difficulties in science learning experienced by high school students? To answer this question, our research of a theoretical nature analyses and synthetizes the results of researches on conceptual scientific understanding. To integrate the results of these researches, we propose a model constituted by the main dimensions of understanding and their reciprocal relations.

2. METHODOLOGY

The theoretical perspective of this research aims at clarify what is general in the various aspects of the conceptual scientific understanding, to highlight variables linked to this understanding and their reciprocal relations, and to formulate them in the form of laws or principles, by trying to abstract it from individual characteristics of learners and from contexts [3]. Moreover, to give a better account of the complex character of the phenomenon of conceptual scientific understanding, we adopted a systemic method where variables are interrelated in the form of a organised whole, represented in form of a modelling schema [4].

To elaborate the model of scientific conceptual understanding, our research method consisted of performing, in an iterative way, the analysis and the synthesis of literature in this domain [5]. We briefly introduce the main steps of this research method:

1) The identification of the corpus of texts to be analysed concerning scientific conceptual understanding

Fundamental topics and texts concerning conceptual scientific understanding were chosen according to this topic. We therefore questioned two educational databases. The first one contains texts which are written in both French and English (FRANCIS). The second database contains texts that are only written in English (ERIC). This first selection of texts was made using the descriptor COMPRÉHENSION or its English equivalents UNDERSTANDING and COMPREHENSION, and by limiting articles and monographs chosen in the education and scientific domain.

2) The segmentation of texts in analysis units

The constituted corpus of texts was later segmented in units of analysis. In an analysis of documents, the unit of analysis is defined as a segment of information which relates to a category [5]. The length of the units of analysis does not coincide with the linguistic segmentation of the text (sentence or paragraph) but rather tries to capture a main idea concerning the understanding of scientific concepts [6].

3) The location and coding of analysis units

Every unit of analysis is described with the aid of one or of several keywords which characterises the information contained in the unit. Using keywords allows one to condense content, and makes it easier to find and compare the research results of the different authors with respect to a topic or a sub-topic of scientific conceptual understanding. To this end, keywords have to be expressed in a way that is general enough to allow comparison (and synthesis) and specific enough to facilitate their location and the treatment of information during the analysis [5].

4) The structuring of results obtained in a modelling schema of the scientific conceptual understanding

Once the thesaurus for scientific conceptual understanding had been constituted, we calculated the frequencies of the keywords appearance and the associations between keywords in the units of analysis [6]. The analysis of these frequencies allowed us to identify the important keywords and to connect them in the form of a schema [7].

5) Validation of the model of scientific conceptual understanding

The modelling schema is later subjected to a technique of validation based on the clarification of paradoxes identified in the studied texts. Indeed, the highlighting of a paradox allows the modification of the conceptual structure of a theoretical schema and the clarification of this paradox allows the refinement of this schema by specifying the limits of the studied concepts [8].

Finally, in spite of the linear character of the steps of the research method described above, the analysis and the synthesis of the content contains feedback loops at every step which allow the process to converge toward a "prototype" of the model of scientific conceptual understanding [5]. Given the theoretical character of our research, we did not undertake an empirical validation of this model so that this validation will have to be completed in subsequent research.

3. RESULTS

Presentation of the model of scientific conceptual understanding

Steps of the model: We specify now the different steps of the model of scientific conceptual understanding and its structure. This model can be conceived as a cognitive system which interacts with its environment by collecting information and producing answers. During the elaboration of one's understanding, the learner's conceptual structure, semantic in nature and constituted by schemas, acts as a cognitive tool which, not only chooses and stores information from its environment, but also transforms it to produce better adapted schemas. As a result, schemas mobilised by the learner when he interacts with the phenomenon are changed during treatment process to gain a more adequate understanding of the phenomenon [4]. As a learning approach, understanding becomes divided into three parts: the conditions of understanding, process of understanding and product of understanding (see fig 1).

Conditions describe the requirements at the entry of the system, which contains two components: the initial state of understanding of the learner and the scientific concepts to be understood. Process describes the way the interaction between the leaner and the scientific concepts takes place. The product specifies the characteristics of the final state of understanding [9].

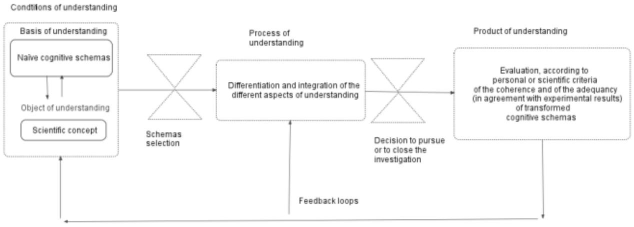

Fig. 1 Schema of the model of scientific conceptual understanding

Main sense of information transfer: The main sense of the information transfer of information is directed from conditions to the product by way of the process [9]. This transfer can be influenced by the choices or decisions of the learner (see fig 1). Indeed, from conditions to process, learner's schemas adapted to the study of the scientific concept are chosen among all of the available schemas according to the characteristics of the concept. From process to product, the learner chooses to continue or to close the activity of understanding if he judges that his state of understanding is satisfactory [10]. The information transfer from conditions to process and from process to product can also be influenced by emotional or social factors. For example, it seems that beginners prefer schemas having a high degree of correspondence with the structure of the studied concept. This preference limits the level at which the beginners can treat information later [11].

Feedback loops: We have described up to now the information transfer from conditions to process and finally to product. However, the information transfer can also take place in the reverse sense. This inverse transfer is called feedback and allows one to reinvest the results of every step at a previous step, constituting feedback loops [12, 13]. The first feedback loop, going from conditions to process and conversely from process to conditions, means that the learner turns his attention to the object of study (concept, phenomenon, law, principle), that some of his cognitive schemas are activated to treat the information coming from this object, and that meanwhile some understanding difficulties appear (see fig 1).

The second feedback loop, going from process to the product and reciprocally from product to the process, means that the new organisation of knowledge changes the understanding process (see fig 1). For example, new links established between some elements of the representation of the learner can lead him to search additional information, to incorporate some contributions of his peers toward the development of a more general schema, etc.

The third feedback loop consists of the use of the products of this approach as new "entry" in the system, which launches a new understanding cycle (see fig 1). This cycle allows one to open the way to new learning: generalization of the new concepts, their use in the resolution of problems, and their application in daily life [12,14]. The repeated use of the understanding cycle allows learner to provisionally occupy a series of states of understanding of increasing complexity [15]. These states distinguish themselves by their degree of organisation of knowledge and the new operations which this organisation allows. The series of states of understanding defines all of the levels of understanding of increasing complexity [4].

