Connecting Research in Physics Education with Teacher Education

An I.C.P.E. Book

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I.S.B.N. 0-9507510-3-0 (English edition)

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General Editors

I.S.B.N. 0-9507510-3-0 (English Edition)
Published by The International Commission on Physics Education

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PREFACE

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The International Commission on Physics Education (ICPE) represents physics educators from many parts of the world who have a wide range of interests. As chairman, I am aware that the Commission makes demands on the time, the energy and the resources of its members. Such demands can be justified only if we can use our unique potential - for promoting international collaboration in order to support physics education across the world. This book is an example of what can be done.

For a work of this type to be produced, four conditions have to be satisfied. Three of these are:

- Occasions for people to meet -so that new ideas can germinate and be fashioned into workable plans.
- Networks - experts across the world have to know one another so that the world's best talents and expertise can be recruited for the task.
- Financial resources - to meet the costs of organisation and production.

The international conferences sponsored by the ICPE and the formal meetings of the Commission provided the occasions for the discussions out of which this book arose. They have also fostered the growth of a network of expertise which is the basis for this book's range of contributers. At the same time, the ICPE acknowledges its parent body, the International Union of Pure and Applied Physics, which has supported its work both financially and through the links with the world-wide community of physicists that it provides.

For finance for this book, the Commission was fortunate in obtaining generous support from UNESCO -we are particularly grateful the Organisation for this help, and to the French mission to UNESCO for their assistance in securing this support.

However, there is a fourth condition :

- A few persons with vision and energy - who will do all the hard work needed to turn the idea into a production.

This is the most important and difficult condition of the four. It has been met through the commitment of the three editors, Andrée Tiberghien, Leonard Jossem and Jorge Barojas, all of whom have also contributed in many other ways to the work of the ICPE. The main credit for this book's appearance belongs to them. I am sure that physics educators in many countries will come to be grateful, to them and to the many authors whom they have recruited, as they benefit from use of this unique and authoritative work.

As the editors make clear, whilst this book may mark the completion of one project, it should also signal the beginning of a longer term and continuing project of linking together researchers in physics education with those who train physics teachers. I hope that the ICPE, the editors and the many contributors to this book, and above all its readers will be inspired to work at this new project in the coming years.

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MAKING THE RESULTS OF RESEARCH IN PHYSICS EDUCATION AVAILABLE TO TEACHER EDUCATORS

Andrée Tiberghien, E. Leonard Jossem, Jorge Barojas
General Editors

A: Introduction

This book was undertaken on behalf of the International Commission on Physics Education (ICPE) of the International Union of Pure and Applied Physics (IUPAP) - with support from UNESCO - to make available the results of research in physics education world-wide to physics educators working with pre- or in-service physics teachers.

Contributors to the book have been drawn primarily from countries where research in physics education is most active, though, of course, considerations of size have prevented us from including more than a representative sample of the active workers in the field.

Organizing the book has been a challenge for several reasons. When a field of research is very recent, no more than 40 years in the case of physics education, there may be difficulty in finding many results which are directly useable in practice. Research in physics education is no exception. Moreover, we are currently in the process of differentiating among the practice of a discipline, the teaching of that discipline, and research on the teaching and learning of that discipline. This process of differentiation has reached different stages in different countries, and teacher educators play a central role since they have to utilize knowledge from each of the three domains: research in physics, research in physics education (didactics), and practical experience in teaching. Moreover, because of the relative newness of research in physics education, there is at present no strong world-wide consensus about a body of knowledge.

For all of these reasons, it is our intention to present different research approaches in order that teacher educators may become aware of the variety and richness of research in the field. To make these differences more explicit, we thought it useful and interesting to include in Sections C, D, and E, a commentary on each chapter written by the author of another chapter in that Section. It is our hope that this will provide a broader view of the state of current research.

The current state of affairs in research in science education tends to lead to the presentation of research results in a somewhat raw form, even with authors writing specifically for teacher educators. As it has already been noted about research results in any field, their transfer into practice is not necessarily straightforward. We consider this book as a starting point of an international cooperative effort to transfer the results of research in physics education to teacher educators and, at the end of this introduction, we discuss a proposal to develop this transfer process.

Organization of the book

In addition to this introduction the book comprises four other sections:

B. Perspectives on physics

C. Students' knowledge and learning

D. Teachers attitudes and practices

E. Curriculum development, assessment and teaching situations

In the well known didactic triangle, the three vertices: knowledge, students, and teachers interact in the framework
of an educational system (Figure 1).

