SCIENTIFIC METHOD, IMAGINATION, AND THE TEACHING OF PHYSICS

by Arthur Stinner

The notion that there is a specifiable and teachable method that describes how science progresses was presented by Karl Pearson in his widely read book, *The Grammar of Science*, in 1892 [1]. The influential philosopher of science, Karl Popper, on the other hand, believed that scientific discovery is not a straightforward activity that is identifiable by a method. In Popper's view there is, in a sense, the suggestion that the scientist struggles toward understanding the world, much like the artist strives to interpret it. [2] Most scientists, however, would agree that a complete picture of scientific enterprise that includes what scientists do on a day-to-day basis, cannot be given by either the Pearsonian or the Popperian picture of science.

Our mandate is to cut the umbilical chord with the conventional textbook and rethink our science (physics) teaching. The teaching of high school physics should have a rich contextual base that is connected to a sound theoretical structure.

As a simple example of scientific imagination, the case of free fall is discussed, as "seen" by Aristotle, Galileo, Newton, and Einstein. It is argued that a fully developed theory like Newton's theory of gravitation, for example, does not come easily and immediately; the question-and-answer procedure necessarily involves experiments, generates problems that must be solved, often using data that is selected on the basis of an incomplete theoretical background. To illustrate the activity and scientific thinking involved in building big theories in physics, the scientific thinking of Aristotle, Galileo, Newton, Maxwell and Einstein's are discussed.

The appearance of a big theory in science, however, is always accompanied by a language barrier. The nature of these barriers is examined for both the scientist and the student in the light of Kuhn's picture of scientific thinking. Kuhn's ideas of pre-paradigm, paradigm, and post-post paradigm activities are discussed under the heading of the *Scientific Methodology Spectrum*.

According to Kuhn, textbooks are "pedagogic vehicles for the perpetuation of normal science" [3]. Today, however, we must go further and ensure that all students leave school with a basic scientific literacy that includes a working knowledge of elementary physics. In order to achieve these goals, we have to make our learning contexts richer and more challenging for the university-bound student who is required to study physics and more relevant for the student who is looking for general physics literacy. We must therefore educate and train young science (physics) teachers to have a good understanding of the history of science and the nature of science and how students learn science concepts.

Our post-Kuhnian mandate then is to cut the umbilical chord with the conventional textbook and rethink our science (physics) teaching. The teaching of high school physics should have a rich contextual base that is connected to a sound theoretical structure. The contextual base should be motivating and related to students' interests and experiences; the theoretical structure, on the other hand, must clarify the status of theory, the relationship between experiment and explanation, and make connections to the history of science. The article closes with examples of textbooks and approaches that have moved toward recognizing the importance of embedding science (physics) teaching in rich contexts, as well as paying serious attention to the research in conceptual development. Future textbooks should accomplish not only that but also include the history and nature of science.

IMAGINATION AND THE "SCIENTIFIC METHOD"

There is still a wide-spread and pervasive belief that scientists use a specifiable and teachable method in going from observation to establishing laws and theories, namely the *scientific method*. The full explication of a specifiable scientific method can be traced to Karl Pearson's picture of scientific thinking [1]. Pearson was a famous statistician and his understanding of scientific thinking is imbedded in a well-articulated statement of method in his influential book *The Grammar of Science*, first published in 1892 [1]. In this book he summed up the conventional wisdom of the late 19th century picture of the nature of the scientific enterprise. Pearson believed that science was essentially an empirical-inductive enterprise that had four characteristics:

1. Science had achieved a superior kind of truth;
2. Science was characterized by inexorable progress;
3. Science was in the possession of the only method of interrogating nature, namely the empirical-inductive method (the scientific method);
4. This method could be simply described and easily taught.

A. Stinner <stinner@cc.umanitoba.ca>, Faculty of Education, University of Manitoba, Winnipeg, Manitoba, R3T 2N2

Specifically, Pearson spelled out the steps of the scientific method:

1. Careful and accurate classifications of facts and observation of their correlation and their sequence;
2. The discovery of scientific laws by the aid of the creative imagination;
3. Self-criticism; the final touchstone of equal validity for all normally constituted minds.

Pearson argued further that metaphysical as well as moral and social questions are fair game for the application of the scientific method. This picture of science appealed to the professional scientist, to teachers of science as well as the general reading public. The scientific method, roughly as outlined by Pearson, and later enshrined and perpetuated in science texts is still with the general public and many science educators. In the physics text the author used as a fledgling science teacher [4] we find the following steps of the scientific method presented to the student:

1. There is a question or a problem;
2. Collect all the facts about the problem;
3. Propose a theory or possible explanation;
4. Test the theory with an experiment;
5. Repeat the experiment and test to find out "if it will always be true." If not reject it;
6. If always true, it becomes a law.

It is interesting to note that "scientific law" follows "scientific theory."

The influential philosopher of science, Karl Popper, on the other hand, believed that scientific discovery is not a straightforward, definable activity that is identifiable by a method, suggesting perhaps that it is just as much an art as it is a science:

> *Science is not a system of certain, or well-established statements; nor is it a system which steadily advances towards a state of finality ..We do not know: we can only guess. And our guesses are guided by the unscientific faith in laws, in regularities which we can uncover-discover. Like Bacon, we might describe our own contemporary science as "the method of reasoning which men now ordinarily apply to nature."* [2, p.278]

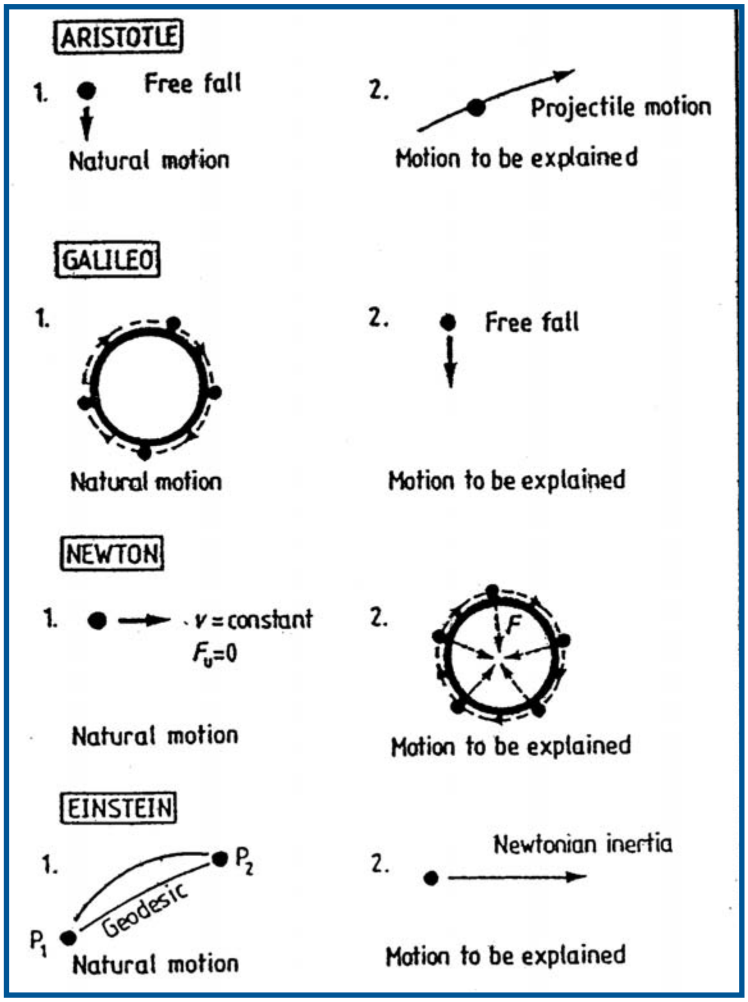

Fig. 1 **The Hierarchy of "Natural Motion"**
For Aristotle natural motion was illustrated by the free fall of a heavy object. For Galileo it was understood as the unimpeded circumnavigation of the Earth by a ship, and for Newton natural motion was the constant velocity motion of a body in deep space (no external forces). Einstein banished the notion of force and described and described the motion of a free particle in non-Euclidean space. For him natural motion became the path of a free particle along a geodesic - the path of minimal separation.

