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INSTITUTO DE FÍSICA
CAIXA POSTAL 20516
01498 - SÃO PAULO - SP
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CONCEPTUAL CHANGE IN SCIENCE AND SCIENCE EDUCATION

A. Villani
Instituto de Física, Universidade de São Paulo

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A. Villani[+] Institute of Physics

University of São Paulo - Brazil

Introduction

Systematic research into alternative conceptions and spontaneous ways of reasoning began to be carried out at the end of the 1970s, after the groups at the University of Paris published their studies (Viennot 1977, Tiberghien 1976). The objective was to promote and analyse conceptual changes (Posner 1982) in high school and university students as well as in science teachers. However, concrete results (in terms of the quality and quantity of changes effected) seem to have been ambiguous and less promising than expected (Driver 1989; also Novak 1987). In fact, relatively few subjects showed any meaningful or stable change after taking a course aimed at the modification of conceptions about scientific principles, nor did the subjects abandon their former beliefs.

Interpretations of these results were presented by several different authors (Hewson 1987, Grimellini 1989, White 1989). In our opinion, however, before it is possible to have a better understanding of what happens in science learning, it will be necessary to know more about the nature and mechanisms of conceptual changes. One source of possible answers to these questions, which, unfortunately, has not yet been explored in a systematic way, may be found in historical and philosophical research into scientific change.

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We think that the models which describe how science conducts its business of inventing, testing and finally accepting or rejecting theories, have much to tell us about the way students accept new, academic views on natural phenomena while, at the same time, they leave behind their "common sense" knowledge.

In this paper we will attempt to explore some characteristics of the Laudan model (1977 and 1984) in order to understand, in an analogous way, some corresponding features of conceptual changes in science education. We will also discuss some practical consequences for education.

Laudan's Theses on Scientific Change

In order to better understand the analogy between scientific change and science learning, it might be interesting to sketch a synthetic view of Laudan's thought before making a comparative analysis of the two areas. The reader who feels sufficiently informed of Laudan's theses may wish to disregard the following item.

"Science aims at solving intellectual problems. Competing theories and different guiding assumptions ("research traditions") are to be evaluated in terms of their problem-solving effectiveness. The problems to be solved are of two types: empirical questions concerning the objects in some domain, and conceptual difficulties concerning contradictions internal to a theory, or between it and other scientific, methodological, or even metaphysical principles. The overall problem-solving effectiveness of a theory is determined by estimating the number and importance of the empirical problems which the theory solves and subtracting the number and importance of the anomalies and conceptual problems which it generates.
It can be rational to pursue investigation of a theory even if it is irrational to accept it. The decision to pursue is based on the rate at which the theory has recently solved problems. The decision to accept a theory is based on its

long-term record. Both judgments require comparison with alternative theories." (Laudan et al 1986 pp 207-208)

By definition, in Laudan's opinion, scientific progress takes place when scientists accept theories that solve problems better. Just what is meant by better performance , however, must be evaluated with care.

"One theory can be a better problem solver than another even though it is incapable of solving some of the problems succesfully solved by the other. Guiding assumptions are judged, in turn, on the basis of the relative problem-solving success of the theories they support.
The most important elements of a set of guiding assumptions are an ontology and an heuristic, the latter being a set of rules which direct the construction of theories and particularize ontology. A set of guiding assumptions may support many incompatible theories at the same time. Guiding assumptions may be regarded as empirically testable to the extent that their ultimate fate rests on the empirical success of the theories they support.
Sets of guiding assumptions typically evolve in such a fashion that earlier versions and later versions of the same "research tradition" may have few if any assumptions in common. This process of evolution is guided by a series of discrete decisions concerning the aim, methods and key ontological assertions of the set. Thus, it may happen that scientists discover that methods they formerly espoused do not promote their aims, or that theories they formerly held fail to satisfy their methodological demands. They may even discover that aims which were once central to their tradition are no longer viable because not realizable. It is through this reticulated process that a series of gradual changes comes to effect major shifts in the core beliefs of the scientific community. It rarely if ever happens that scientists change their theories, methods and aims at the same time. "Revolutions" are always such piecemeal affairs, which need not involve global incommensurabilities" [Laudan et al 1986 pp 208-209].