External influence on the approach of understanding: Moreover, the approach of understanding is opened to external influence of emotional or social nature. Knowledge which the student uses often comes from interactions with daily objects. As such, learner's conception of science, the value he grants in scientific activities and the competence he recognizes in the accomplishment of these activities were influenced by an extended contact with the school environment [16].

Viewing the whole approach of understanding: By viewing the whole approach of understanding in sciences, we first notice that it is initiated when the cognitive schemas of the learner are mobilised for representing the object and its properties [17]. This representation includes two distinct processes: the identification of various aspects of the object (differentiation) and the synthesis of these aspects in a consistent conceptual structure to fulfil different scientific functions (integration) [5]. The higher or lower ability of the learner to differentiate and to include the various aspects of the object (that it is a phenomenon, a concept or a scientific law) results into the acquisition of more or less efficient cognitive schemas to predict and to explain this phenomenon [15]. These cognitive schemas constitute new entries during the launch of a new understanding cycle. Therefore, these new schemas can contribute to the study of various situations that are similar or different from the initial situation, favouring generalization or knowledge transfer. Understanding is therefore iterative, continuing until learner is satisfied [10].

Regulation of the approach of understanding: Finally, the presence of explicit regulation mechanisms in the schema of the approach of understanding results in several important consequences for learning: 1) they partly explain the gap between qualitatively different conceptual structures, 2) they lead to the organisation of a hierarchy of acquired knowledge. Indeed, the reinvestment of the products of understanding as new entries does not only increase the knowledge of the learner, it transforms the way information is treated since schemas are the conceptual tools with which the learner interprets and organises his environment [4,14]. Moreover, this reinvestment facilitates self-regulation, i.e. when the learner regulates his or her learning. More precisely, learners having good self-regulation skills generate feedback for themselves providing information about what learning objectives have been mastered and what it is necessary for them to do in order to pursue new objectives, while in comparison, learners not having such skills rely on external feedback, given by the teacher or the school textbook [16].

4. PEDAGOGICAL APPLICATIONS TO THE TEACHING OF KINEMATICS

Description of the student's evolution of understanding

If the schema of approach aims at describing factors which influence understanding and their organisation, at least in its main lines, the choice of instructional strategies to favour understanding depends on the particular characteristics of pedagogical situation [5]. As a result, to go from the description of the way understanding evolves to the choice of activities allowing to favour this understanding, one first needs to specify the evolution of the understanding of learning and secondly to specify requirements relating to each step of the approach of understanding by taking into account characteristics of the pedagogical situations found in sciences. We aim in this section to satisfy the first requirement and in the next section to satisfy the second.

With respect to the first requirement, the structural organisation of concepts is likely to depend upon the domain of physics chosen. Among the physical phenomena studied in the secondary, we chose the learning of motion, or kinematics, since this domain is important for the students for several reasons: 1) the acquisition of concepts of time, of speed and acceleration constitutes a precondition in the learning of concepts of mechanics; 2) in kinematics, the student learns new methods, such as building Cartesian graphs, measurement and systematic collection of data, problems solving, etc. which will be useful in more advanced physics courses.

And yet, if there is a domain which causes a lot of difficulties to the students, it is the kinematics, defined as the study of the motion of objects without being concerned about its causes [18]. These difficulties may be caused by the everyday schemata students develop before arriving in the physics that can interfere with learning, especially if teaching does not take them into account.

In this respect, to describe the evolution of the understanding of learning in kinematics, our approach consists in simulating what would be an approach of ideal understanding when it is carried out according to steps and by respecting relations between its elements [19]. In that way, by applying this approach repeatedly, it is possible to explain the various progressions of the learner's understanding. Indeed, if conditions and products of understanding define the states of departure and of the arrival, the process of understanding allows to link these two states. And yet, the process of understanding in sciences is constituted of two operations: the identification of pertinent factors of a concept and the formulation of a rule which allows to link those factors to produce a new concept [17].

These operations act on two types of variables: on one hand, all the concepts of domain, say kinematics, and on the other hand, all of the learners' representations. Moreover, this approach is applied whatever is the learner's actual level of understanding and is therefore independent of the specific understanding cycle (see section 3). As a result, this approach ramifies by iteration into various paths according to the state of understanding (partial or complete) of different concepts of the aimed domain. The set of all these paths constitutes what we call a network of understanding [20]. As regards the the kinematics phenomena, their properties can be classified along the characteristics of two main physical models: 1) the straight motion at constant speed; (2) the constant acceleration (or deceleration) in straight line [21]. An example of such network is given in the figure 2 with respect to the speed concept [17]. Due to space limitations, we don’t present the understanding network of acceleration (see 17 for details).

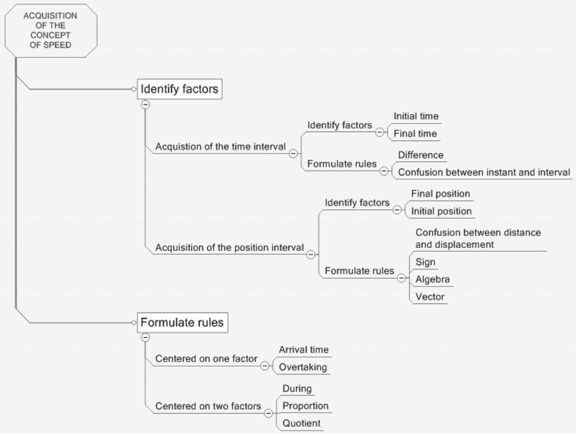

Fig. 2 Understanding network of speed

Instructional strategies fostering scientific conceptual understanding

To formulate instructional directives, it is necessary for us to first specify the frame in which these are going to be inserted. Our approach, centered on significant learning, aims at studying the development of the understanding of the student in the educational contexts which it influences [17]. In regards to the approach of understanding, we aim to show the complementarity of instructional strategies intended to guide the student in their approach of understanding by respecting the systemic character of this approach [22, 23]. It is from this perspective that we suggest the following instructional strategies of education for each of the steps of the approach of understanding: 1) establish the conditions of understanding; 2) favour the process of understanding; 3) favour the evaluation of understanding by the student; 4) favour the self-regulation of the approach of understanding.