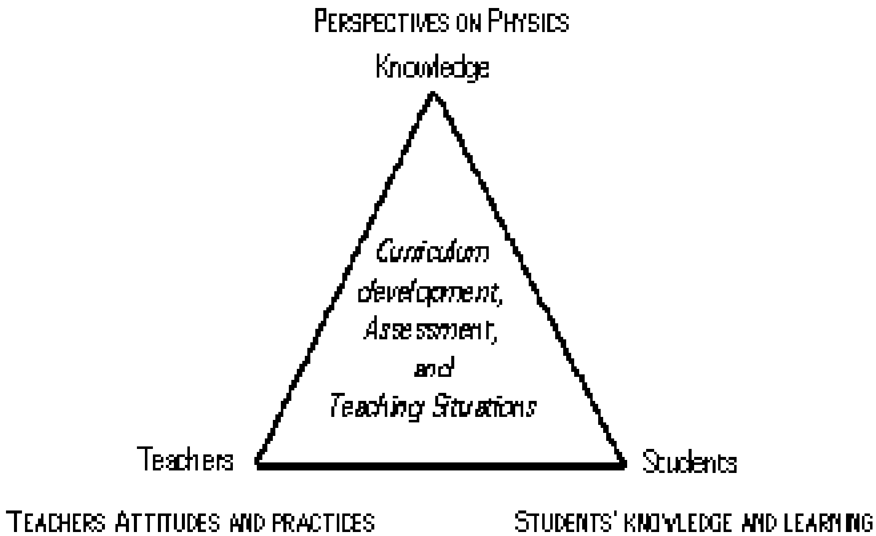

Figure 1: Relations of the parts of the book to the didactic triangle.

This triangle is a way of structuring the field of education from the perspective of teaching and learning in a specific field, which in our case is physics. Three of the four sections of the book are directly related to a vertex of the triangle, although interactions with the other vertices are taken into account. One part: "Curriculum development, assessment and teaching situations" deals simultaneously with all three vertices. This is perhaps closest to the way in which non-specialists view research in education; however it appears as the more difficult aspect to grasp.

The Sections of the book and their links

We consider first the sections of the book dealing with each vertex.

Perspectives on physics

Physics teachers have a unique practice of physics. As teachers, they have to "engineer" knowledge in order to teach it, i.e. to make it learnable by their students. Usually, they do not directly use the knowledge created by the researcher, but, rather, an intermediate knowledge which has already been reformulated. This knowledge has been the object of transpositions made under various constraints, e.g. the conditions of teaching, and the objectives of teaching (which depend on the choices of the society in which they live). Another constraint is that a physics curriculum has to be legitimized by the physics community. In such transpositions, the ways of looking at physics knowledge can be very different - although these differences are not explicitly involved in teaching practice. It seemed to us useful for teachers to have an appreciation of this variety of ways of viewing physics and the three chapters of Section B present three different aspects of physics knowledge.

Chapter B1, by A.P. French, presents physics as a structured body of knowledge: "how the consistent aim of physics is to relate our knowledge of phenomena to a minimal number of general principles".
In chapter B2, M.H. Krieger takes the point of view of a professional researcher in physics, a point of view which generally is not familiar to teachers. We know that it is difficult to establish communication between people of different professions - communication between academic research and industry is a frequently mentioned example - and that between teaching and research is no exception, unless they are practiced by the same person. It is in the interests of improving mutual understanding that this chapter has been introduced.
Chapter B3, by R.H. Stuewer, is devoted to the relations between the history of physics as viewed by physicists and as viewed by historians. These relations again show the difference between the presentation of a body of knowledge as it is usually done in a teaching process, and the process by which this knowledge was, in fact, created. The first case is based on a logical presentation of the material, while in the second case the complexities of human nature and human societies are in play. We hope that teacher educators and teachers themselves will become aware of these differences and question the apparent link between a logical presentation of physics and its effectiveness for learning.
Learning processes do involve human complexity, so in the didactic triangle the vertex "knowledge" refers not so much to a beautiful logical body of physics knowledge, as to a diversity of types of knowledge which play diverse roles in the teaching and learning processes.

Students' knowledge and learning

Section C is specifically devoted to studies of students' knowledge and learning. This domain of investigation is the oldest in physics education research, and the development of innovations in the sixties and seventies has produced as a side effect well developed research on students' difficulties with the conceptual aspects of physics, variously called "students' conceptions" or "alternate conceptions". The results of this research constitute an important body of available knowledge. The chapters in this section deal with mechanics (C1 by L.C. McDermott), electricity (C2 by R. Duit and C.von Rhöneck), and thermodynamics (C3 by L. Viennot), areas which are well developed and which are presented from recent points of view. Another chapter (C4 by R. Millar) addresses aspects of student understanding of procedures of crucial importance in physics, i.e. methods of scientific inquiry.

The results of these studies can be used directly in teacher education as Chapter C5 by P.H.Scott, H.M. Asoko, and R. Driver has shown. This is why this paper is included in this Section. This body of knowledge also plays an important role in research on curriculum, assessment and teaching situations.

Teachers attitudes and practices

Teachers, and, more generally, teaching activity, are rather recent subjects of physics education research. As a result of the work of researchers with different approaches to the subject we are beginning to comprehend the relations between teachers' beliefs about physics and about teaching and learning on the one hand, and the effectiveness of their teaching activities on the other hand, a domain of research which is of great interest to teacher educators.

In Section D Chapter D1, by R. Gunstone and R. White, is devoted to the links among teachers' attitudes, classroom practice, and students' attitudes. They show that teachers' attitudes, to be effective, have to be compatible with the aims of teaching established by the society, with the ways of assessment, and with students' attitudes. It is important to take into account that relations between teachers' attitudes and their effectiveness in teaching are complex.
Chapter D2, by S. de Sousa Barros and M.F. Elia, is concerned with establishing how physics teacher's attitudes affect the reality of the classroom.
The third chapter, D3, "About the epistemological posture of science teachers" by J. Désautles and M. Larochelle, is mainly centered on the teacher's relation to the science s/he has to teach. In Chapter D4, D. Gil Perez and A.M. Pessoa de Carvalho write directly on teacher education, the principal focus of this book.