This picture of scientific quest for the comprehension of the world seems far removed from that of the Pearsonian understanding of scientific activity in terms of a scientific method. There is, in a sense, the suggestion that the scientist struggles toward understanding the world, much like the artist strives to interpret it. After all, both are using imagination to see new patterns emerging from a web of constraints. What Pearson seems to have understood by imagination in scientific thinking is "the clever manipulation of the data." He cautions against unbridled hypothesizing: "the imagination must not replace the reason in the deduction of relation and law from classified fact" [1, p.37]. Clearly, he considered the act of imagination a necessary component of a specifiable method, but only after all relevant facts have been put together. Unfortunately, Pearson does not make clear to what extent the role of the imagination is beyond method.

Popper, on the other hand, believed that science progresses by scientists making imaginative and daring hypotheses (he called them "conjectures"), and then testing them against the world. He argued that, since the inductive approach to arrive at theories is doomed to failure, theories in science cannot be proved – they can only be falsified. Scientists must propose daring hypotheses and then test them. Since laws or theories can never be verified, Popper recommended that scientists should actively try to falsify them. For example, if light did not bend in the gravitational field of the sun as predicted, according to Popper, Einstein's general theory of gravity would be falsified. For the purpose of this paper, however, we will ignore the Popper's notion of falsification, a contentious aspect of the Popperian picture of science, recently discussed by the philosopher Robert Crease in *Physics World* [5]. However, I agree with Popper's claim that science progresses partly by leaps of imaginative hypothesizing that is beyond method.

Most scientists would agree that a complete picture of scientific enterprise that includes what scientists do on a day-to-day basis, cannot be given by either the Pearsonian or the Popperian picture of science. A contemporary philosopher of science, Rom Harré, sums up the wide range of activities of scientists saying that the scientists' activities and imagination should span the discovery spectrum "ranging from informal intuitive steps to formal devices" [6] According to his argument there is a spectrum of scientific involvement that ranges from identifiable mechanical procedures to high-grade activity involving the educated scientific imagination.

SCIENTIFIC IMAGINATION: THE CASE OF FREE FALL

Let us begin our discussion with the easily accessible example of *free fall*, understood as a *scientific fact* and how its meaning has changed (rather evolved) from Aristotle to Einstein. The observation of free fall of heavy objects close to the surface of the earth, described as a scientific fact, will change (rather evolve) from the Aristotelian to the Einsteinian view. An Aristotelian would see free fall as a natural motion that requires no other explanation or quantitative description. A Galilean would see free fall as a constantly accelerating motion, where both instantaneous velocity and acceleration are defined in terms of time and distance: it is a law-like motion but not natural in the Aristotelian sense. Natural motion now is understood as the unimpeded ("inertial") motion of an object circumnavigating the earth. A Newtonian would see free fall as the motion determined by the inverse square law of gravitational forces and the second law of motion. Natural motion for Newton now becomes a thought experiment and is pictured as the inertial motion of an object in deep space with zero net force and traveling at a constant speed in a straight line. For an Einsteinian, free fall is seen as motion in a four dimensional continuum of space and time. Natural motion now is seen as the motion of a free particle along a geodesic, the path of minimal separation (See Figure 1).

Each of these views is based on a particular picture of the world; on a constellation of presuppositions that required a particular set of ordered questions for working out the consequences of that picture of the world. What would constitute proper data for one view would be inappropriate for another. According to Pearson, however, data that precede hypothesizing are supposed to be independent of a point of view. Moreover, in the wake of a revolutionary reorientation (for example, from Galilean to Newtonian physics) when scientists are struggling with the appropriate questions and their proper ordering, what is most perplexing is to decide what the relevant data are.

A fully developed theory like Newton's theory of gravitation, does not come easily and immediately; the question-and-answer procedure necessarily involves experiments, generates problems that must be solved, often using data that is selected on the basis of an incomplete theoretical background. The struggle to achieve a conceptual basis for such a theory involves a continual ordering and reordering of questions in response to experimental results and corresponding changes in deciding what the appropriate physical quantities must be that will appear in the definitions and laws. Moreover, the presuppositional structure changes in response to this approach. Einstein had to rebuild his structure of physics (mechanics) and redefine such physical quantities as mass and energy, in the absence of the most fundamental concept in Newtonian physics, the concept of force. It is difficult to see how the application of a specifiable method like the Pearsonian scientific method could be used in rethinking Aristotelian physics and arrive at Newton's theory of universal gravity, or rethinking Newtonian physics and arrive at Einstein's theory of general relativity.

Popper's picture of how science progresses may be more appropriate in understanding the complex passage from one theory to another (that, in fact, contains the first and has greater explanatory power). However, a large portion of scientific activity may still be connected with specifiable activities that can be spelled out. In order to investigate the relative places of specifiable procedure and imagination in theory construction, we will begin by responding to the question of how we can go from observation to theories and, in turn, from theories to explaining phenomena. This question was discussed by Aristotle, Galileo, Newton, and Einstein [7,8]. The scientific thinking of Aristotle, Newton and Einstein are depicted in Figs.2, 3, and 4).

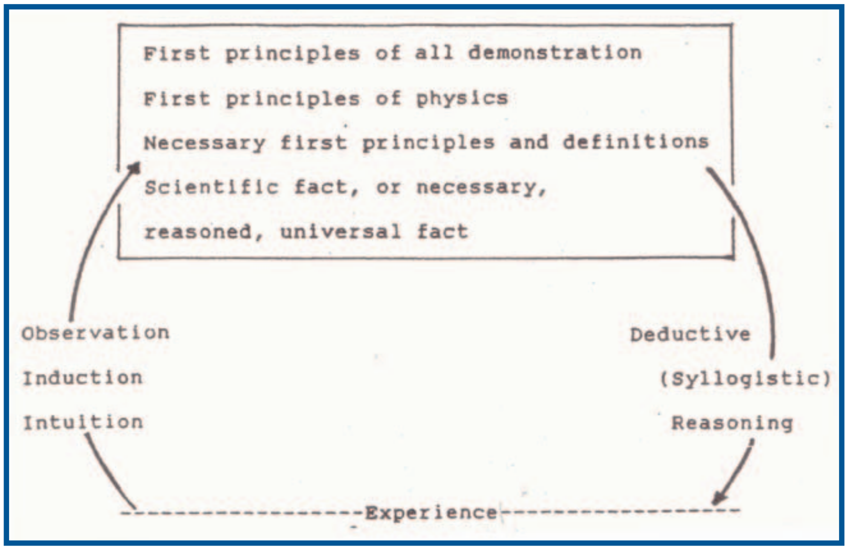

Fig. 2 **Aristotle's Physics**
Aristotle believed that we can go inductively from observation (by way of intuition and imagination) to general principles and then back to observations by deduction. He was convinced that properly formulated first principles of science, together with their deductive consequences, could not be other than true.

SCIENTIFIC IMAGINATION AND THEORY BUILDERS

Aristotle believed that we can go inductively from observation (by way of intuition and imagination) to general principles and then back to observations by deduction (See Fig. 2).He was convinced that properly formulated first principles of science, together with their deductive consequences, could not be other than true. By separating two distinct realms of inquiry, the celestial, with perfect circular motion, and the terrestrial, with natural and violent motion, he was able to confirm his physics with naked eye observation. Newton also believed that we can find by induction a deductive system consisting of definitions, laws and principles from which we can explain diverse phenomena (See Fig. 3) However, what he understood by induction was a complex process of give-and-take between evolving mathematical constructs (models), thought experiments and physical reality. Moving imaginatively between mental models and empirical confirmation, continually testing new ideas and concepts, aided by his newly discovered mathematics of the *calculus* (Fluxions), ultimately produced the Newtonian system.