Establish the conditions of understanding

Above all, conditions allowing interaction between the cognitive schemas of the student and aimed scientific concepts must be set up. On one hand, this interaction requires that the activities (either to explain a scientific phenomenon or to resolve a problem) allow students to mobilise their current cognitive schemas and, on the other hand, that these schemas, once activated, could be made public and explicit in order to be studied, either by the student (metacognition), or by the teacher (diagnosis of previous knowledge).

Regrouping students in small groups may favor the expression and comparison of ideas about physical phenomena. However, to help the teacher supervise their work in small groups, it is best to have the students complete a guide of activities. This guide introduces various cases of uniform and accelerated motion. Each case includes activities (questions, graphic to draw, etc.) which guides the modelling process of the students. This modelling process can be structured according to a POE task (Prediction> Observation> Explanation) [24]. With respect to kinematics, the teacher presents his students POE tasks about different cases of motion. Every task POE takes place in the following way. A physical situation represented under a concrete form by a physical set up is explained to the students in the guide. Questions linked to this case ask the student to predict what is going to arrive if experience is performed. Then, they note their predictions in their notebook. The students in groups of four or five accomplish then the assemblage linked to this case according to the instructions of the guide. We will describe here two POE tasks: 1) case 1 is about the simple case of contant speed motion (see fig. 3); 2) case 2 is about a more complex situation about two balls separated by an initial distance with initial zero speed allowed to undergo a constant acceleration followed by a constant deceleration (see fig. 4).

Case 1 Constant speed straight motion: Let consider the case of constant straight motion. The description of this case is in the student guide [17]: “A ball is thrown on a horizontal rail. The circle in grey points out its initial position at the time of launching. The circle (with symbol 1 inside it) points out the position of the ball after 1 second.” (fig. 1)

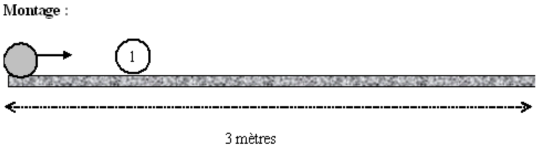

Fig. 3 Motion of a ball running an horizontal rail

The task POE consists then in predicting what will be the successive positions of the ball at every following second, knowing the distance traveled in the first second. Some of the main conceptions expressed by the students can be classified in the following categories [25]:

1) The speed of the ball increases in the beginning, stay constant in the middle part, then decelerates later. It is to note here that among the students who advocate a non- zero acceleration in the ball at first, some have tendency to merge the initial time with the time when the ball is put in motion by the experimenter.
2) The speed of the ball remains constant till the end, without notable slowing down. Some people explain that the length of the rail is too short or that slowing down is too weak to be disclosed.
3) The speed of the ball diminishes gradually until it stops. The students who maintain this conception invoke friction as reason of slowing down.

During exchanges in small groups, the students justify their choice of a conception on the basis of visual obviousness such as the ball seems to decelerate. From these predictions, the guide asks the students to draw a graph of what would be the curve of the position according to time. Indeed, it is important to encourage the students to specify their prediction in a concrete way. Such a precise prediction will allow them to compare it more easily with experimental results [24].

Case 2 Two balls separated by an initial distance undergoing first an acceleration and second a deceleration: More complex cases can be proposed to students, such as the motion of two balls running downwards then upwards along two successive rails making an angle between them
(fig 4). The guide asks the students if and when ball A will possibly catch up with ball B. In the prediction part, the students must predict the respective positions of balls A and B in the course of time. Afterward, the students must draw, from their predictions, the position-time and speed-time graphs of both balls. With respect to their predictions, some students think that ball A will catch up with B before the end of the descent since starting from a higher position, it acquires a greater speed or a greater acceleration. Some students will say that ball A will strike ball B at the end of the ascent (second segment) just after ball B reverses its motion. Others will put into play some conservation principle to state that somewhere in the second segment, ball A will catch up with B since the highest the ball B can reach in the second segment is still lower than what ball A can reach. Although the last statement is correct, it does not tell us the exact point where the two balls will meet, which is part of the original question. Although this situation represents a challenge for students at all levels, its familiar character favour the participation of all in a lively debate [25 Trudel and Métioui, 2011].

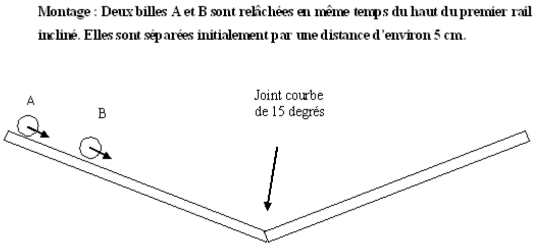
Montage : Deux billes A et B sont relâchées en même temps du haut du premier rail incliné. Elles sont séparées initialement par une distance d'environ 5 cm.

Fig. 4 Motion of two balls running downwards then upwards along two successive rails making an angle between them

Favour the process of understanding

To fill up the gap between the aimed concepts and the previous knowledge of the student, two approaches have been offered [14,26,27]:

- Assuming the naïve schemas of the student and scientific concepts are irreconcilable, the first approach plans to replace these naïve schemas with scientific concepts by fulfilling some conditions.
- Assuming the naïve schemas of the student and scientific concepts share common points, the second approach aims at the gradual modification of the naïve schemas first into scientific concepts by giving the student support and adapted guidance.

These two approaches led to the development of distinct instructional strategies. In the first approach, the replacement of the student's cognitive schemas by scientific concepts is made by stressing the conflict between the two and by persuading the student of the necessity to replace the first with the second. To this end, it is necessary to lead the students to express their schemas in relation to the aimed concept (represented by a scientific phenomenon), then to lead the students to become aware of the insufficiencies of their schemas to explain properties of the selected phenomena. It is then a matter of introducing the scientific concept as a credible, comprehensible and fruitful alternative [10,27].

The second approach consists in favouring the progress of the student towards a better understanding of scientific concepts from what he understood already, by offering structured activities which guide the student's approach [26]. In this respect, we listed two types of intervention. The first type aims at leading the student to progressively model a group of phenomena associated the same concept or principle, allowing the student to identify important factors and to formulate the rules which explain the observed properties [28,29]. The second type encourages the student to compare its schemas directly with the scientific schemas, for example by offering analogies or conceptual models allowing the student to choose pertinent information, to organise it and to connect it with its previous knowledge [30,31].

While the first approach has been widely used and studied in science education research, it had failed to lead to consistent results [32]. It is not to say that the the second approach, consisting mainly of modelling activities in the science laboratory, is devoid of difficulties.