Curriculum development, assessment and teaching situations

This Section which deals simultaneously with the three vertices illustrates how complex these objects of study can be. Perhaps it is for this reason that curriculum development has been object of many innovative projects. Instead of taking a detour through research, innovations aim to improve education directly; they are seen as direct answers to the difficulties in physics education.

As discussed in Chapter E1, by P. Lijnse, the innovations of the sixties and seventies in the USA and in several European countries are now being called into question; thirty years later the effect appears as quite small. Nowadays a variety of research programs are appearing which, considering the complexity of the subject, augurs well. However, it may seem surprising that this domain of research is not usually integrated as such into teacher education programs. For the most part we still are in a state of lack of clear differentiation between a professional activity - teaching, and another professional activity - research on the phenomena of teaching and learning. This lack of differentiation is heightened to the extent that teachers are the main actors in the process of modification of teaching situations. The activity of teaching is just starting to be the object of explicit knowledge, and so it can hardly, as yet, be an object of teaching in teacher education. We are at the very beginning of the process of an elaboration of such knowledge. In their papers in Section C, P. Lijnse, and P.H.Scott, H.M. Asoko, and R. Driver give some elements in this direction, making explicit the role of teachers.
M. Méheut in Chapter E3 and D. Psillos in Chapter E4 present good examples of research dealing simultaneously with the three vertices, and we see that we are moving in the direction of creating a body of knowledge very important for physics education.

In this section also, the aspect of assessment and evaluation has been included, since it is a crucial "regulator" of any teaching activity. This domain has been an object of research for a long time, and Chapter E2 by P. Black has caught the essential educational aspects of assessment, the variety of the roles they play, and their importance to the functioning of educational systems in our societies. It shows, also, the importance of teachers being aware of the need for enlarging the range of assessment methods used. This last aspect is crucial if educational systems are to keep pace with the rapid evolution of living styles in our societies.

Links between the Sections

One of the three vertices, physics knowledge, is involved in all of the presentations whereas the other vertices are not systematically considered explicitly, even if strong links exist.

However, knowledge is present in very different forms. In Section B, as we have already emphasized, the diversity of physics knowledge is involved. In Section C the analysis of students' conceptions leads us back to physics knowledge in order to understand what specific aspects are not only difficult but crucial for constructing physics meaning. Section D deals with teachers' views on physics knowledge and with the interplay between these views and their teaching practice. A teaching situation is a place of teacher-student interactions where physics knowledge and understanding is at stake. In Section E, physics knowledge is again involved in curriculum development, assessment and teaching situations i.e. in a social context. In the assessment perspective it is strongly emphasized that "public examinations have particular power over the future of physics".

These chapters show the variety of ways in which physics knowledge is taken into account in a teaching perspective. In the innovations of the sixties the physicist's view of the logical structure of physics were emphasized (cf. Steuwer, Chapter B3). In the research on teaching sequences, this logical structure of physics is not taken for granted. The "engineering" of knowledge to match students' learning capabilities and the essential aspects of the physics involved, is the result of compromises; it leads to choosing and organizing different aspects of physics in specific ways to match the needs of teaching at a specific level.

Physics knowledge is one of the main links between the sections, not as such, but as involved in interaction processes, either between persons - i.e. students, students-teachers - or between institutions - physics community, educational system, civil society. These interaction processes constrain the forms taken by the knowledge. Therefore it appears that interactions between persons and between institutions are also a crucial aspect of all chapters. Physics education is in its essence an interaction process which implies complex objects of study and complex professional practices; so we are involved in a difficult but fascinating area.

PERSPECTIVES

Nowadays, the evolution of our societies will probably lead to a considerable increase in the variety of educational situations, resulting in particular from new technologies of communication. This may pose a conflict between the long time-scale of achieving research results and the rapid evolution of teaching/learning situations. Do the research results remain relevant when the society evolves? Yes, if the research orientation takes into account, on the one hand the relevant aspects of human behavior, and, on the other hand, an analysis of teaching situations in terms of parameters which can influence students' activities. In other words, the aim is to establish relevant possible components of teaching situations which play a role in the activities of the students. In that case, the results may be transposable among different teaching situations, or may provide a good hypothesis for designing new situations. We believe that relevant research in such a social context requires the development of relations between research and practice, relations which will be all the more productive as these two activities are distinguished. This is why we consider this book as a starting point of a continuing discussion between teacher educators and researchers. The links between research in physics education and teacher education are crucial for both the relevance of research and the effectiveness of education.

It is for these reasons, also, that we are establishing an Internet site for a discussion group in three languages : English, French, Spanish. The main aim of this group discussion is to exchange ideas, research results and practices in physics education. We consider it as a tool to improve physics education both from the research point of view and from the professional point of view. Interactions between them are crucial to developing research and to improving teaching practice.