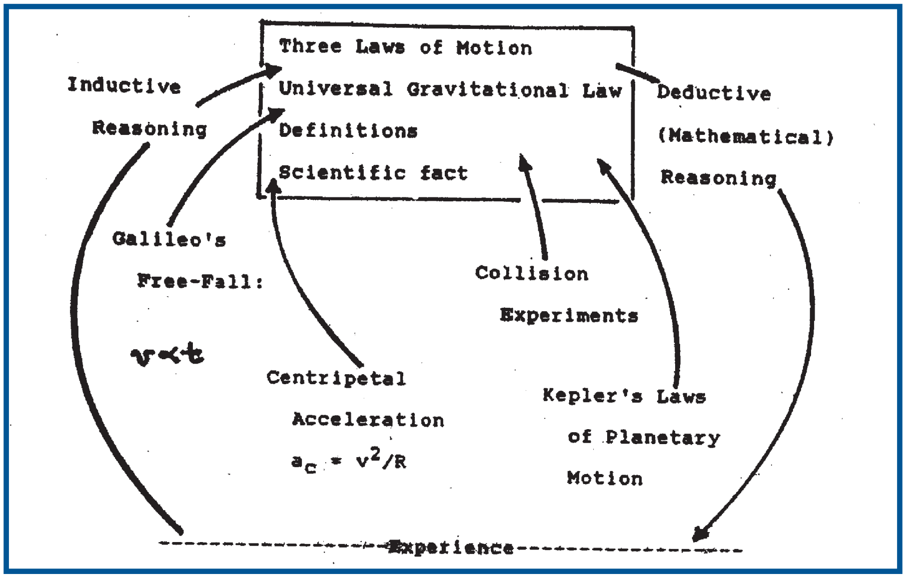

Fig. 3 Newton's Physics
Like Aristotle, Newton believed that we can find by induction a deductive system consisting of definitions, laws and principles from which we can explain diverse phenomena (See Fig. 2) However, what he understood by induction was a complex process of give-and-take between evolving mathematical constructs (models), thought experiments and physical reality. Moving imaginatively between mental models and empirical confirmation, continually testing new ideas and concepts, aided by his newly discovered mathematics of the calculus (Fluxions), ultimately produced the Newtonian system.

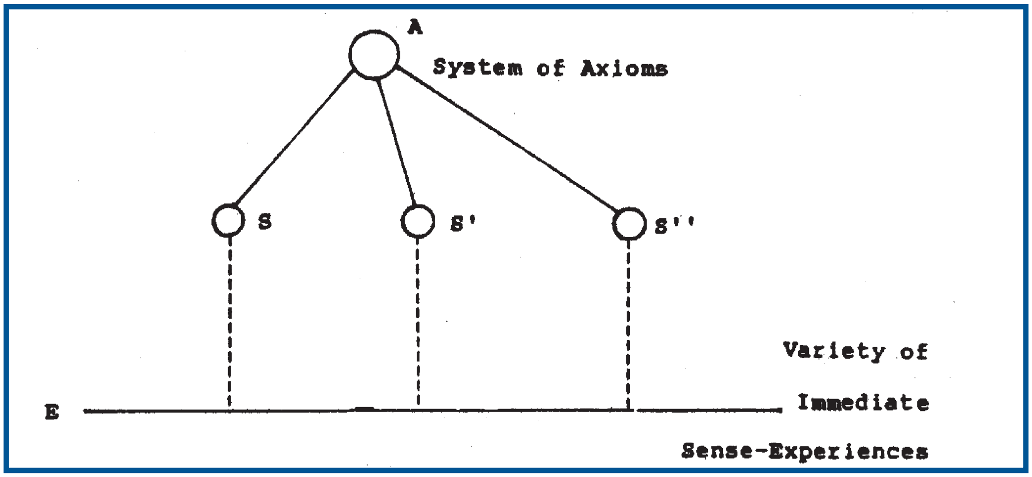

Fig. 4 Einstein's Physics
Einstein believed that it is not possible to arrive at a theory like the special theory of relativity, by a logical argument from the particular scientific fact. By his own admission (see Einstein's letter to Maurice Solovine, in *Einstein A Centenary Volume*, ed. A.P. French, Harvard University Press, 1979, pp. 270-272). The diagrammatic representation of his scientific thinking given below is a reproduction of his *own* sketch found in the letter to M. Solovine. In reference to the diagram Einstein says :

1. The E (direct experiences) are given to us.
2. A are the axioms, from which we draw consequences ... there exists no logical path leading from E to A, only an intuitive connection.
3. From the A are deduced, by a *logical path*, particular assertions S that can claim to be exact.
4. The S are brought into relation with the E (testing by experience). This procedure belongs also to the extra-logical (intuitive sphere), because the connection(s) between the concepts appearing in S and the immediate experiences in E are not of logical a nature. See Figure 4.

Newton's mechanics unified terrestrial and celestial phenomena: it explained such diverse phenomena as the oscillation of a pendulum, the movement of the tides and the motion of the planets. It took almost 200 years to work out the consequences of this great theory. Newton's successors had two major tasks: one was to fully understand and work out the mathematical consequences presented in the *Principia.* This task was accomplished by about 1840 by Euler, Lagrange, Laplace, and William Rowan Hamilton among others. The second task was to lay the foundations for understanding other phenomena which were outside the scope of his dynamics, namely light, electricity, and magnetism. This task was accomplished only with the works of Coulomb, Ampere, Faraday, and Maxwell.

The security of the presuppositional structure of Newtonian physics, however, began to be threatened by the late 1880s, with Maxwell's Electromagnetic Theory, and later with Mach's devastating critique of the presuppositions of absolute space and time. One of Newton's presuppositions was that disturbances propagated in empty space instantly (action-at-a-distance). Maxwell had to abandon this presupposition: in his theory disturbances propagated with a high but finite velocity through the ether, like ripples in a pond.

The task Maxwell set himself seemed straight-forward: summarize the experimental findings of Coulomb, Ampere and Faraday and give them a theoretical basis. At first glance this program may sound like a fine example of the application of an inductive scientific method, along the lines of Karl Pearson's picture of science. Upon closer examination, however, it becomes clear that the road Maxwell had to take in order to arrive at his electromagnetic theory was arduous and required intellectual daring and imagination that was beyond method. Maxwell used extraordinary imagination to find the laws of electrodynamics, a non-Newtonian system, but using Newtonian dynamics as a starting point. To achieve this he used physical analogy and mechanical models of the ether to "embody the dynamical relationship between electric and magnetic forces" [9, p.216]. We must remember, the physical ideas associated with Newtonian physics were particles, fluids, and elastic solids, all obeying Newton's laws of dynamics. It was well known to Maxwell that Faraday found in the theory of the two fields, the electric and the magnetic, that the first was generated by electric charges at rest, while the latter by electric currents, that is, charges in motion. There was, however, an additional way to generate an electric field, namely by a time-varying magnetic field, as described by Faraday's induction law. The corresponding possibility, however, did not exist for generating magnetic fields. Thus the early version of Maxwell's equations were flawed as judged by, what may be called, *visual symmetry*.

Maxwell, however, was convinced that these equations were wrong as they stood. So he gave a plausible physical explanation that allowed them to look symmetrical. The argument was based on what he considered the necessary conditions for the final form of these equations: a) symmetry with respect to the electric and magnetic fields must prevail, b) the conservation of charge principle must be satisfied, and c) the equations, when applied to free space (vacuum) must remain mathematically symmetrical with respect to the two fields. Moreover, the requirements of these necessary conditions implied the existence of a displacement current that was not detected by Faraday. If this effect is real, why did Faraday not discover it? The answer to this question is rather surprising: the displacement current exists but it cannot be detected, much like the presence of charge on the surface of a conducting sphere cannot be detected inside the sphere. The resultant equations then correctly predicted that all electromagnetic radiation traveled at the speed of light, soon confirmed by the experiments of Heinrich Hertz.