Scientific Change and Science Learning

1) Scientific work is essentially a rational enterprise. This rationality consists primarily in an adequate choice of means to attain an end. The general objective of science is to produce theories which are highly efficient in solving intellectual problems. The means are the rules for assessing, accepting, pursuing, modifying or

changing theories and assumptions. Such rules are not fixed inasmuch as they depend on the problems to be solved and on the beliefs about them.

Other objectives, such as the approximation to truth, the development of technologies, or the promotion of social welfare, are contingent and depend on various factors.

Students' academic activities are, in general, a rational enterprise, and their rationality consists in an adequate choice of the means necessary to attain their end. Students have as their general objective the receiving of an official certificate which attests to their competence in academic activities. The means are the rules imposed for the purpose of adapting their behaviour to the teacher's requests with a minimum of effort. Such rules are not fixed and depend on the institutional context.

Other objectives, such as the students' cultural growth, the development of intellectual operations, or the improvement of their problem-solving ability, are contingent and depend on various factors.

Sometimes the students' general objective is pursued by behavior such as "rote learning" or "cribbing", which contrast with the teacher's general objective, which is meaningful learning on the part of the students (see White 1989). On the other hand, science learning on the part of the students cannot take place without their own personal involvement and effort in the solution of intellectual problems. As a consequence, no conceptual change will result from teaching activities unless some degree of explicit compatibility and resonance between students' and teacher's general objectives can be reached.

One example of the problems generated by a divorce between students' intentions and those of the teacher is given in Baird and Mitchell's report (1986) on the PEEL Project. Another example is the written comment of an Italian high school student, after many months of classes on collisions and related principles:

"The analysis of collisions by means of concepts of Energy and Linear Momentum is very interesting, but people who wish to become competent in construction have many other important things to do; therefore, an intuitive analysis of collisions is sufficient."

A second consequence is that the analogy between scientific change and science learning will be meaningful only in those cases in which academic activities are recognized by students as effectively promoting their institutional success in such a way that the rules chosen for obtaining success coincide with those for obtaining learning. Such conditions are automatically fulfilled in all the activities freely chosen by students to promote the understanding of the world in which they live.

2) Scientific progress is primarily intelligible as a change in "research traditions", which are relatively large-scale, long-term conceptual structures which function as guiding assumptions for research. In many cases, this change includes modifications in the ontology (i.e. the explanatory and theoretical entities), in the methodology (i.e. the methodological standards used to assess their

theories) as well as in the scientific aims to be pursued in the field.

According to this view, scientific practice is badly described by the positivistic claim which sees scientific progress as an accumulation of experimental data and observations, sistematized by concepts which are directly linked to the observations, and a set of theories which are more and more encompassing. Consequently, scientific change seems to be at odds with some idea of a linear process dominated by the logical acceptance of ever more evident and all-embracing theories.

In an analogous manner, effective science learning can be described as a process which includes not only changes in the learner's ideas or his acceptance of new conceptions concerning phenomena but, primarily and more importantly, changes in the nature of questions, in the methods and in the aims to be pursued by such learning(Hewson 1990). For example to ask why the elimination of all resistances produce a constant motion (spontaneous question) is very distant from postulating that all inertial frames are equivalent (scientific answer). Science learning can be viewed as a non-linear process in which there is a place not only for the accumulation of new information on empirical data and their inductive sistematization, but also for many other learning phenomena, such as to invent or to exploit hypotheses,to change the relevant questions, to use abstract principles and deduce consequences from them, and so on.

Every day, teachers come across interference between students' prior conceptions and new scientific ideas and with their regressions to old ways of reasoning when the application of new ways becomes more complex. Sometimes we find that academic activities must reach a threshold, without which students' retention is very limited but, when present, makes more rapid learning possible. It is also common to detect great resistance on the part of students to use mathematical language and, above all, to the interpretation of such language.

These and other phenomena seem to us to support the conception of science learning as a long-term process analogous to scientific change, in which great importance must be given to the discovery and evaluation of long-term effects. Among these, the most significant are those referring to the changes in the questions that must be answered with new knowledge as well as in the methods to be used to attain such knowledge.