Hence, kinematics is often learned with a high degree of mathematical abstraction to whom the students are not accustomed [18]. Moreover, during these laboratory activities, it seems that students do not have enough opportunities to propose their own hypotheses [33]. Indeed, a study of protocols included in Quebec science laboratory textbooks demonstrates that the students are seldom offered the opportunity to get involved in an authentic research [34].

Thus, to favour the comparison between students' ideas and the properties of phenomena, it has been proposed that the various steps of an experience be supported by the use of technology. As such, the use of specially designed software and equipment like sensors could make easier the collection of experimental data as well as supporting students in their analysis [35]. An example of this approach, called the "video-based laboratory ", make use of a digital camera with which the students can record the motion of objects in form of videos. The students can then transfer the content of these videos to a laptop computer and measure, with the help of data collecting software (REGAVI[1]), the positions

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[1] The REGAVI software allows the collection of data from a video of an object in movement in the form of an AVI file. This software contains functions allowing the measure

according to time of the images of objects in the video in clicking repeatedly with the mouse. These data are then automatically organised by the software REGAVI in tables. These tables can be put in form of Cartesian graphs when the students transferred their content to a data analytical software (REGRESSI[2]) [36]. As such, the software REGRESSI can help students make various calculations, such as the slope of the tangent to a curve, and help them model their results with regression analysis. As a consequence, the students can test their hypotheses faster and more efficiently and, if needed to be, change the parameters of physical situations to explore other possible relations between kinematical variables [37]. Such an approach has several advantages: 1) it allows to the student to concentrate on the generation of hypotheses and the interpretation of results, two skills not well developed in the traditional laboratory; 2) it allows to the student to generate and to prove several hypotheses in a quicker time, making it easier to use strategies of variation of parameters [38]; 3) in physical situations where it is necessary to return on the results of an experience to verify the quality of the data collected or possibly to change the original hypothesis, computer-aided experimentation can allow the traditional laboratory to become iterative in spite of the constraints of the school environment. Indeed, it is often necessary to the student to return on the results of an experience to study reasons of the gap between his ideas and the results obtained, facilitating conceptual change in sciences [17, 39].

With respect to case 1, the computer system allows the student to measure displacements of the ball in the different intervals of successive time in order to establish the constancy or not of the speed. Besides, the study of the position-time graph obtained experimentally (fig. 5) allows the students to compare it with their predictions. Indeed, by comparing the form of both curves, the students realise that contrary to their predictions, the displacement between intervals of successive time is identical and that friction plays a negligible role.

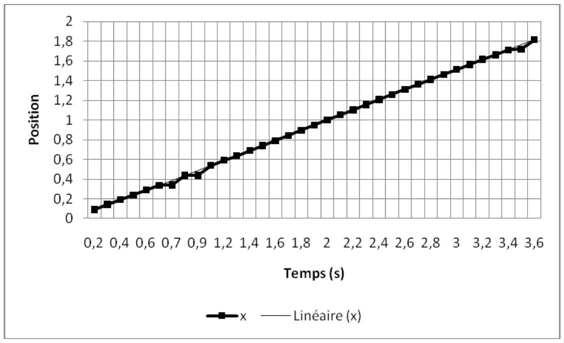

Fig 5 Position-time graph of uniform straight motion

For case 2 (fig. 4), the prediction of the position-time graph introduces a particular difficulty because it is constituted of an upwards parabola (acceleration) followed by a downwards parabola (deceleration) (fig 6). In this regard, the continuity of the speed, represented by the tangent to the position-time curve requires an inflexion point between both trajectory segments. According to fig. 6, the distance between the two balls in the first segment will be approximately constant (because the acceleration according to the inclined plane is the same as well as their zero initial speed). Moreover, the change in motion (from acceleration to deceleration) happens later in ball A than ball B, meaning the ball A accelerates during a greater time interval and, thus, attains a greater final speed that ball B. In some conditions, which depend especially on the initial separation between the balls, the ball A will be able to catch up with ball B before this last one reaches the summit of its trajectory.

This situation clearly puts many concepts into play and the space misses us to describe the different strategies adopted by the students. Even if it is possible by reasoning to produce persuasive arguments in support of one or the other idea expressed by the students, the possibility of collecting quickly the positions of both balls as well as obtaining position-time and speed-time graphs allows to the students to decide between the various opinions expressed and, thus, to progress towards a deeper understanding of the kinematical concepts.

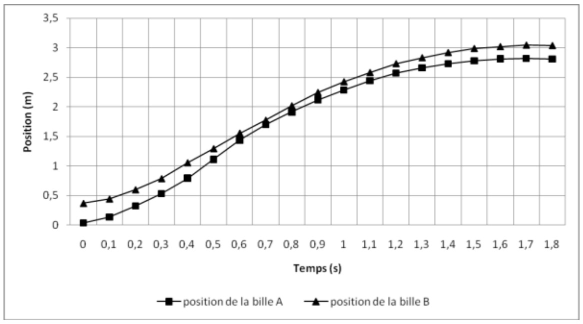

Fig. 6 Position-time graph of balls A and B

The figure 7 below represents the speed-time graph of balls A and B from this case of chase. One can note in the first

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of the successive positions of this object which it organizes in form of tables. It is possible later to transfer these data in the REGRESSI software for analysis (see details in the following Internet site: (www.micrelec.fr/equipelabo/pics_art/pdf/M0314G26.pdf · PDF file).

[2] The Regressi software accomplishes cartesian graphs of data previously transferred by a software of collection such as Regavi. Regressi software also contains functions allowing to calculate new variables (speed, acceleration) from the measurements of position and of time and to find the best curve of group of experimental points, etc. (Durliat et Millet, 1991).

part (left segment in fig. 4) that the speed of both balls increases regularly with the same acceleration (the slopes of the two lines are approximately the same). Furthermore, it is interesting to note that the final speed of the ball A is larger than the speed of the ball B (this result could be predicted by taking into account that the ball A is speeded up on a greater time interval than the ball B). Finally, it is also curious to note that, in the second part, the speed of the ball A is less than the ball B. This inversion takes place after the speed of balls A and B became equal, at a time of about 7 seconds. A credible explanation would be that balls A and B entered in collision at this instant and part of the impact contributes to the reduction in the speed of the ball A.