It seems then that visual symmetry plus plausible physical argument (even if the latter seems to have no empirical basis) sometimes may produce another kind of visual symmetry in the equations of physics. It should be kept in mind, however, that Maxwell's arguments, although based on the guiding idea of symmetry, did invoke certain necessary conditions that were based on well established physical principles. This kind of imagination in science, based on the notion of visual symmetry therefore must be intrinsically connected to more fundamental symmetries whose validity we do not doubt.

According to Nersessian [9], Maxwell treated the specific mechanism generically, in the way a spring is treated in physics text books to represent the class of simple harmonic oscillators. Finally, the mechanical analogues were rejected and what physics students now learn are the mathematical equations alone. Later (1895), the great physicist Henrik Lorenz, building on Maxwell's electrodynamic theory, tried to produce a physical theory of the ether that postulated the yet undiscovered electrons moving about in an all-pervasive, absolutely resting ether. In order to explain electromagnetic phenomena Lorenz had to postulate three different sorts of electrons, for polarization, conduction, and dialectrics. Moreover, he showed that the Maxwell-Lorenz equations, relative to the ether, the velocity of light is independent of the sources motion and is always a constant value of c (about 3×10^8 m/s). However, this may not be the case when the velocity of light is measured in a reference system moving relative to the ether, that is, in an inertial reference system. Therefore, reference systems in the ether were preferred reference systems. Still, by 1905, when Einstein's paper on special theory of relativity appeared, physicists generally felt that Lorenz's physical theory of the electron was on secure grounds. Lorenz's theory of the interaction between the electron and the ether was able to explain such effects as the presumed contraction of length, the observed variation of mass with velocity, and the fact that the measured velocity of light was always the same.

By 1904 Einstein, however, realized that light exhibiting particulate properties could not be explained by physical theories, such as Lorenz's electron theory. He concluded in his unpublished calculations that classical electromagnetism "failed in spacial regions as small as the electron" (cited in [10], p.51). In his *Autobiographical Notes* he said: "I despaired of discovering the true laws by means of constructive efforts based on known facts" [10, p.50]. Moreover, he concluded that physicists "were out of their depth" trying to explain such phenomena by way of physical theories of the kind produced by Lorenz. He also understood that the Maxwell-Lorenz equations remained unchanged under the modified space and time transformations. However, the laws of mechanics that were transformed between inertial reference systems according to the Galilean-Newtonian transformations did not remain unchanged. Einstein could not accept this glaring asymmetry. The laws of dynamics, he thought, must be the same in all inertial frames. Finally, the transformation rules for the laws of mechanics seemed to depend on two different notions of time – one physical and the other mathematical. Einstein concluded that current physics, therefore, could not accommodate mechanics and electromagnetism – these had to be unified [10].

Einstein saw that the basic problem confronting physics was the problem of understanding the equivalence of viewpoints between moving observers. His paper begins with a simple example of an asymmetric phenomenon in electromagnetic induction. What is noteworthy is that he did not consider it necessary to use mathematics to convince the reader that Maxwell's electrodynamics led observers on the wire loop and those on the magnet to different interpretation of the measurable current induced in the conductor. He then went on to refer to the null result of ether-drift experiments, but without directly mentioning the famous Michelson-Morley experiment. His great imaginative leap was to link the experiment of magnet and conductor to the ether drift experiments. Electromagnetic induction depends on the laws of mechanics and electromagnetism (and thus optics as well). The two principles (now called postulates) of his axiomatic system then quickly followed.

In summary then: Aristotle tried to find a deductive system (emulating Euclid), consisting of first principles of all thinking, principles of physics, definitions, and rules of inference. From here he was ablt he could logically explain physical phenomena. Newton also set himself the task of finding a deductive system consisting of fundamental assumptions, principles, laws, and definitions, from which he could explain such diverse phenomena as the motion of the pendulum, the tides, and the periods of the planets. Maxwell struggled to establish a small number of differential equations that summarized the experimental findings Coulomb, Ampere, and Faraday. In order to achieve this, he had to take recourse to mechanical analogies and mechanical models, only to discard them later. Lorenz laboured mightily to build a physical theory within classical (Newtonian) physics where electrons moved about in an all-pervasive, absolutely resting ether. Finally, Einstein was forced to completely change the presuppositional basis of physics in order to clear up the asymmetries produced when the classical laws of mechanics were applied to optical phenomena. Einstein combined visual thinking with thought-experiments to arrive at his two basic postulates, the foundation of his theory of special relativity.

Based only on this brief and spotty account of how some of the big theories in physics were constructed, it is clear that there is no easily describable passage from observation to theory. In each case there was a struggle to form new concepts, to find new patterns, and to see analogies between disparate events, that emerged slowly from a web of constraints. While there may be mechanical procedures involved, it seems that the big theories in science (physics) are more the product of imagination than of a procedure. In each case we discussed the educated scientific imagination that often goes beyond method and a "simple interplay between experiment, theory and inherited concepts" [11, p.8]. Rather, there are illogical, nonlinear, often unscientific elements that are juxtaposed on the logical nature of the concepts themselves. Gerald Holton even argues for the importance of "passionate motivations, intuitive leaps, and serendipity or sheer bad luck ... the incredible tenacity with which certain ideas have been held despite the fact that they conflicted with plain experimental evidence" [11, p.8].

The appearance of a big theory in science, however, is always accompanied by a language barrier. This barrier can be daunting and sometimes difficult to overcome for the physics student as well as the newly initiated scientist. But we must remember that it was also an arduous task for the theory builders to establish a new theory by way of new concepts, thought experiments, models, and analogies.

THE "LANGUAGE BARRIER" FOR THEORY BUILDERS

The physicist Freemen Dyson wrote in 1958, clearly anticipating some of the ideas of Thomas Kuhn:

> *The reason why new concepts in any branch of science are hard to grasp is always the same: contemporary scientists try to picture the new concept in terms of ideas which existed before. The discoverer himself suffers especially from this discovery: he arrived at the new concepts by struggling with the old ideas, and the old ideas remain the language of his thinking for a long time afterward.* [12, p.76]

A little later, again anticipating Kuhn's notion of incommensurability, he says, discussing Maxwell's theory and quantum mechanics:

> *Maxwell's theory and quantum mechanics are examples of physical innovation at its deepest level. Such innovation occur when experimental facts are seen to be incomprehensible within the bounds of earlier conceptions. A new style of reasoning and imagining has to be groped for, slowly and painfully, in the dark.* [12, p.78]

Of course, we could easily insert at the beginning of the above paragraph Aristotle's physics, Newton's theory of gravitation, and Einstein's special theory of relativity. We will briefly look at the theory building of Aristotle, Newton, Maxwell, and Einstein, in the light of the above statement by Dyson. Aristotle's physics was a deductive theory, modeled after Euclidean geometry. We have no record of Aristotle's conceptual struggle to arrive at the first *principles of all reasoning, the principles of physics*, and the *appropriate definitions*. It is clear, however, that he had fewer empirical constraints to contend with because he was interested only in matching theory with naked eye observations and common sense.

Aristotle physics was introduced into medieval Europe and represented the last word in our understanding of physical phenomena. Every attempt to construct an alternative theory had to first recognize and confront Aristotelian physics. The conceptual struggle required to go from Aristotle's rational physics to Newtonian mathematical-empirical physics was enormous and took at least 100 years, from Galileo's early attempts to establish a "New Science" to the publication of Newton's *Principia* in 1684. It is well documented, but generally omitted in textbooks, how Newton struggled to establish the notion of force as a unifying concept [13,14]. He had to free himself of the idea of impetus and transform this notion into the concept of inertial mass, eventually arriving at a complete separation of force and motion. Another conceptual struggle was connected to the fact that he had available three distinct sets of observations that could be connected to three distinct meanings of the notion of force: Free fall and the pendulum, the motion of the conical pendulum, and the collision of wooden balls used as pendula. In addition, he seemed to have had great difficulty in getting rid of the idea of centrifugal force in describing a body in circular motion. Finally, he took as one of his fundamental presuppositions *action-at-a-distance* and argued for absolute space and time, using powerful and imaginative thought experiments [13,14].