3) Scientific problems that must be solved refer to the matching of a theoretical construction with experimental results and observations or to the compatibility between various types of assumptions and beliefs. The solution which a theory brings to such problems are always evaluated in a comparative context, in opposition to the corresponding solutions of rival theories.

This has some important consequences. Empirical difficulties alone never compel one to abandon a theory. Predictions of phenomena, even though they may be only

approximately correct, are no less useful for a theory, and often their inaccuracy is recognized only in the light of later solutions. Newly solved problems turn out to be anomalies contrary to a theory only when they are solved by some other theory, for in such cases they directly threaten the theory's efficiency in solving problems. In these situations, anomalies tend to favour the process of scientific change.

Intellectual problems that must be solved by students when learning science usually involve either a correspondence between their predictions and the results of laboratory experiments, the application of a new principle to simplified situations, or the discovery of correlations between some of the variables.

The solutions to such problems does not require the rejection of a spontaneous way of viewing natural phenomena; in fact they involve neither the high degrees of rigour (and of conceptual development) nor the elaborate processes of inferences and deductions which are necessary to provoke and develop cognitive conflicts between spontaneous and academic knowledge.

Accurate predictions of experimental results, the successful application of academic models and intelligent "inventions" of correlations between variables are often treated by students as isolated cases of knowledge with no special implications for their conceptual structure.

A process of conceptual change, in our opinion, begins only when spontaneous ways of reasoning systematically fail in the pursuit of institutional or personal aims and when, therefore, academic models prove necessary for the performance of the tasks at hand. Only in such cases is the learner forced to seek out the potentialities of the new theory, using and coordenating its principles in order to arrive at empirical or conceptual conclusions. He must also work over all the new information dealing with the tasks until a deeper and more personal meaning is attributed to them.

We faced this situation, for example, when we participated in the preparation of a few students for the Olympic Games of Physics. Students engaged in writing theses to complete their school degree showed analogous processes. While performing these tasks, students were involved in the systematic assessment of the plausibility and usefulness of new knowledge, while simultaneously experimenting that commonsense reasonings were failing in the solution of their problems . The cumulative effect of the process was that the learners became familiar with new ways of reasoning to the extent that new cognitive values were incorporated and old ones progressively neglected.

4)Scientific progress occurs when more efficient theories are produced. This production can take place in two ways: either by starting from presently existing theories and then introducing successive changes into them without significantly modifying their guiding assumptions, or by beginning with a different and incompatible set of guiding assumptions and developing rival theories.

The two processes seem to be quite different. Kuhn (1962) gave the name of "normal science" to the former while he called the latter "revolutionary science" because it often includes ontological, methodological and axiological changes. In Laudan's opinion, however, the difference between the two processes is not all that great: "normal" science is not so normal while "revolutionary" science is not as revolutionary as it was thought.

In fact, minor changes gradually introduced into guiding assumptions may turn out to be very important, finally characterizing a real conceptual change. This process is facilitated by corresponding shifts in scientists' opinion about what should be considered a relevant or irrelevant change in the guiding assumptions. On the other hand, when a new theory, based on different guiding assumptions, is successful, it is accepted independently of these very assumptions, because the link between theory and guiding assumptions is usually not of a nature that would justify our speaking of a biunivocal implication. Only after considerable progress with the same type of theory do new and more radical assumptions become acceptable, thus completing the process of conceptual change.

In science education we may come across a similar situation: at the beginning of a learning process, students may demonstrate conceptions with a strong internal structure which are basically different from the model to be learned;

they may also, however, have conceptions which are similar, at least in some aspects, to the new, academic ones.

It has been suggested by Rowell (1989) that the two contexts should be treated with different teaching strategies. In the first case it would be better to introduce ex novo a new academic model and to use it in many simplified examples, finally comparing it with the original model, thus completing a process of conceptual change (Rowell 1985). In the second case it would be better to start directly from the students' ideas, working them over and generalizing them as far as is possible, introducing the necessary changes and experiences progressively, while at the same time making them compatible with the knowledge which is being learned (Karmiloff Smith 1975).

The two strategies may appear very different inasmuch as the first seems to involve a process based on knowledge imposed from outside, while the second appears to be the "natural" development of the students' own knowledge. In our opinion, however, the differences between the two learning processes are not so striking.