Finally, the editors wish to express their appreciation and thanks to the contributing authors of this book, and to all of those whose assistance and encouragement have helped to make it possible.

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THE NATURE OF PHYSICS

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INTRODUCTION

The world is full of experiences that cry out for explanations. Think, for example, of the colors of rainbows and soap bubbles, the vapor trails of high-flying aircraft, the fact that liquid water abruptly changes into solid ice at a certain temperature, the production of lightning and the thunder that follows it in a storm, the beautiful hexagonal symmetry of small snowflakes; all these, and a limitless list of other phenomena, fall within the province of the science of physics. The essence of science in general is the observation and exploration of the world around us with a view to identifying some underlying order or pattern in what we find. And physics is that part of science which deals primarily with the inanimate world, and which furthermore is concerned with trying to identify the most fundamental and unifying principles. The first of these conditions -- restriction to the inanimate world -- separates physics, at least provisionally, from biology; the second separates it from chemistry, which, at least in its theoretical aspects, builds on some specific areas of physics but can ignore some others. Mathematics, of course, although indispensable to the practice of physics, is an entirely different field of study, since it is self-contained and is ultimately independent of observations of the real world.

The subject of this article could be approached in many different ways. One way of obtaining some insight into the nature of physics is to look at the story of how physics has developed from its beginnings until now. That is what this article does, although it makes no attempt to be exhaustive and omits many topics that some might consider important or even essential. Its main purpose is not to offer a chronological survey for its own sake, but just to illustrate how the consistent aim of physics is to relate our knowledge of phenomena to a minimal number of general principles.

ARCHIMEDES AND THE LEVER

It can be plausibly argued that physics began with mechanics -- the science of machines, forces and motion. There has always been a close link between physics and practical devices, and this connection was already established in mechanics in ancient times. The best example is perhaps the lever, the principle of which was recognized by Archimedes about 250 B.C.: "...unequal weights are in equilibrium only when they are inversely proportional to the arms from which they are suspended." Here, in a simple case, was a theoretical statement, a generalization of particular experiences, of the kind that typifies the nature of physics. This result may have been the first example of an actual physical law. It became the basis of a weighing device -- the steelyard or Roman balance (Fig. 1) -- that has been used since Roman times and is still in use today. It is worth taking this example a little further. Presumably the balancing of unequal weights was initially an empirical matter. Then Archimedes produced his quantitative and general statement of the relationship. But he was not content with this, and he sought to base it on one of the most powerful concepts used by physicists -- that of symmetry. Archimedes took it as axiomatic (and certainly easily verifiable) that equal weights (W) at equal distances (l) from the pivot (the fulcrum) were in balance. He then imagined one of these weights being replaced by two weights of magnitude W/2, one at the fulcrum and the other at a distance $2l$ from the fulcrum. Since the first half-weight would clearly exert no turning effect about the fulcrum, he argued that it was obvious that W/2 at $2l$ would balance W at l, and that the general law of the lever could be inferred from an extension of this argument.

Fig. 1. A Steelyard medal struck for Frederick I (1688-1713)

The argument is in fact not valid. If the law of the lever were $W_1 l_1^2 = W_2 l_2^2$, it would still be true that equal weights at equal distances would balance, but it would not be true that W/2 at 2*l* would balance W at *l*. The correct law had to be based on actual observations with unequal weights. Nevertheless, an appeal to symmetry, where it is justified, is an extremely fruitful tool, as we shall see.

ARISTOTLE TO GALILEO: SPACE, TIME AND MOTION

Even before Archimedes and his work in mechanics, Aristotle (384-322 B.C.), who introduced the Greek word for physics into our vocabulary, had considered the motion of bodies. Certainly, space and time have traditionally been the most fundamental concepts in our view of nature, and position as a function of time has always been the basis of our description of motion. Aristotle discussed these matters, but he made a distinction between what was viewed as the perfect circular motion of stars, etc. (actually, of course, a reflection of the earth's rotation on its axis), and the imperfect trajectories of objects at the Earth's surface. But it was clear that, when it came to physics, Aristotle did not study phenomena at first hand. He made the famous assertion that "a weight which is twice as great will fall from the same height in half the time" -- something that could have been disproved by a single experiment. The Middle Ages saw a number of investigations of motion of projectiles, but it was not until the 17th century that Galileo (1564-1642) established by a combination of experiment and theory the correct picture of free fall and the parabolic motion of projectiles. I mention this not for the sake of the particular result, but because it points to another essential feature of physics -- the dependence on direct observation or experiment. Without such direct interaction with Nature, we could not have a science of physics. It has often been said that such observational or experimental evidence is the starting point from which all physical theories are constructed, but this, I think, is going too far. All that one can justifiably say is that the progress of physics depends on a continuing interaction between experiment and theory. It may well be that a theory comes first, and suggests the possibility of experimental tests by which it will either be supported or discredited. It has never been the case that a given set of observations points uniquely to a fundamental theory that accounts for them, although it may be true that experiment points uniquely to a particular connection between observed quantities -- e.g., distance proportional to the square of the time in free fall under gravity (but that is not a theory of gravitation).