Dyson argues that the basic difficulty physicists had with Maxwell's theory (and indeed was a difficulty for Maxwell also, at least at the beginning of his work), was found in their inability to conceive an electric field in terms other than a mechanical model. In terms of such models, however, Maxwell's equations appeared neither simple nor natural. Maxwell had to slowly free himself from the tyranny of the mechanical images and models and picture electric and magnetic field as something which exist separately, in their own right. Heinrich Hertz, for example, grappled with Maxwell's equations and was unable to make consistent sense of them [15, p.188]. Buchwald, like Dyson before him, argues that Hertz was unable to "translate Maxwell's language into his own language" [15, p.189]. He tried to fit Maxwell's field-based ideas of electricity into his conductor based model. Herzt's model thus led to a dualism in the concept that was lacking in Maxwell's field equations. Not surprising, British physicists had little trouble in understanding Maxwell's field equations.

We have already discussed in detail Einstein's intellectual struggles in arriving at his special theory of relativity. He combined visual thinking with thought-experiments to lay the axiomatic foundation of the theory of relativity, consisting only of two principles. He thought that the conventional notions of time and simultaneity "resulted in a physics burdened with asymmetries, unobservable quantities, and *ad hoc* hypotheses." The paradoxes raised by his two famous thought experiments (traveling with a light wave and comparing the simultaneity of light emission on the train with those of an observer on the ground) suggested to him that key to these paradoxes was to be found in the absolute character of time, viz., of simultaneity.

Contrary to popular belief, the theory of special relativity was not instantly recognized as revolutionary. One of the reasons for this was the interpretation of Einstein's work as a valuable generalization of Lorenz's theory of the electron only. But the main reason must be that a number of the presuppositions of Newtonian mechanics were abandoned and replaced by Einstein's postulates. These produced deeply counter-intuitive consequences imbedded in a new language of scientific discourse.

THE "LANGUAGE BARRIER" FOR THEORY LEARNERS

It is well known that scientists, when confronted with a new theory in adult life, find it difficult to assimilate it. Indeed, Planck once remarked that before a new theory can be completely assimilated by the community of physicists the "old guard" must die. Thus, we had Aristotelians clinging to their physics until the beginning of the 18th century and Newtonians rejecting the findings of the special theory of relativity until the 1920s. In this paper we have referred to natural philosophers encountering Newton's *Principia* in the late 1600s, physicists grappling with Maxwell's equations in the 1870s, and those trying to understand the counter-intuitive results of Einstein's special theory of relativity after 1905.

Scientists growing up with a theory, of course, also encounter significant and identifiable conceptual difficulties. Concepts such as instantaneous velocity, inertia, and centripetal acceleration are early stumbling blocks for all students, including future physicists. Later, Maxwell's equations and the application of relativistic mechanics present conceptual difficulties that are often not overcome. Scientists become acquainted and comfortable with difficult concepts only after a long apprenticeship that ensures repeated exposure to increasingly more sophisticated levels of presentation, imbedded in progressively richer contexts of inquiry. Physicists, however, tend to forget the time when they did not understand the notion of inertia or the concept of centripetal acceleration. As a consequence, when they teach fledgling physicists they believe that what is a clear and logical explanation (to them) must also be clear and comprehensible to the student. That this is not so has been well demonstrated by research into conceptual development in physics [16].

Researchers have found clear parallels between students' intuitive conceptions in science (mechanics, electricity, heat) and historical prescientific conceptions [17,18]. Although this finding suggests that it may be possible to have the learning process recapitulate the historical process, closer examination of the complex thinking involved in scientific discovery shows that setting such a goal is probably unreasonable. A plausible case, however, can be made for a limited recapitulation of the historical process in domains, such as pre-Newtonian mechanics, that are experientially familiar to the students [13,14].

For pre-Newtonian physics the conceptual development depends on common sense perceptions based on personal kinaesthetic memory. On the other hand, post-Newtonian concepts are related to internalist notions such as thought experiments that are difficult to connect to ordinary experience. Moreover, it may be that physics teachers themselves have generally limited acquaintance with the ideas of Mach and Einstein. Teachers therefore tend to believe that the "discovery argumentation" [18, p.179] required for presenting these ideas would be too difficult for beginning physics students. It may, however, be possible to also achieve partial recapitulation of post-Newtonian ideas of force and motion with high school physics students.

One way to accomplish this would be to find appropriate analogies, limiting case analyses, thought experiments, and imaginistic representations for partial recapitulation of the historical process of the concept of force, the concept of field, and the concepts of special relativity. High school physics students are generally very interested in Aristotle's ideas about force and motion. They are also fascinated by the claims of modern physics, especially Einstein's ideas. But the ideas of Aristotle about force and motion are generally dismissed and trivialized by textbook writers and those of Einstein are considered abstract and often made inaccessible to high school physics students. I have argued elsewhere that a history-based exposure to the conceptual development of Newtonian mechanics is superior to a conventional textbook-centered approach, because it is contextual, shows the intellectual struggle involved in scientific thinking and relates better to students' knowledge and experience [8,13,14]. The questions asked by post-Newtonian physicists about such assumptions as absolute space and time, simultaneity, and the constancy of the speed of light then make more sense to students, leaving open the door for post-Newtonian discussion at an early stage.

KUHN'S IDEAS AND THE SCIENTIFIC METHODOLOGY SPECTRUM

If there is no specifiable scientific method that can be taught, then how can we describe what scientists do? Accounts of how science progresses vary from giving a method that can be clearly spelled out, much along the lines of Pearson, to referring to a mysterious process and saying: "anything goes ... no holds barred", as the late philosopher of science Paul Feyerabend argued in his celebrated book, "*Against Method*" [19]. We can picture scientific work along a continuum or a spectrum of activities, beginning with specifiable procedures and ending with the imaginative thinking of great scientists. It may be convenient to think of the complexity of scientific activity as ascending from specifiable mechanical procedures, to complex scientific activities that scientists engage in, to high-grade scientific activity (see Figure 5).

Specifiable mechanical procedures	Scientific activities of "normal" science	High-grade activity of scientists working on the "edge" of a paradigm

Fig. 5 SCIENTIFIC METHODOLOGY SPECTRUM (SMS)

So far we have discussed imagination in science of front-rank physicists, that belongs to the third column of our *science methodology spectrum* (SMS). Is there a place for imagination in science for activities shown in the first and second columns? In order to answer this question I will draw on the most influential work in how science progresses, namely Kuhn's *Structure of Scientific Revolutions* [3] and his later reworking of some of the main ideas presented in that work.

Kuhn argued that it is not a recognizable method, or an identifiable set of rules that describes a group's particular common and shared way of seeing, but rather it is the particular paradigm of their tradition that guides their scientific thinking. He generally seemed to identify a paradigm with what it is that underlies and gives coherence to a research tradition. He argued that in the absence of a recognizable method and a competent body of rules we can understand both the productive work and the allegiance of the scientist to a paradigm in terms of Wittgenstein's notion of "family resemblances."

Kuhn then went on to maintain that scientists learn to identify problems and techniques associated with a research tradition. We recognize these because of a resemblance to already successful achievements within the corpus of science, *and not because they are a product of a "method," or a set of rules*. Scientists (physicists) in fact become members of a tradition and believers in a paradigm by virtue of their training and education, the literature they read, and what they recognize as standard models and problem-solutions of their craft. According to Kuhn scientists learn their science through the study of the application of a theory to some concrete range of natural phenomena, and "never learn concepts, laws and theories in the abstract and by themselves" [3, p.46]. Students of physics, for example, learn their craft by studying specific applications and concrete examples ("exemplars") which involve working with instruments in the laboratory and practicing problem solving.