First of all, if the two strategies are seen as leading to effective and stable learning, they must be applied over a long period of time and deal with a considerable amount of content if they are to give rise to an autonomous learning process. The results to be attained include not only the assimilation of concepts and relations in a given field, but also new ways of viewing and working with that content. In other words, both strategies must be aimed at conceptual change. Only after a long and complex

process can new ways of reasoning (such as the rigorous use of principles or statistical modes of inference), new epistemological demands (such as generalization and internal coherence), new cognitive values (such as the preference of abstract notions and principles or the tendency to mathematical formalisation) be incorporated to the students' analyses of natural phenomena.

The learning processes adopted by students are a second aspect which suggests a similarity between the two strategies. In the first case students give personal meaning to the new, imposed knowledge, select what they consider most interesting and change this process with time. As a result, new knowledge first becomes intelligible as "what the teacher considers important in order for the students' competence to be recognized". Next, new knowledge appears as "that which is composed of various relationships, some of which are interesting and useful." Finally, it is assimilated as "that which is necessary in order to understand a large group of phenomena and to arrive at new conclusions". In the second case, when the initial conceptions are those of the students, the process of elaborating them is guided by the teacher, using methods and pursuing values which are imposed because they are not part of the guiding assumptions of spontaneous knowledge. Consequently the results of such activities are equally distant from the students' way of seeing things, with the result that the same processes of attributing personal meanings are still present, as they were in the first strategy.

5) One of the most remarkable characteristics of scientific progress is the presence of an intermediate changing phase called the "pursuit" of new models. During this phase, scientists continue to accept the dominant research tradition because of its general track record in solving problems, but they also check out new ideas and theories by testing their possibilities in specific situations.

The credibility of old guiding assumptions is not undermined by giving more attention to new ones. On the one hand, the prestige due to past successes obliges the community to treat the old science as if it were true. On the other hand, the interest in new models becomes more and more intense, because they provide a high rate of success at dealing with problems currently under investigation. This situation is so common that we often come across a scientist working with two different and even mutually inconsistent sets of guiding assumptions. All this demonstrates that the development of new ideas alone does not necessarily imply abandoning of the old ones. The growing use of Quantum Mechanics with its uncertainty principle and the strenuous research for hidden variables are an impressive exemple of such situation in Physics.

Is this phase compatible with scientific rationality, or must we admit the presence of some inconsistency in this behaviour?

Two different kinds of reasons seem to support the idea of maintaining the old theories and pursuing the new ones at the same time.

The pursuit of a new theory seems to be based, at least at the beginning, on the promise of success in the solution of the problems presently under investigation. Several qualities of the new model seem to attract the interest of scientists and compensate for the effort required from working with it over a long period of time. Among these, we could include the precision and novelty of some of the predictions of the new theory, the possibility of simplifying the intelligibility of some phenomena by eliminating "ad hoc" hypotheses, the hope of widening the field of application of a new idea, and the possibility of qualitatively organizing formerly confused data.

A high rate of local success, however, does not immediately transform promises into facts. In other words, it does not change a model into a theory with a large number of solved problems, this being the final criterion for its acceptance. The rational course of action, therefore, seems to be to accept the old research tradition which continues to show such global characteristics.

It seems to us that this is one of the most important points supporting the analogy between scientific change and conceptual change in science education because during a large part of the learning process, students are elaborating new academic models without leaving behind their spontaneous models.

The spontaneous way of seeing phenomena was constructed over a long period of time and is the result of many personal interactions. It provides a way of directly dealing with many natural phenomena, of speaking and communicating in an intelligible way with the social community and of predicting qualitatively what to do in a new situation. Consequently it is a most useful means for effectively solving many everyday problems. For this reason students accept spontaneous knowledge and believe that its method of reasoning is the most efficient for treating the natural world.

On the other hand, during the science learning process at school, students' involvement with new disciplinary knowledge is, at least at the beginning, very local: they must solve the problems that the teacher has suggested and such problems refer only to specific and simplified situations. The solution of these tasks has two effects: the new knowledge becomes more familiar and the process of putting more effort into it is justified. As a consequence, students become able to discuss their ideas with classmates and teacher, receiving important feedback for their process of internal reorganization.