COLLISIONS AND THE FIRST CONSERVATION PRINCIPLES

The first great flowering of physics came, as is well known, in the 17th century, and its basis was the study of the collisions between objects. It was Isaac Newton (1642-1727) who first realized that the results of all such experiments were consistent with a single conservation principle -- the conservation of linear momentum.*

* Others (including Descartes) had contributed to this principle in a less complete or correct way. Newton had the genius or good fortune to use it as the basis of his mechanics.

This, by itself, did not explain in detail the results of every possible type of collision. Nevertheless, the conservation of total momentum (mv) was never violated in the collision of two objects. The statement of this principle involved two important concepts:

1 The concept of *mass*, defined in a somewhat intuitive way as the *quantity of matter* in a body;

2 The concept of a physical *frame of reference*, with respect to which the velocity of other objects could be measured, and which could be taken, in these early experiments (and even in similar experiments today) as being provided by the seemingly immovable body of the Earth.

Both of these concepts have been subjected to much discussion and refinement since those early days, but this fact illustrates another very important aspect of the nature of physics -- an acceptance of working hypotheses that are quite adequate at a particular stage in the development of the subject, but which are always liable to later modification. Thus, for example, it was well known, even in the 17th century, that the Earth was not stationary, but was rotating on its axis and orbiting around the Sun, but both of these facts could be ignored in the analysis of laboratory-sized experiments on collisions. Only when larger-scale motions were involved did these facts become relevant; to introduce them at the beginning would make for unnecessary and obstructive complications.
Another important but less general conservation principle was recognized at about the same time as the conservation of momentum. It was limited to what are called *elastic collisions*, in which two colliding objects recoil from one another as vigorously as they approach. If one considers a collision along a straight line between two objects of masses m_1 and m_2, and if one denotes their initial and final velocities by u_1, u_2 and v_1, v_2, then the conservation of momentum is expressed by the equation: $m_1u_1 + m_2u_2 = m_1v_1 + m_2v_2$. This held good whether the collision was elastic or inelastic (less than perfect rebound). But, if the collision was elastic, it was also true that the following relation held: $m_1u_1^2 + m_2u_2^2 = m_1v_1^2 + m_2v_2^2$.

With the further development of mechanics, it came to be recognized that this second relationship was an expression of the *conservation of kinetic energy* in elastic collisions, where the kinetic energy of a body was later defined as $mv^2/2$, not mv^2, for reasons that we will not go into here.

In addition to these conservation principles, another fundamental physical principle applicable to collisions was recognized by Newton's great contemporary Christian Huygens (1629-1695). This was what we would now call the equivalence of different frames of reference. Huygens considered an elastic collision between two equally massive spheres with equal and opposite velocities (± v). He argued that, by symmetry, they would recoil with their velocities reversed. He now imagined such a collision taking place on a boat that was itself moving at velocity v with respect to the shore (Fig. 2). If this collision were observed by a man standing on the river bank, he would see it as a collision between a stationary sphere and one moving with velocity 2v. Or, if the boat were moving with speed u, the initial velocities of the spheres would be u + v and u - v. In both cases the velocities as seen by the man on the bank would be interchanged by the collision. In other words, on the basis of the original symmetric collision one could predict the results of all collisions between these two objects occurring with the same relative initial velocity.

Figure 2. An elastic collision between two spheres as seen from two different reference frames. (From C. Huygens, Oeuvres Complètes, Vol. 16, The Hague: Martinus Nijhoff, 1940). (The diagram above the sketch was added by Ernst Mach in his book, The Science of Mechanics.)

Underlying all these phenomena was another condition, never explicitly stated. This was that the total mass of the objects involved in a collision remained constant -- the principle of the conservation of mass. This was taken for granted in these physical systems, but an explicit statement of the *conservation of mass*, based on direct experiment, did not come until more than a century later, in chemistry, when Antoine Lavoisier (1743-1794) established it for chemical reactions, involving much more drastic rearrangements of matter than did the collision experiments of Newton's contemporaries.

This is by no means the last we shall hear of conservation principles, but before continuing on that path we shall consider some other matters.

CAUSE AND EFFECT: NEWTON'S SECOND LAW

Observers of the physical world have always been interested in discovering or recognizing the causes of things. Perhaps the most famous example of this is the modern mathematical statement of Newton's second law of motion -- $F = ma$. On the left is the force; on the right is the mass multiplied by the acceleration produced in it by the force. In other words, the left side is interpreted as a cause, and the right side as the effect produced by that cause. The two sides of the equation do not play equivalent roles. This is a feature that one does not find in the equations of mathematics. Nor are all physics equations of this type. For example, what is probably the most famous equation in all of physics -- Einstein's $E = mc^2$ -- is a simple statement of the equivalence of mass and energy. But when a physical equation is the expression of a cause/effect relationship it assumes a special significance.