"Normal science" comprises largely what Kuhn calls a "mopping up operations," performed within the confines of the paradigm. Some of these are: a) increasing the precision of agreement between observations and calculations based on the paradigm; b) determining the values of universal constants, c) formulating quantitative laws in order to extend the articulation of the paradigm; and d) deciding which alternative ways to apply the paradigm to new areas of interest is most satisfactory. Normal science then is an activity that spans the range from involving specifiable mechanical procedures to complex scientific judgements.

Taking any of the above "mopping up operations" that comprise normal science, one could place the activities along the SMS. Much of the time the scientist in a given specialization (say an experimental physicist) performs mechanical procedures that can be easily taught to student assistants and routinely performed by them. Even the more sophisticated methods of obtaining data from instruments and many of the interpretations of these data can be done routinely. Sometimes even new and unexpected discovery can be made this way. However, the judgement of whether or not the data fit the requirements of the paradigm must be made by the scientist.

In order to give a more complete description of the SMS, Kuhn's later notion of "Disciplinary Matrix" (DM) is important. He describes the DM in terms of four components: *metaphysical assumptions, symbolic generalizations, values, and concrete problem solutions*. In other words a research tradition can be characterized by its presuppositions, research methods that depend on a particular formalization of language, values in articulating its findings, and worked-out typical problems that both illustrate and characterize certain areas of interest.

The first component can be seen as a presupposition of a science. For example, for a Newtonian physicist (in the 18th century) it was a presupposition that space is Euclidean and time absolute. The second component comprises the formal aspects of a discipline: laws, such as Newton's second law of motion $F= ma$; and definitions, such as the definition of resistance in Ohm's law. Laws, like the second law of motion, however, must be understood as a *law-sketch*, or a *law-schema*, rather than a specific law. For example, the law can be used to describe a simple case of free fall, the more complex case of the motion of a pendulum, and the very complex case of the motion of a projectile in a resisting medium. The mathematical representation of this motion would be unrecognizable to the student of elementary physics. The confidence with which we have our students carry out these progressively more difficult applications of an apparently simple law attests to both the belief we have in the law-like behaviour of matter in motion (at least on a large scale) and to our pedagogical success in transmitting this knowledge efficiently to successive generations. Values, the third component, are the qualities probably most prized in a discipline: they provide a sense of community to the practicing scientists. One values a theory for its predictive power, internal consistency, and fertility in suggesting problems. The main function of values, however, is to provide guidance during a period of intense confrontation, for example, when the members of a group have to choose between incompatible ways of practicing their discipline. Values also concern aesthetic judgements, which depend on the individual scientist.

The fourth component of the DM is perhaps the most important for science educators, because of its relevance to science education. Kuhn called this aspect of the DM "exemplars," and thinks of it in terms of a group's shared commitments. The notion includes both "the concrete problem solutions students encounter from the start of their scientific education, whether in laboratories, on examinations, or at the end of chapters in science texts," and "the technical problem-solutions found in the periodic literature that scientists encounter" [3].

All students of elementary physics instantly recognize problems that cluster around such *prototype problems* and *prototype instruments* in physics as the inclined plane, the simple pendulum, the conical pendulum, the oscillating spring, and Keplerian orbits; instruments such as the vernier calliper, the calorimeter, the Wheatstone bridge, Young's interference apparatus, and the spectrometer. More recent example of instruments are the linear air track collision apparatus, the electronic air table, and the electron deflection tube. Kuhn believed that the exemplars, or concrete problem solutions, are at the heart of the education of both the student of elementary physics, in the context of conventional classroom activities, as well as the mature scientist working within the confines of normal science. The need to abandon a research tradition in favour of a new one is signaled by the accumulation of long-standing problems.

These are problems that are unyielding to the research methods of old traditions, however cleverly applied by the most skillful normal scientists or puzzle solvers. With the piling up of such problems a crisis period is reached when scientists actively look for alternative ways of solving them.

Eventually, one of them, based on a new set of metaphysical assumptions and new methods of solution, wins the allegiance of most scientists. A new DM develops that is able to solve these problems. What counted as scientific knowledge in the old tradition is re-conceived, re-evaluated, and sometimes discarded. Textbooks are rewritten, science education is changed, and the scientist "sees the world differently" [3, p.62].

Not surprisingly, the new way of seeing, based on the new paradigm, or DM , produces a new language of discourse. Scientists, who have grown up with the old paradigm find it difficult to communicate with the young generation who have been converted to a new way of understanding. In fact, he believes that the old generation is never converted and can only find access to the new way of thinking by persuasion. Kuhn argues that two paradigms, like Newtonian physics and Einsteinian physics become incommensurable, that is, discussion across the paradigms is doomed to failure. Even within classical physics, as was shown earlier, Maxwell's field equations were very difficult to understand for those who first encountered them as adult physicists. Of course, scientists have been aware of this incommensurability, or language barrier between theories, long before Kuhn published his ideas. We need only to mention Planck's dark comment about the necessity of the "old guard" to die before full progress can be made in a new paradigm like quantum mechanics and Freeman Dyson's early understanding of the implications of a "language barrier" for both physicists and physics students.

According to Kuhn, then, science progresses on two levels: during the long period of normal science, and also during the shorter period of a successful revolution that ushers in a new research tradition. There is no need for the working normal scientists to examine the foundations (what we call presuppositions here) of a research tradition critically, for they must be taken for granted. This constraint, of course, limits the range of inquiry of a tradition. Kuhn claimed, however, that without the concentration that only the security of normal science can give, progress in science would be slow, if not impossible.

KUHN AND THE TEACHING OF SCIENCE (PHYSICS)

It is generally agreed that science (especially the physical sciences), from middle school to college, is taught chiefly by way of the *established "scientific fact" and the finished product of mathematical formulation* [8,20,21,22,23]. Efforts to give these *scientific facts* and the mathematical formulation evidential, historical and experiential support appropriate for the student seldom go beyond the instantiation experiments of the type "Proving Newton's Second Law of Motion." Such experiments, of course, promote an inductivist picture of science and make no contact with the scientific imagination required to establish a law like Newton's second law of motion.

Students, in turn, are trapped by the comfort of memorizing the scientific fact and the efficiency of applying the formulas in solving exercise problems. The correct solution of the exercise problems then is thought to provide evidence for the teacher of the success of his or her teaching and it gives the student a sense of confirmation of mastery and understanding of the material [8,21,22].

This overemphasis of the mathematical formulation of a topic at the expense of the imagination required to establish it and the appropriate *evidence* to support it, is apparent in the study of the physical sciences, especially in elementary physics. As former science (physics) students we remember in particular solving countless problems by using formulas based on laws, principles, and definitions, and performing experiments to verify these laws. Newton's second law, for example, has been "proved" by students over the years, whether it involved the use of *Atwood's Machine, Fletcher's Trolley*, or the use of the *electronic air table*. Newton's first law, the textbook may have told us, is just a special case of the second law. But does that follow deductively? Can we perform experiments to prove the first law? Did Newton base his laws on experiments? If so, what experiments did he perform? On what presuppositions are these laws based? Did he use inductive reasoning in arriving at these laws? If so, how is it that his laws are used as one would use a deductive system in geometry? Finally, why is it that if someone claims that Newton's laws were disproved on a special electronic air table no one will take that claim seriously?