During this process, students manage to articulate different pieces of information and apply new knowledge to new situations (or at least to old situations but in a new way). They also begin to arrive at some unexpected conclusions and give new meaning to their previous knowledge.

All of these gains are partial, of course. They are necessary steps in the pursuit of new academic knowledge and in the attainment of their goal of receiving official recognition of knowledge. Without them, students resort to

other types of behavior which does not lead to effective and meaningful learning. All of these gains have no effect in immediately changing their spontaneous way of reasoning, whose usefulness is called into question only in a limited number of specific situations.

Many students fall into the habit of pursuing academic knowledge only when the teacher proposes clearly stated problems and continue using their spontaneous knowledge in all other cases. This is the easier course to be followed, as the number of problems it solves is much greater than if they put their new knowledge to work.

Concrete acceptance of academic knowledge really begins only when the number and the importance of the problems solved is significantly greater. The process of conceptual change becomes an effective alternative only when the external tasks involved in succeeding at school consist of a large number of non-simple problems, requiring a continuous effort with academic knowledge. Conceptual change may also take place when students autonomously begin to elaborate types of problems which cannot be solved without implicitly accepting at least some of the values of the new knowledge.

Among the thinking activities which are extraneous to more spontaneous methods of reasoning, we could include the possibility of generalizing some laws, the systematic research into of conditions of applicability of new principles, the investigation into the relations between them, and the checking of consistencies between new and old knowledge. These areas are sources of many other sub-problems whose solution depends on conceptual change on the part of students.

6) The change-over from one set of guiding assumptions to another, wholly different set, implies the modification not only of the central problems, but also of the techniques, the basic explanatory hypotheses, the methods used to assess the theories, and the aims of the research in the field.

How can such a change be rational? That is, how can it be justified by a series of reasons or criteria universally accepted by the scientific community?

"Although the elements of a set of guiding assumptions form an interconnected, interrelated and interacting network, the related components of this network do not constitute a "take it or leave it package"; scientists treat these components as individually negotiable and individually replaceable" (Laudan 1986 p.213)

"Disagreements between advocates of wholly different sets of guiding assumptions are sometimes resolved because scientists change their minds about each of the disputed components one at a time, over a period of time, rather than via an all at once conversion experience" (Ibid p. 214).

So disagreements over standards for assessing theories may be discussed on the basis of agreements on the aims of science, or on the preferred theory, or on the underlying ontology. On the contrary, disagreements over the appropriate ontology which the theory should exemplify or over preferences for one or another specific theory may be dealt with via agreements on the aims of science and the standards chosen for assessing theories.

The important point here is that scientists are choosing between the currently available options rather than deciding about the best of all possible alternatives, which may itself remain as a point of disagreement.

It seems to us that the change from a spontaneous way of seeing natural phenomena to an academic one involves an equally global change concerning central problems, methods for assessing ideas, basic explanatory hypotheses and the aims of knowledge. As a result, the question of the rationality of such change may be stated once again, and the answer to it seems to be analogous. Every partial change can be the basis of successive changes via some shared opinions between teacher and students.

Initial disagreement as to the ends of school activities may be bypassed by means of agreement on single activities whose sucessful results may be a starting point not only for other activities but also for a conceptual progress or a methodological discussion. The result may be an occasion to raise other questions and state other problems, and so forth, in a complex process whose permanent results are never linear.

In fact, more articulated conceptual gains appear only after many successful exercises. Methodological changes come about after many successful conceptual steps and many consequent reflexions about them. Finally for axiological changes to take place, it is also necessary that a larger basis of positive results also exist.

During a long-term experiment involving Italian high school students (Grimellini 1989) and learning of collisions and conservation principles, we faced many situations which seem to corroborate these opinions.

During one laboratory experiment concerning elastic collisions between still balls, some students "invented" that the sum of the vectorial quantities mv of the balls was invariant before and after the interactions and convinced their classmates of this rule. In a later test with a stroboscopic photograph representing interacting balls, no one used this new rule. Only after many exercises, discussions and experiments were a good number of students able to regularly use such a model and, even then, in the less difficult cases. Only after several discussions about linear momentum and energy conservations did students begin to accept the idea that collisions were a regulated phenomena, thus also admitting the possibility of precise predictions in new contexts and situations. Very often, local success in collective analysis of difficult problems were not followed by similar success in simpler, individual tests. On other occasions, however, results of previous discussions or experiments were used to back up new ideas in new situations. At the end of the teaching experiment, very few students were convinced that the conservation principles held universal value and that the preceding ways of looking at the phenomena were largely inaccurate for performing a scientific analysis.