CLASSICAL PHYSICS EXPANDS

During the two centuries after Newton, the scope of physics grew enormously. Already in his time the science of optics was well developed, and Newton himself was a major contributor to it. But then, during the 18th and 19th centuries, the knowledge of the physical world expanded to include such areas as heat, sound, electricity, and magnetism. Initially these, as well as mechanics and optics, were seen as separate fields of study, but then something very important happened: connections between them began to be perceived. Sound, for example, came to be understood as the mechanical vibrations of air columns, strings, and so on, and heat as the chaotic mechanical motions of atoms and molecules (for, although atoms as such could not be observed, there was a confident belief in their existence). Along with this came a great enlargement of the concept of energy and its conservation. It came to be realized that, when mechanical energy apparently disappeared -- as for example in the inelastic collision of two objects -- one could account for the loss in terms of a transfer to the thermal energy of the colliding objects, as expressed in an increase of their temperature. Thus *conservation of energy* came to be seen as a general principle, although the extension of it to electricity and magnetism did not happen immediately.

Early in the 19th century, connections between the phenomena of electricity and magnetism were discovered: the flow of electric charge through a wire caused magnetic effects, and a changing magnetic field could produce a current in a closed loop of wire. And then, toward the end of the century, the great physicist James Clerk Maxwell (1831-1879) showed how, by uniting the equations that described electric and magnetic fields, he could account for the transmission of light through space at the amazing speed of about 3×10^8 meters per second -- a value that was already known from experiment.

The net result was a tremendous *unification* of physics. For many years it had seemed that the diversity of physical phenomena was expanding almost without limit as new discoveries were made. Then it came to be seen that the divisions traditionally made between different areas of physics were really the result of our ignorance of their fundamental interconnections. As a matter of convenience, but perhaps unfortunately, these different areas continued to be treated for the most part as separate fields of study, and textbooks continued to be divided up accordingly. This was not very serious, however, as long as it was recognized that, in a fundamental sense, physics was a single discipline.

THE NATURE OF LIGHT

One of the main goals of physics is to develop plausible conceptual models, as they are called, in terms of which various physical phenomena can be described and explained. Perhaps the outstanding example of this is the attempt to find a successful model for the phenomena of light. According to some of the ancient Greeks, our ability to see an object depended on the emission of something from the eye -- an idea that should have been easily disprovable by experiment (for example, the invisibility of an object in a darkened room). Others, more plausibly, thought that an object became visible by virtue of particles of some sort emitted by the object itself. The production of sharp shadows by a small luminous source led naturally to the picture of light as consisting of particles traveling in straight lines from a source or from an object illuminated by it. This model was reinforced by the discovery of the law of reflection of a beam of light at a plane mirror -- angle of reflection equals angle of incidence. Newton favored and supported this particle model. But his contemporary Huygens devised and promoted a very different model -- that light consists of waves traveling through a medium. He considered that the immense speed of light, and the ability of beams of light to pass through one another without any interaction, were evidence against light being composed of material particles. Also he thought that vision must depend on the retina of the eye being shaken by the light. He was able to explain the rectilinear propagation of light as arising from the superposition of circular or spherical waves that originated from different points on the advancing wave-front of a beam.

It seemed obvious at the time that the particle and wave models of light were mutually exclusive. Thanks primarily to the great authority of Newton, the particle model became generally accepted, and remained unchallenged for about 100 years. But then something very astonishing happened. In about 1801 Thomas Young (1773-1829) showed that a beam of light, if divided into two overlapping beams, showed the phenomenon of *interference* -- the production of alternating bright and dark regions on a screen placed to receive the light (Fig. 3). The appearance of dark regions -- destructive interference -- was inconceivable on a particle model; how could one particle of light be annihilated by another? Thus the particle model of light was abandoned, and evidence supporting a wave model of light continued to accumulate during the remainder of the 19th century. The culmination came when, as mentioned in the previous section, Maxwell showed that he could account for the propagation of light as an *electromagnetic disturbance* passing through a medium that was called the ether, and that was conceived as filling all space. The triumph of a wave model of light seemed complete and permanent, but this was not to be. What had been assumed to be a simple case of either/or turned out to be something much more surprising and mysterious, as we shall discuss shortly.

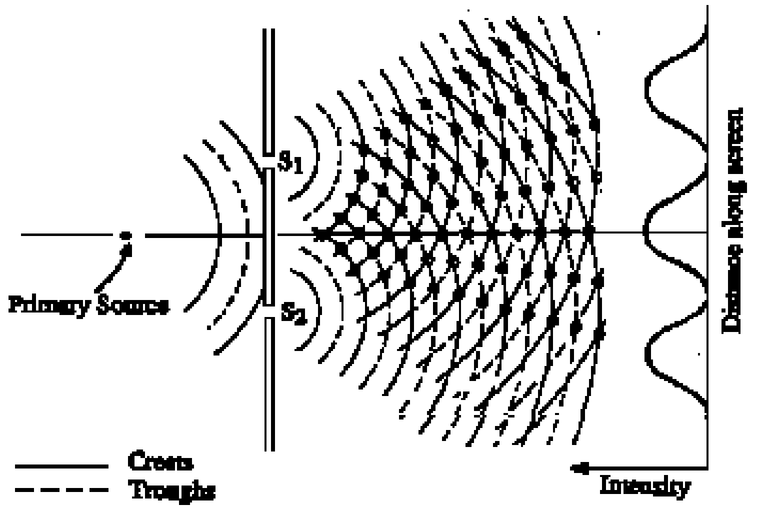


Fig. 3. A schematic diagram of Young's two-slit interference experiment. Places where the waves from the two slits reinforce are shown by black dots, places where they cancel are shown by open circles. The interference pattern has a central maximum and other maxima on each side. In practice the wavelength of the light is very small indeed compared to the spacing of the slits; this means that the interference fringes are extremely numerous and very close together.