We cannot turn to Kuhn for clear answers to these questions. Kuhn does not make direct recommendations for science education, but argues that conventional textbook-centered teaching provides the basis for initiation into the normal science activity of the working scientist. Indeed, according to Kuhn, textbooks are "pedagogic vehicles for the perpetuation of normal science" [3]. It should be stressed, however, that Kuhn does not recommend algorithmic problem-solving of the kind that seems to be at the heart of conventional science (physics) teaching. Rather, he argues, that "by doing problems the student learns consequential things about nature." In elementary physics, for example, these are the problems that are related to such exemplars as the *inclined plane, billiard ball collisions, the conical pendulum*, and *Atwood's Machine*. These problems, Kuhn insists, should be developed and sequenced so that the laws (for example Newton's second law, F = ma) are not seen as a finished product of mathematical formulation to be committed to memory and then applied to problems algorithmically. Rather, Kuhn argues that students should learn to think of such laws as "symbolic generalizations" that *gain new meanings in different contexts*.

Unfortunately, Kuhn's argument that "doing problems is learning consequential things about nature" may be true only in a restricted sense. Science teachers generally teach science from textbooks that present subject matter ahistorically and only as a finished product. In addition, they tend to trivialize Kuhn's recommendation by providing mostly inconsequential problems. For the majority of students, doing problems is to practice algorithms and memorize scientific facts. Kuhn, of course, was intimately acquainted with physics textbooks and the conventional teaching practices of physics teachers (he was a trained physicist himself). However, he still insisted that textbook-centered science teaching has been very successful in producing proficient scientists for research and technology. Nevertheless, he has misgivings about its effectiveness in producing the kind of high-grade thinking required to periodically examine the foundations of a science:

> *But for normal scientific work, for puzzle-solving within the tradition that the textbook defines, the scientist is almost perfectly equipped .... Even though normal crises are probably reflected in less rigid educational practice, scientific training is not well designed to produce the man who will easily discover a fresh approach.* [3, p.166]

Finally, Kuhn argues that the textbook does not question the presuppositions of a science and in fact it "systematically disguises" the history of its discipline [3, p.136]. However, it was argued that knowledge of historical context is an indispensable part of an understanding of the role imagination plays in scientific thinking. We need to impart this knowledge as an integral part of our teaching.

INJECTING IMAGINATION INTO SCIENCE (PHYSICS) TEACHING

Kuhn seems to be saying that all is well with science (physics) education that is textbook based, because it is very efficient in teaching the *exemplars* of a science (physics) in preparing scientists for research work. He seems to suggest that this preparation has been so successful that, even though it does not prepare the scientists well for discovering a fresh approach, it should not be abandoned.

The foregoing discussion about the role of imagination in science, however, suggests that a fairly radical change from the conventional text book-centered physics teaching is required if we want to teach an authentic science (physics) to future physicists as well as scientific (physics) literacy to the general public. Granted, the main task of physics educators has always been to prepare young people for physics research and the professions that require a good basic understanding of physics. Today, however, we must go further and ensure that all students leave school with a basic scientific literacy that includes a knowledge of elementary physics. In order to achieve these goals, we have to make our learning contexts richer and more challenging for both the university-bound student who is required to study physics and the student who is looking for general physics literacy. However, providing rich contexts is a necessary but not sufficient condition for successful teaching of authentic science. We must also educate and train young science (physics) teachers to have a good understanding of the nature and history of science and of how students learn science.

Our post-Kuhnian mandate then is to cut the umbilical chord with conventional textbook-centered and rethink our science (physics) teaching. Our discussion suggests that the teaching of high school physics should have a rich contextual base that is connected to a sound theoretical structure. The contextual base should be motivating and related to students' interests and experiences; the theoretical structure, on the other hand, must clarify the status of theory, the relationship between experiment and explanation, and make connections to the history of science. This theoretical structure may be called *the contexts of inquiry*, consisting of *presupposions, questions, problems,experiments*, and *new question*. Fig. 7 gives a detailed description of the *contexts of inquiry* for Newtonian physics. A complete discussion of this approach with respect to Aristotle, Galileo, Newton, and Einstein can be found in [7] and [13].

At the very center of the *contexts of inquiry* approach is a cluster of *large context problems* (LCP) (See [13]). It is convenient to see the contexts that surround the LCPs as consisting of three levels of historical and conceptual development, a *foundation level*, a *research level*, and a *pedagogical level* (See Fig. 5). The foundation level refers to the thinking and the activities involved when a theory (paradigm), like Newton's dynamics, is constructed; the *research level* refers to the working out of the consequences of that theory (normal science); and the *pedagogical level* refers to the presentation and the content of science (physics teaching). Conventionally, physics is taught only on the pedagogical level, making little or no connections with the other two, the

FOUNDATION LEVEL

(The conceptual thinking and activity involved
when a theory is constructed)

RESEARCH LEVEL

(The working out of the consequences of the theory)

PEDAGOGICAL LEVEL

(The method of presentation of the theory
and its consequences)

Fig. 6 Levels of Investigation for the Contexts of Inquiry

The Contexts of Inquiry for Newtonian Physics:

Presuppositions:

Mathematics is the core of physical description and explanation.
Mass points interact via central forces.
Space id Euclidean
Time is absolute
Mass points interact instantaneously (Action-at-a-distance)

Questions:

Is there an axiomatic system, expressed in the language of mathematics, that can describe both celestial and terrestrial phenomena?
What are the fundamental physical quantities in terms of which we can describe the dynamics of free fall, collision and centripetal acceleration?
Assuming that the laws are valid for the motion of the planets how can we describe the gravitational force between a planet and the sun?
How can we describe the dynamical equilibrium between the non-linear motion of a planet and its gravitational attraction to the sun?

Problems:

To find the mathematical description of centripetal acceleration.
To find the nature of the path of a planet obeying an inverse-square force law.
To show that Kepler's laws of planetary motion are derivable from the laws of motion and the gravitational law of force.
To show that Galileo's law of free fall is just a special case generated the second law of motion. (This is an answer to Galileo's question about the "cause of motion" in free fall).
To show that a spherically homogeneously distributed mass has the same gravitational effect as a point equivalent mass.

Experiments:

Collision experiments using pendula
The conical pendulum
Atwood's machine
Cavendish's experiment

Thought experiments:

First law of motion
The rotating bucket
Two spheres rotating in a void

New Questions:

Can force and mass be expressed in a non-circular way?
Is inertia a local effect or is it dependent on the mass of the stars?
Why inertial and gravitational masses equivalent?
Can we quantitatively demonstrate how particles of matter in motion endowed with forces produce the observed phenomena in nature, for both large and small scale phenomena?

Fig. 7 The Contexts of Inquiry for Newtonian Physics

research and foundation levels. Using the *contexts of inquiry* approach, the pedagogical level of each context will connect to the other two levels, offering a philosophically and historically sounder and therefore more interesting, relevant and authentic science

I have discussed the rationale and the design of LCPs, embedded in a rich theoretical background provided by the *contexts of inquiry* in detail elsewhere [7,13]. LCPs are contextual settings that are designed by the teacher in collaboration with students. Each LCP should be so designed that most of the physics for a particular topic would have to be used for the successful completion of the problems suggested by the context. What is so attractive about this kind of setting is that the questions and problems are generated *naturally* by the context and will *include* problems that are given *out of context* (in a contrived way) in a textbook for a given topic. Designing contexts on this scale gives the instructor the status of researcher and the student the feeling of participating in an on-going research program. Indeed, many of the questions and problems generated do not have obvious answers for the student or the instructor. The ability to answer questions and solve problems that do not have textbook answers, using elementary physics only, is very rewarding for both students and teachers. A contextual approach to the teaching of physics may be more time-consuming then the conventional textbook approach. However, the understanding of the student as well as the quality of interaction between the student and the teacher is lifted from an ordinary to a high-grade level. Indeed, solving problems that are naturally generated by a context that attracts the imagination of the student are more likely to make contact with nature than solving contrived problems in text books.