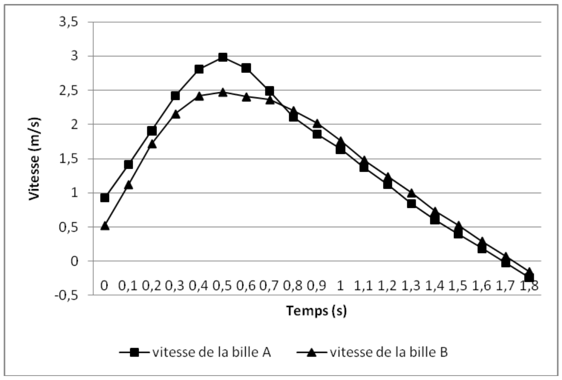

Figure 7 Speed-time graph of balls A and B

Favour the evaluation of understanding by the student

To make sure that the product of understanding, that it is a concept or a model, answers scientific criteria, the student can review the concept or model in a retrospective way. This is done by critically examining the approach undertaken to acquire this concept or this model or in a prospective way by proving that the concept or model allows the fulfillment of various scientific functions (prediction, explanation, etc.) [40,41]. In the former option, evaluation allows to reconsider the characteristics of the approach of resolution of scientific problem to show possible variations and to foresee directions of investigation allowing to generalize the schema or the acquired model. In this respect, it is important to teach the student not only how to work out models of a given domain, but also to teach the way of reviewing them while leading him to reflect on their nature and their role [29]. In the latter option, it is a question of first determining if the constructed schemas can be applied to similar situations or favour the acquisition of new knowledge as well as to specify the limits of the solutions found and their application field [42].

Considering what precedes, it is appropriated to consider if a certain responsibility should not fall to the student to supervise the progress of his learning himself by appropriating the criteria of evaluation as well, using them as a guide in the acquisition of purposeful competences [43]. As a consequence, in the process of elaborating kinematical models, the taking over by the students of the evaluation criteria could help them to review and ameliorate their models [28, 29]. In this respect, the concept of formative evaluation relates to an approach where the student anticipates and plans his actions, appropriates objectives and criteria of evaluation, and regulates his own learning [43].

Such a formative evaluation assumed by the learner may differ depending upon the type of problems encountered. In kinematics, as well as in other areas of physics, there are two main types of problems: simple problems and complex problems [44]. A simple problem, such as problems associated with constant speed motion offered in high school manuals requires only a restricted number of choices made by the students and often results in the application of a procedure, for instance to find appropriate equation of constant motion (such as $v = s/t$ where v is the speed and s and t are the displacement and the time elapsed respectively) and to replace the variables of this equation with constants according to the information contained in swording [45]. Even in this case, it appears that the concept of constant speed does not seem to be mastered by high school students and that their alternative conceptions about motion continue, for the majority of them, up to the adulthood. Such situation may not be discerned by the teacher if he offers to his students the simple problems of movement where initial conditions are determined beforehand. Difficulties appear when the situations of movement are introduced as part of experiments where real objects are put into play, notably when, contrary to the tasks of comparison of previous research, the attention of the students is directed toward the trajectory of the object in movement, as for example the case of a ball traveling on a horizontal track (case 1).

A different situation arises when complex scientific problem, such as problem of pursuit between say two balls (see previous case 2), requires the student to break up the task into several steps, so that the student must make at every step choices between different alternatives. In this type of problem, the number of choices inreases and is often left in the judgment of the student, the criteria of evaluation is not much defined or complex, different solutions are possible, what makes the student assess them according to their pertinence and according to their effectiveness [44]. It is in such situation that the acquisition of the evaluation criteria associated with model building and problem solving becomes particularly important.

In such complex phenomena, it may be helpful to first introduce the problems to students under a qualitative form.

Unlike what happens in their quantitative counterparts, information is given in qualitative problems under a qualitative form, that is by words or figures which do not point out quantity but only order so that one cannot on their basis formulate a conclusion of quantitative nature. In that case, resolution requires of the student to reason in a qualitative way, that is he can link up various qualitative information provided to formulate a conclusion which gives information in a rough way about the properties of the studied phenomena [26, 46]. Such an approach is helpful to the students for several reasons: 1) qualitative reasoning is familiar to the students because it is used in everyday life [46]; 2) qualitative reasoning allows to the students to better detect links between concepts because they are not distracted by the necessity to use a a mathematical procedure; 3), qualitative reasoning makes easier the recognition of the limits of found resolution and constraints of physical situation [47]. However, qualitative reasoning has also limits: 1) in several situations, it remains indeterminate, that is it is not possible to determine specific result [48]; 2) it does not allow to detect relations between several variables, because it remains restricted to comparisons between changes in couples of variables [49]; 3) units of variables are not taken into account because these units are determined by the process of measurement which refers to the existence of an operational definition of concept [50].

To palliate this insufficiency, the combination of qualitative and quantitative reasonings in a strategy of resolution of problem allows the students to understand physical concepts better and ameliorates their skills at resolving of problems [51]. Therefore, the strategy of formative evaluation proposed here aims at developing the student's skills of resolution of problems and their understanding of physical concepts by offering problems integrating qualitative and quantitative reasonings regarding these concepts. Here are its main characteristics:

- A qualitative problem has several solutions so that it is possible to discuss different solutions offered by the students. Case 1 and 2 have been designed to foster discussion between students for such a purpose [17].
- A problem can be broken down into several parts by identifying the intervals of values in relation to certain factors from whom the property is distinct qualitatively [44].
- A qualitative problem allows to the student to define the conditions of problem [47]. In fact, it is possible to guide he student to define the conditions of a problem in order to allow the study of qualitatively distinct physical situations. Later, the introduction of quantitative data via experimentation allows to the students to realize that the same problem can generate several quantitative problems the mode of resolution of which is similar [52]. It is something we observe in case 2 where students may ask what will happen when the initial distance between the two balls is increases or decreases. Surprisingly, some students make the hypothesis that the variation of the initial distance between the balls will affect the point where the balls will meet.

What is difference between qualitative and quantitative problems? First of all, we observe that the most part of the numerical values have disappeared. There remains some some, not sufficient to determine a unique solution, but sufficient enough to allow the student to feel at ease in front of a format of problem which is familiar to him. It is only later he realizes that certain data are away and that he must define them in anticipation [47]. He can, for instance, specify the intial speed of the ball in case 1 or the distance between the two balls in case 2, in order to make a specific prediction or test the generality of the rule he just proposes. If he works in group, other students will offer him other values and their interpretation of the phenomena. This could lead to contradictions. Such contradiction may lead the student to the restructing of his previous ideas. In an opposite way, if he finds his ideas confirmed by the results of the experiment, he may want to extend his results by varying conditions. In case 2, some students may invoque a principle, such as the conservation of mechanical energy to explain that the balls must meet in the second track. Studying various values of its initial conditions, the student may be able to observe that the formula he obtained in theses various conditions is similar in structure whatever are the chosen values, which can encourage him to make generalizations of his results [52].