PANDORA'S BOX BREAKS OPEN

As the 19th century approached its end, the physicists of the time felt that physics was almost a completed subject. Its primary ingredients were absolute space and time, the causal laws of mechanics, electricity and magnetism (embodying a wave model of light), and a picture of matter as consisting of discrete and indivisible particles obeying these laws. But such complacency was about to be shattered. In the space of less than 10 years came radioactivity, the discovery of the electron, the quantum of energy, and special relativity; each of them, in its way, called for a drastic revision of our picture of the physical world.

a) Radioactivity

This phenomenon, discovered in 1895 by Henri Becquerel (1852-1908), had as its chief feature the spontaneous emission of various kinds of previously unknown radiations from certain of the heaviest atoms known to chemistry. The source of these emissions and their energy was a great puzzle, and it was at one stage suggested that the principle of the conservation of energy would have to be abandoned. Further research showed that this was not necessary, but an even more precious principle had to be sacrificed: the unique relation of cause to effect. For it came to be clear that, in a group of identical radioactive atoms, the times at which they underwent a change to a different kind of atom were quite random; there was nothing, so far as could be discovered, that caused a particular atom to undergo a radioactive change at a particular time; the atoms decayed spontaneously and independently. This was established in an experiment by Ernest Rutherford (1871-1937), the dominant figure in the early days of nuclear physics. But physics did not cease to be an exact science with immense predictive power. We shall have more to say about this later.

b) X Rays and the Electron

During the last decade of the 19th century, much research was focused on the subject of electric discharges in gases at low pressures. This became possible, in large part, because of the development of efficient ways of producing vacuum -- a good example of how advances in technology directly affect the progress of fundamental physics. A whole range of new phenomena came into view. Perhaps the most dramatic of these was the discovery of x rays by Wilhelm Conrad Roentgen (1845-1923). The ability of these rays to penetrate the human body and expose its internal structure was quickly exploited. At first the nature of these rays was a mystery, but after a few years it was established that they were electromagnetic waves, like light but of a much shorter wavelength (by a factor of about 1000). But behind these x rays lay something destined to have a much greater influence on the course of physics. They were produced by the impact on a solid "target" of so-called *cathode rays*, emitted from a negatively charged electrode in an evacuated tube. What were these cathode rays? It was Joseph John Thomson (1856-1940) who found that they were negatively charged particles with a far smaller mass, in relation to their charge, than any particle previously known. In fact, if one assumed that the size of their charge was equal to that of a hydrogen ion in electrolysis (a proposition that was verified by experiment later) their mass was less than 1/1000 of the mass of a hydrogen atom. Furthermore, their properties did not depend at all on the material used as the cathode (negative electrode) from which they came. The implication was that all atoms had an internal structure that included these novel particles, which of course we know today as electrons. The old idea of atoms as indivisible (the Greek basis of their name) was gone forever. The question naturally arose: what other constituents went into the structure of atoms, which were electrically neutral? That question was not properly answered for more than another 10 years, when Rutherford found that the positive part of the atom was a nucleus smaller in diameter by a factor of about 10,000 than the atom as a whole. We shall return to that development in the next section of this article.

c) The Quantum

A general acquaintance with the radiation from hot objects is as old as mankind, yet a full understanding of its properties did not come until the dawn of the 20th century. Well before then, it had come to be realized that radiant heat was a form of electromagnetic radiation, which became visible when an object was sufficiently hot but also included radiation at much longer wavelengths. The spectrum of such radiation (intensity versus wavelength) for a body at a particular temperature was a rather uninteresting-looking curve (Fig. 4), whose peak shifted to shorter wavelengths as the temperature of the radiating body was raised. Attempts to explain this spectrum in terms of the basic classical theory of electromagnetic radiation-- a well understood theory -- did not work at all well.

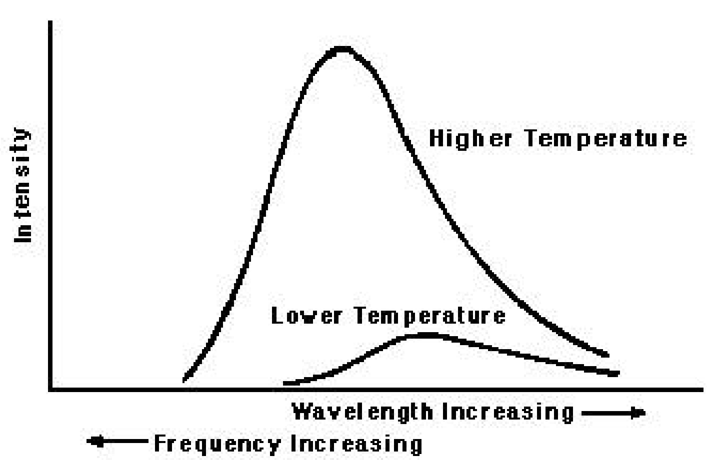


Fig. 4. A qualitative graph of intensity versus wavelength or frequency for the radiation from a hot body. As the temperature is raised, the overall amount of radiation increases and the peak shifts toward shorter wavelength (higher frequency).