The important point to be stressed here is that effective learning is a long struggle in which no partial

success nor any partial defeat is definite. Every successful activity, however, turns out to be the basis for various types of future changes.

Some Consequences for Science Teaching

Many suggestions have been given for improving science teaching, with the objective of effecting a process of conceptual change. Nevertheless, many questions seem to have remained unanswered until now.

Is conceptual change a viable objective at every school level? Or should we seek less dramatic and more accessible goals at the end of a science course? Are some teaching methodologies and strategies really more efficient than others in pursuing these aims? Is it possible to draw up any general conclusions concerning the practice of conceptual change?

It seems to us that the considerations developed above may be useful for treating all these questions in a consistent way.

Above all, we must begin by distinguishing two phases of conceptual change, which correspond more or less to the phases of pursuing or accepting new academic knowledge: we call them conceptual change "latu sensu" (C.C.L.S.) and conceptual change "strictu sensu" (C.C.S.S.). In the former, (C.C.L.S.), we have the co-presence of new and old knowledge, because the changing process is happening with localized successes and a clear preference for the idealized situations ; in the latter case (C.C.S.S.), the new academic knowledge as well as its ways of reasoning and intellectual values implicit in its scientific use are accepted by the learner, who succeded in integrating them in a coherent and efficient conceptual system. The changing process is reaching a stable configuration (a final state) when the learner is able to use scientific principles as instruments to make deductions which link scientific concepts with mathematical formulas and experimental results.

The previously discussed analogy between conceptual change in science and in science education seems to us to support another important consequence : the objective of C.C.S.S. is viable only at the university level and with some curricular modification (at least in Brazilian schools).In fact it is a long term process aiming at a stable final state;it involves a large resonance between teacher's and students' effective objectives;it must include changes in the methods of producing and assessing knowledge and in the values to be reached by the knowledge;it has cognitive conflict as a keystone of the process; it aims to reach growingly abstract scientific conceptions; it must support successes and results reached in collective activities with learner's individual reflections and personal elaborations. All these characteristics suggest that some long-term task, viable only at the university level, should be introduced, such as a thesis, a monograph or the planning and execution of a complex experiment, in order to foster the systematic exploration of new knowledge and the systematic involvement of the learner's intellectual abilities. The university students' aim of attaining professional competence seems to

us to justify the long-term effort needed in such an enterprise.

For the primary and secondary school levels, C.C.L.S. seems to be an adequate explicit objective; the teacher must concentrate his efforts on creating activities and proposing tasks sufficiently interesting to stimulate the students' progressive intellectual involvement. In order to best bring about resonance between teacher's and learners' aims, the secret of teacher's efficiency seems to be in discovering the potentialities of his students by detecting the difficulties they come up against during the course, and to clearly and firmly commnunicate his requirements to them.

It seems to us that one of the most important conditions for such success is the teacher's conceptual change at least in regards to the scientific content, since his way of treating phenomena and principles will constitute the first model for the students. The teacher's own conceptual change concerning teaching and learning will facilitate this task.

In regards to teaching strategies and methodologies, preference should be given to those which include explicit and progressive reflections on modes of academic reasoning, methodologies, values and aims. Such selection, to be effectively meaningful, must be based on and take as its reference, learning activities which have already been successfully completed. It would also seem important to undertake a corresponding reflection on the characteristics of spontaneous knowledge only after the completion of some learning activities which have included implicit conflicts between it and academic knowledge. The analysis of the historical development of scientific concepts may be an occasion to begin this reflection and to focus the analogies between them and students' ideas.

Finally, it would seem useful to detect the questions which students spontaneously formulate during the learning activities and to satisfy them in ways that will improve the changing process. This means that the teacher must reorient and reformulate such questions in a wider context without, however, losing the specificity of the students' intentions. This seems the best way to develop the students' thinking activity without abandoning an academic perspective.

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