Favour the self-regulation of the approach of understanding

When the instructional approach is constituted of very structured activities, it limits the opportunities offered to the students to choose, and its implementation is then regulated by the teacher who must make sure that its various interventions are in agreement with the present state of understanding of the student. Yet, considering the diversity of experiments and knowledge of the students, it is unlikely that such an instructional approach is suitable for all students and as a result allows an optimum regulation of their approach of understanding [53].

That is why an approach favouring the self-regulation of the approach of understanding by the students should include instructional strategies that encourage them to take control of their own learning. To this end, this approach should include various dispositions to encourage the students to mobilize and combine their cognitive strategies (such as metacognition and motivation) in order to identify their knowledge and skills, to plan their approach and to reflect on the results obtained in order to possibly change their cognitive strategies and give them a higher efficiency [16]. In this respect, the following strategies proved to be efficient to develop the metacognition and the self-regulation of the students:

1) Strategies combining the modelling of phenomena, the evaluation of models produced by the students according to some criteria and debate between students on the role and the utility of models [29];
2) The environments which, while giving challenges adapted at the level of the students, guide them in their approach by giving them different supports such as various information sources, feedbacks and simulation [54].

However, time constraints, pressures to cover the science curriculum and limits upon the availability of material and equipments may hinder the opportunity offered to students to engage in self-regulatory activities. Some answers to these difficulties may be found in the context of informal learning of science, such as science day camps, science museums, science centres, and science fairs. Hence, in the context of informal learning of science, more freedom is allowed to students in the choice of the scientific subjects according to their interests. Morevover, in many informal learning activities, students use tools and strategies that enhance reflexive thinking, such as diaries [55]. Also the use of daily materials, which is often the mark of these activities, allows to the young person to perform rapprochement between science and their daily life. Finally, these activities often take place in the presence of adults, that it is the parents who accompany their children in the science museum, the animators of the scientific camps which supervise the young persons, creating proximal zones of development favouring the negotiation of sense between the more experienced adults and the young persons [56].

5. DISCUSSION

In this article, we argued for a systemic approach to study scientific conceptual understanding. Hence, the model of understanding proposed here can be defined as a cognitive system composed of elements in interaction. One of main characteristics of this model consists of its regulation mechanisms that guide the learner toward his goals, which makes it a cybernetic mechanism [57]. This regulation can be made in an external way, for example by the teacher, or in an internal way, by the learner himself, who then takes charge of his own learning processes, i.e., reflecting on his actions, assessing them and planning according with he has learnt, while using his auto-regulated skills.

In such a case, the model of scientific conceptual understanding can be classified as a second order cybernetic mechanism [58]. Its essential characteristics are similarity between cycles of understanding and auto-reference throughout each cycle. Indeed, by going through the different paths of the understanding network, (see fig. 2 for the speed), we can observe that relations between neighbouring concepts are governed by two processes (identification of factors and integration of these factors into a new entity) which repeated themselves from the left (most basic concepts) to the right of the network (acquisition of the speed or acceleration concept).

The self-reference generates the paradoxes that have been mentioned earlier (see section 2). For example, one such paradox is the learning of autonomy in an educational situation. Indeed, one can wonder how it is possible to teach a student how to take care of his own understanding. Let say for example that we succeed in this teaching, and as a result the student has acquired a greater autonomy. Obviously, a direct teaching approach would not be the appropriate teaching strategy, since one can hardly imagine a student acquiring autonomy simply by being told, and explained, how to be autonomous. But even in the case of more active situations where the student, for example, learns to model the properties of chosen phenomena, can we say that he has acquired autonomy?

Research has shown that it is not the case. As such, using or developing models to predict and explain scientific phenomena may not be enough for students to use these skills in other contexts. In fact, it may impede the construction of the models itself. Schwarz and White [29] have shown that it may be necessary, in addition to activities of modelling and inquiry, to include knowledge about the use of models as well, i.e. meta-modeling knowledge. Referring to the model of scientific understanding described here, their activities would include the second feed-back loop, developing models of scientific phenomena and reflecting and evaluating their nature, purpose, and utility in predicting and explaining properties of these phenomena.

6. CONCLUSION

Difficulties experienced by students during scientific learning find their origin partially in misunderstandings which manifest themselves in a manifold way in different domains while sharing some similarities. To explain these difficulties and to plan efficient interventions intended to favour students' understanding, it is important to explain the way scientific conceptual understanding takes place. In this respect, our model of scientific conceptual understanding accomplishes this objective with two conceptual tools: 1) a network of understanding, which allows for the description of different paths of learning when a student advances in understanding; 2) a schema of the approach of understanding, which describes the organisation of different stages of understanding so that it is possible to choose strategies of education most adequate to each of the stages of approach.

In regards to the limits of our research, the method of content analysis using keywords tends to rigidify the collection and analysis of data. Indeed, the keywords that appear from the analysis do not allow one to give an account of the nuances brought by the authors. In addition, by classifying units of analysis with the aid of keywords, the coding method does not take into account the evolution of terms used in the field of the understanding of concepts in sciences [59]. Moreover, the accent put in this research on the identification of variables and their interrelations cannot give an account of the wealth of other perspectives, some for example more centered on specific characters of context or of individuals [60].

Despite these limits, the integration of the results of research on understanding in a scientific conceptual model can enrich pedagogic practices linked to understanding and to point out new research avenues. Above all, the approach suggested here to favour understanding allows the teacher to choose according to the learner's actual state of understanding the instructional strategies most adapted to guide its progress.

Finally, it is important to include the emotional and social aspects in the model which would aim at the entire development of the student. More precisely, the influence of emotional and social factors in the development of understanding should be explained more. For example, we can assume that dispositions provoking interest would allow to engage students in the understanding process. Inversely, factors of emotional nature as a weak tolerance for ambiguity (for example when a student in transition between two levels of understanding is confronted with contradictions between his schemas and new knowledge) can unsettle the development of his understanding [61]. It is also important to identify factors allowing for the support of motivation throughout the approach of understanding if we want as educators to withdraw all of benefits of our interventions [62].

7. REFERENCES

[1] K. Kovacs, "Prévenir l'échec scolaire". **L'observateur de l'OCDE**, Vol. 214, 1998, pp. 8-10.