Examples of LCPs that we have developed over the years are: "Physics and the Bionic Man", "The Physics of Star Trek", "Physics and the Dam Busters", "Hitchhiking on an Asteroid", "Calculating the Age of the Earth and the Sun", "Pursuing the Ubiquitous Pendulum", and "Sudden Impact: The Physics of Asteroid/Earth Collisions"(See references).An example of how one can use the contexts of inquiry and the history of science in a major topic is : 'The Story of Force: From Aristotle to Einstein" [14].

Even a cursory survey of journals like *The Physics Teacher*, will provide the physics instructor with plenty of examples of such contextual settings: "The Physics of the Play Ground", "The physics of Toys", "Physics and Skiing", and historical surveys, like "Is Maxwell's displacement current a current?" [24], "Newton's Thermometry: The role of Radiation" [25], and "The search for electromagnetic induction" [26]. These papers could be easily adapted and transformed into LCPs or investigations using *the concepts of inquiry*.

CONCLUDING REMARKS:

Innovations in science (physics) teaching all seem to rest on one simple premise: *a better learning experience results from the active engagement of the* student. Many of these innovations can be placed in the following categories: (1) microcomputer-based laboratories, (2) active engagement in lectures, (3) collaborative learning, and (4) structured problem solving. *Workshop Physics* by Priscilla Laws and her group at Dickinson College replaces the standard calculus-based physics course; and the web-based virtual physics experimental site, Physics 2000, are good examples of the first approach. Harvard professor of physics, Eric Mazur's *Peer Instructor*; and the physics education research group at the University of Minnesota have developed "rich context problems" for collaborative learning. The last approach is used by the University of Washington Physics Education Group who have developed a series of exercises, based on their research, to help students with conceptual difficulties. Finally, I would like to mention the work done by my colleague Wytze Brouwer at the University of Alberta in improving physics education. The detailed account of his collaborative approach, replacing the conventional lecture-centered teaching of large classes in first year physics, is well described in [27].

As far as textbooks are concerned, we are seeing a shift toward recognizing the importance of embedding teaching in rich contexts, as well as paying serious attention to the research in conceptual development by science educators. This research clearly shows that students are able to solve problems on physics tests with inadequate understanding of the concepts involved. [16,27], There are also textbooks that incorporate the history of science in more effective ways than just placing entertaining vignettes in the text [28].

Finally, the work of Paul Hewitt must be mentioned. His book *Conceptual Physics* is a successful attempt to present the qualitative aspects of concepts in physics. This is done through visuals, demonstrations, hands-on (minds-on) activities, verbal explanations and dialogues. There is a quantitative aspect to this approach, but the presentation of "formulas" is kept to a minimum.

James Trefil and Robert Hazen's *The Sciences: An Integrated Approach*, tries to present the concept of physics qualitatively, as Hewitt does, but uses much more quantitative support. Laws and definitions are given verbally, graphically and pictorially first, and only then expressed symbolically. It is a nice attempt to balance the quantitative and qualitative aspects of physics, somewhere between the conventional textbook and Hewitt's book.

Cutting the umbilical chord with conventional textbook-centered teaching will be successful only when textbook writers and teachers of science (physics) have a deep understanding of the *qualitative/quantitative* requirements of good physics teaching and how students learn concepts in physics. However, this is only a necessary but not sufficient requirement for good science teaching. To rise above the conventional textbook-centered, lecture-centered teaching of science (physics), we need to explicitly incorporate the history and the nature of science. Our post-Kuhnian mandate then is to move beyond the role of textbooks as "pedagogic vehicles for the perpetuation of normal science" to a more inclusive approach that better serves the future scientist (physicist) as well as the future scientifically literate citizen.

ACKNOWLEDGEMENT

Many thanks to the reviewer of this article. The suggestions made were insightful and certainly improved the quality of the paper.

REFERENCES

1. Pearson, K. (1936). The grammar of science. London: J.M. Dent & Sons Ltd. (Original work published (1892).
2. Popper, K. (1968). The logic of scientific discovery. New York: Harper and Row, Publishers.
3. Kuhn, T., *The structure of scientific revolutions,* Chicago: The University of Chicago Press, (1962).
4. Eubank, H., *Basic physics,* Toronto: The Macmillan Company of Canada, (1963).
5. Crease, R., “Finding the flaw in falsifiability”, *Physics World,* pp. 15-17 (Dec. 2002).
6. Harré, R., “The principles of scientific thinking”, Chicago: University of Chicago Press, (1970).
7. Stinner, A., “The teaching of physics and the contexts inquiry: From Aristotle to Einstein”, *Science Education*, **73**(5), 591-605, (1989).
8. Stinner, A., “Philosophy, thought experiments, and large context problems in the secondary physics course”, *International Journal of Science Education*, **12**(3), 244-157, (1990).
9. Nersessian, N. (1995). Should physicists preach what they practice? Science & Education, 4(3), 203-226.
10. Miller, A.I., *Imagery in scientific though,* Cambridge, MA: The MIT Press, (1986).
11. Holton, G., *The scientific imagination*, New York: Cambridge University Press, (1978).
12. Dyson, F., “Innovation in physics”, *Scientific American*, **129**(3), 74-82, (1958).
13. Stinner, A., “Providing a contextual base and a theoretical structure to guide the teaching of physics”, *Physics Education*, **29**, 375-381, (1994).
14. Stinner, A., “The story of force: From Aristotle to Einstein”, *Physics Education*, **29**(2), 77-86, (1994).
15. Buchwald, J., “Design for experimenting”, in P. Horwich (Ed.), *World changes: Thomas Kuhn and the nature of science* pp. 196-207, Cambridge: The MIT Press, (1993).
16. Hestenes, D. *et al.*, “Force concept inventory”, *The Physics Teacher*, **30**, 141-151, (1992).
17. McCloskey, M., “Intuitive physics”, *Scientific American*, 122-130, (1983, April).
18. Nersessian, N. (1989). Conceptual change in science and in science education. Synthese, 80, 163-183
19. Feyerabend, P., “Against Method”, Humanities Press, (1975).
20. Merzyn, G., “The language of school science”, *International Journal of Science Education*, **9**(4), 483-489, (1987).
21. Hewitt, P. G.. “Conceptually speaking”, *The Science Teacher*, **35**-57, (1990, May).
22. Baeyer, H.C. von., “Two-way street”, *The Sciences*, pp. 13-15, (1990, November).
23. Rigden, J.S. *et al.*, “Tune in, turn off, drop out”, *The Sciences*, 16-20, (1991, Jan.).
24. French, A., “Is Maxwell's displacement current a current?”, *The Physics Teacher*, **38**, 274, (2000).
25. French, A., “Newton's Thermometry: The role of Radiation”, *The Physics Teacher*, **31**, 310, (1993).
26. Devons, S., “The search for electromagnetic induction”, *The Physics Teacher*, **16**, 9, 625-631, (1978).
27. Brouwer, W., “Towards a more conceptual way of teaching physics”, *Physics in Canada*, **55**-61, (1995).
28. Lerner, L., *Physics for Scientists and Engineers,* Boston, Jones, and Bartlett, (1996).

RECOMMENDED FURTHER READING :

Stinner, A. (1980), “Physics and the bionic man”, *The Physics Teacher*, **18**(5), 352-362.

Stinner, A. & Winchester, I. (1981), “The physics of Star Trek”, *New Scientist*, **92**(1285/1286), 884-888.

Stinner, A. (1995), “Science textbooks: Their proper role and future form”, in S. Glyn & R. Duit (Eds.), *Learning science in the schools: Research reforming practice*, Erlbaum.

Stinner, A. (1998), “Linking ‘The Book of Nature' and ‘The Book of Science': Using Circular Motion as an Exemplar beyond the Textbook”, *Physics in Canada*, **Jan./Feb.**, 38-50.

Stinner, A. (2000), “Hitchhiking On An Asteroid: A Large Context Problem”, *Physics in Canada*, **Jan/Feb.**, pp. 27-42.