[2] M. Kjaernsli, C. Angell, & S. Lie, "Exploring population 2 students' ideas about science". In D.F. Robitaille et A.E. Beaton (Eds.), **Secondary analysis of the TIMSS Data,** pp. 127-144, Boston : Kluwer Academic, 2002.

[3] J.M. Van der Maren, **Méthodes de recherche pour l'éducation (2ème éd)**, Montréal : Presses de l'Université de Montréal, 1996

[4] M. Luffiego, M. F. Batista, F. Ramos & J. Soto, "Systemic model of conceptual evolution".

International Journal of Science Education, Vol. 16, No. 3, 1994, pp. 305-313.

[5] R. Legendre, **Dictionnaire actuel de l'éducation,** 3ème éd.**,** Montréal : Guérin, 2005

[6] R. Mucchielli, **L'analyse de contenu : Des documents et des communications,** Issy-Les-Moulineaux : ESF Éditeur, 2006

[7] P. Dunn-Rankin, G.A. Knezek, S. Wallace, S. Zhang, **Scaling methods, 2nd ed.,** Mahwah (NJ): Lawrence Erlbaum Associates, 2004

[8] H.A. Slaate, **The pertinence of paradox : A study of the dialectics of reason-in-existence**, Washington (DC) : University Press of America, 1982

[9] J. Biggs, "What do inventories of students' learning process really measure? A theoretical review and clarification", **British Journal of Educational Psychology,** Vol. 63, 1993, pp. 3-19.

[10] K. Appleton, "Analysis and description of students' learning during science classes using a constructivist-based model", **Journal of Research in Science Teaching,** Vol. 34, No. 3, 1997, pp. 303-318.

[11] K.D. Forbus & D. Gentner, D. (1986). "Learning physical domains: Toward a theoretical framework". In R.S. Michalski, J.G. Carbonell, & T.M. Mitchell (Eds.): **Machine learning: An artificial intelligence approach**,Vol. 2, pp. 311-348, Los Altos (Californie) : Morgan Kaufman, 1996.

[12] J. Hattie & H. Timperley, "The power of feedback". **Review of Educational Research**, Vol. 77, No. 1, 2007, pp. 81-112.

[13] L. Skyttner, **General systems theory: Problems, perspectives, practice**, Hackensack (New Jersey) : World Scientific, 2005.

[14] P.R.J. Simons, "Transfer of learning: Paradoxes for learners", **International Journal of Educational Research**, Vol. 31 (chap. 3), 1999, pp. 577-589.

[15] J. Biggs, **Teaching for quality learning at university: What the student does,** 2nd ed., Berkhire, UK: Open University Press, 2003.

[16] G. Schraw, K.J. Crippen, & K. Hartley, "Promoting self-regulation in science education: Metacognition as part of a broader perspective on learning", **Research in Science Education,** Vol. 36, 2006, pp. 111-139.

[17] L. Trudel, **Impact d'une méthode de discussion sur la compréhension des concepts de la cinématique chez les élèves de cinquième secondaire**, Thèse de doctorat, Université du Québec à Montréal, Montréal, 2005.

[18] A.B. Arons, **A guide to introductory physics teaching**, Toronto, John Wiley & Sons, 1990.

[19] G.J. Klir, **Conceptual frameworks.** Chap. in **Facets of systems science,** 2nd ed**.,** pp. 41-69, New York: Kluwer Academic/Plenum Publishers, 2001.

[20] B. Davis, "Interrupting frameworks: Interpreting geometries of epistemology and curriculum". In W.E. Doll, Jr., M.J. Fleener, D. Trueit, & J. St. Julien (Eds.), **Chaos, complexity, curriculum, and culture: A conversation,** pp. 119-132. New York: Peter Lang, 2005.

[21] I. A. Halloun, **Modeling theory in science education**, Boston: Kluwer Academic Publishers, 2004.

[22] K. Roy, "On the critical paradoxes of cupid and curriculum". In W.E. Doll, Jr., M.J. Fleener, D. Trueit, & J. St.Julien (Eds.), **Chaos, complexity, curriculum, and culture: A conversation**, pp. 235-245, New York: Peter Lang, 2005.

[23] M. St-Germain, "Vers une définition opérationnelle des paradoxes". Dans J.-P. Brunet et L. Brunet (Eds**.), Les paradoxes en éducation,** pp. 27-71, Outremont (Québec) : Les Éditions Logiques, 2001.

[24] R. White, & R. Gunstone, **Probing understanding**, London: The Falmer Press, 1992.

[25] L. Trudel, & A. Métioui, "Conception of a computer-aided physics laboratory to facilitate the understanding of kinematical concepts". **Proceedings of the 5th International Multi-Conference on Society, Cybernetics and Informatics**, Vol. 1, ICMSCI' 11 , 2011, July 19th – July 22nd , pp. 186-191. Orlando (FL).

[26] M.F. Legendre, "Le rôle du raisonnement qualitatif dans les processus de changement conceptuel et ses implications pour l'enseignement et la formation des enseignants". In R.M.J. Toussaint (Ed.), **Changement conceptuel et apprentissage des sciences : Recherches et pratiques,** pp. 177-201, Outremont (Québec) : Les Éditions LOGIQUES, 2002.

[27] G.J. Posner, K.A. S. Strike, P.W. Hewson, & W.A. Gertzog, "Accomodation of a scientific conception: Toward a theory of conceptual change". **Science Education,** Vol. 66, No. 2, 1982, pp. 211-227.

[28] A. Acher, M. Arca, & N. Sanmarti, "Modeling as a teaching learning process for understanding materials: A case study in primary education". **Science Education**, Vol. 91, 2007, pp. 398-418.

[29] C.V. Schwarz & B.Y. White, "Metamodeling knowledge: Developing students' understanding of scientific modeling". **Cognition and Instruction**, Vol. 23, No. 2, 2005, pp. 165-205.

[30] T. Bryce & K. MacMillan, "Encouraging conceptual change: The use of bridging analogies in the teaching of action-reaction forces and the "at rest" condition in physics", **International Journal of Science Education**, Vol., 27, No. 6, pp. 737-763.

[31] R.E. Mayer, "Designing instruction for constructivist learning". In C.M. Reigeluth (Ed.), **Instructional design: International Perspectives**, Vol. 2 of **A new paradigm of instructional theory,** pp. 141-159. Mahwah, NJ: Lawrence Erlbaum Associates, 1997.

[32] K. Appleton, "Analysis and description of students' learning during science classes using a constructivist-based model". **Journal of Research in Science Teaching**, Vol. 34, No. 3, 1997, pp. 303-318.

[33] P.-L.Trempe, "L'enseignement des sciences au quotidien : Six études de cas au primaire et au secondaire (problématique, méthodologie, interprétation, synthèse générale de l'information)". **Monographies des sciences de l'éducation,** Vol. 1, No 1, 1989, Trois-Rivières, Université du Québec à Trois-Rivières.

[34] A. Métioui, & L. Trudel, "Analyse critique des expériences proposées dans les manuels destinés aux jeunes de 8 à 12 ans: Magnétisme, électrostatique et circuits électriques". CDROM : Critical Analysis of School Science Textbooks, P. Clément (Ed.),

IOSTE International Meeting Tunisia Hammamet, 7 to 10 February, 2007, 12 pages.

[35] D. Jonassen, J. Strobel, & J. Gottdenker, "Model building for conceptual change", **Interactive Learning Environments,** Vol. 13, Nos. 1-2, 2005, pp. 15-37.

[36] G. Durliat, et J.M. Millet, "L'informatisation des dosages phmétriques avec l'interface Orphy et le logiciel Regressi ", **EPI,** Vol. 64, 1991, pp.163-172.

[37] E. Koleza & J. Pappas, "The effect of motion analysis activities in a video-based laboratory in students' understanding of position, velocity and frames of reference", **International Journal of Mathematical Education,** Vol. 39, No. 6, 2006, pp. 701-723

[38] M. Riopel, **Conception et mise à l'essai d'un environnement d'apprentissage intégrant l'expérimentation assistée par ordinateur et la simulation assistée par ordinateur,** Thèse de doctorat, Montréal, Université de Montréal, 2005.

[39] J.-Y. Lin, "Responses to anomalous data obtained from repeatable experiments in the laboratory", **Journal of Research in Science Teaching,** Vol. 44, No. 3, 2007, pp. 506-528.

[40] R. Gott, & S. Duggan, **Understanding and using scientific evidence: How to critically evaluate data**, Thousands Oak: Sage Publications, 2003.

[41] J. McKendree, C. Small, K. Stenning, & T. Conlon. "The role of representation in teaching and learning critical skills", **Educational Review**, Vol. 54, No. 1, 2007, pp. 57-67.

[42] S. Bailin, "Critical thinking and science education". **Science & Education**, Vol. 11, 2002, pp. 361-375.

[43] L. Talbot, **L'évaluation formative: Comment évaluer pour remédier aux difficultés d'apprentissage**, Paris : Armand Collin, 2009.

[44] F. Reif, **Applying cognitive science to education: Thinking and learning in scientific and complex domains,** Cambridge (MA): MIT Press, 2008.

[45] L. **Trudel, & A.** Métioui, A., "Favoriser la compréhension des concepts du mouvement rectiligne à vitesse constante à l'aide d'une investigation scientifique assistée par ordinateur", **Recherches en didactique des sciences et technologies,** accepted**.**

[46] R. Mualem, & B.-S. Eylon, " "Physics with a smile"-Explaining phenomena with a qualitative problem-solving strategy", **The Physics Teacher**, Vol. 45, 2007, pp. 158-163.

[47] M. Goffard, "Partager le savoir, partager le pouvoir", **Science et Vie,** No 180, 1992, pp. 84-89.

[48] S. Parsons, **Qualitative methods for reasoning under uncertainty**, Cambridge (Mass.): MIT Press, 2001.

[49] M. Someren, & H. Tabbers, "The role of prior qualitative knowledge in inductive learning". In M. W. Someren, P. Reimann, H. P.A. Boshuizen et T. de Jong (Eds.), **Learning with multiple representations**, pp. 102-119, New York: Pergamon, 1998.

[50] T. Mäntylä, & I. Koponen, "Understanding the role of measurements in creating physical quantities : A case study of learning to quantify temperature in physics teacher education", **Science & Education**, Vol. 16, 2007, pp. 291-311.

[51] E. Graigher, J.M. Rogan, & M.W.H. Brown, "Exploring the development of conceptual understanding through structured problem-solving in physics", **International Journal of Science Education,** Vol. 29, No. 9, 2007, pp. 1089-1110.

[52] J. Bernhard, "Insightful learning in the laboratory: Some experiences from 10 years of designing and using conceptual labs", **European Journal of Engineering Education**, Vol. 35, No 3, 2010, pp. 271-287

[53] J. Rasmussen. "Learning, teaching, and complexity." In W.E. Doll, Jr., M.J. Fleener, D. Trueit & J. St. Julien (Eds.), **Chaos, complexity, curriculum, and culture: A conversation,** pp. 209-234. New York: Peter Lang, 2005.

[54] M.C. Linn, P. Bell, & S. Hsi, "Using the Internet to enhance student understanding of science: The knowledge integration environment". **Interactive Learning Environments**, Vol. 6, Nos 1-2, 1988, pp. 4-38.

[55] C. Quigley, K. Pongsanon, V.L. Akerson, "If We Teach Them, They Can Learn: Young Students Views of Nature of Science during an Informal Science Education Program", **Journal of Science Teacher Education,** Vol. 22, 2011, pp.129–149

[56] D. Ash, "Dialogic inquiry in life science conversations of family groups in a museum", **Journal of Research in Science Teaching,** Vol. 40, No. 2, 2003, pp. 138-162.

[57] E. von Glasersfeld, **Radical constructivist: a way of knowing and learning,** Washington (DC): Falmer Press, 1995.

[58] G. Lerbet, **Pédagogie et systémique**. Paris: PUF, 1997.

[59] Q. He, "Knowledge discovery through co-word analysis", **Library Trends**, Vol. 48, No1, 1999, pp. 133-159.

[60] P.J.J.M Dekkers, **Making productive use of student conceptions in physics education: Developing the concept of force through practical work,** Thèse de doctorat, Université de Vrije, Amsterdam, 1997.

[61] K. Merenluoto & E. Lehtinen, "Number concept and conceptual change: Towards a systemic model of the processes of change. **Learning and Instruction,** Vol. 14, No. 5, 2004, pp. 519-534.

[62] P. Pintrich, R. Marxk, & R. Boyle, "Beyond cold conceptual change: The role of motivational beliefs and classroom contextual factors in the process of conceptual change", **Review of Educational Research**, Vol. 63, No 2, 1993, pp. 167-199.