The German physicist Max Planck (1858-1947) set himself the task of finding a better fit. To his surprise and chagrin, he found himself driven to the conclusion (in 1900) that energy from a hot body could only be released in discrete amounts, proportional to the frequency (inversely proportional to the wavelength) of the emitted radiation, according to the formula $E = hf$, where f is the frequency and h is what quickly came to be known as Planck's constant. Thus the *quantum* was born. Planck shrank from proposing that the radiation itself was quantized -- the classical wave theory of light still stood supreme -- but Albert Einstein (1879-1955) advanced this hypothesis in what he called a heuristic way (something that works but may not be the last word) in 1905. Its consequences were very far-reaching; we shall come to that later.

d) Relativity

The discoveries in atomic physics and radiation were enough to shake classical physics to its core, but more was to come. Ever since the time of Newton, it had been accepted that space and time were absolute, even though Newton himself acknowledged that we could not identify absolute space and had to content ourselves with the study of relative motions. But then, in 1905, Einstein came forward with his revolutionary proposal that neither time nor space was absolute, that they were related to one another, and that both depended on measurements made with respect to a chosen frame of reference, which had to be identified. This meant, in particular, that one could not state categorically that two events occurring at different places were simultaneous; the judgment as to whether they were simultaneous or not depended on the frame of reference that one was in.

This theory -- *the special theory of relativity* -- is not basically difficult or complicated; in a simplified form, it can be presented with nothing more than high-school algebra. Its challenge is a conceptual one, because it requires us to abandon intuitive ideas that all of us grow up with. It is no trivial matter to make such an adjustment, but it soon became clear to Einstein's contemporaries (at least, to many of them) that the new theory had a predictive power that could not be denied. The slowing down of a clock that is in motion with respect to us, for example, might seem to be science fiction -- and in the form of the "twin paradox" with a human traveler staying young, while his brother on Earth gets old, it is; nevertheless, the basic effect has been directly confirmed by observations using precise atomic clocks transported around the Earth in commercial jet aircraft.

One aspect of relativity that was particularly troubling to the traditionalists was its denial that there existed a single preferred frame of reference. Such a frame was assumed to be defined by what Huygens called the ether -- the hypothetical medium that was deemed to be essential as the carrier of light and all other kinds of electromagnetic waves. The notion of waves that did not require any material medium to carry their vibrations was regarded as an absurdity. But the failure of all experiments to detect the motion of the Earth through this medium was one of the important supports for the correctness of Einstein's ideas. Physicists had to get used to the idea that electromagnetic waves did not need a medium to wave in; this picture was required only if one demanded a purely mechanical model of the wave propagation. In the latter part of the 19th century, much effort was expended on creating such mechanical models, until Einstein made them superfluous.

THE NUCLEAR ATOM

By the beginning of the 20th century it had come to be accepted that atoms were objects with diameters of the order of 10^{-10} m. Prominent among the reasons for this belief was the knowledge of the value of Avogadro's number -- the number of atoms or molecules in a mole of an element -- which had been inferred from such phenomena as the viscosity of gases, and which also emerged from Planck's theoretical analysis of thermal radiation. (Notice once again the interconnectedness of physics!) Assuming that in materials such as metals the atoms were closely packed together, it was just a matter of geometry to deduce the approximate diameter of an individual atom.

After the electron had been discovered and the magnitude of its electric charge known, classical electromagnetic theory could be used to deduce that its diameter was of the order of 10^{-14} m.*

* In modern theoretical models, this particular value is no longer accepted. The electron is treated as a point particle.

Given this number, together with the fact that electrons accounted for only about 1/10,000 of the mass of an atom, it was natural to picture the atom as a ball of positively charged material with a diameter of about 10^{-10} m, with the almost point-like electrons embedded in it. This was the model that J. J. Thomson himself invented. There were various problems with this model, however; one of them was its inability to account for the wavelengths of the light emitted by atoms.

Then, in 1911, the situation was completely turned around when, as mentioned earlier, Ernest Rutherford discovered, from the violent deflections suffered by alpha particles (ionized helium atoms) fired at thin metal foils, that most of the mass of an atom of materials such as gold or silver was concentrated within a radius of about 10^{-14} m.

Building on this discovery, Niels Bohr (1885-1962) in 1913 proposed his famous model of the atom as a kind of miniature solar system, with electrons orbiting like planets around the positive nucleus. Nobody appreciated better than Bohr himself that it was a very arbitrary model. He simply postulated, without any theoretical justification, that electrons in their orbits emitted no light (which classical electromagnetic theory would have required them to do). He also proposed, with an ingenious use of Planck's idea of the quantization of energy, that these orbits were limited to a discrete set of radii. It was really a thoroughly makeshift theory -- but it worked! It accounted triumphantly well for the known spectrum of light emitted by hydrogen atoms, and predicted other sets of hydrogen lines (in the ultraviolet and infrared) that had not previously been observed.

The theory did, however, have serious limitations. It had little success in explaining spectra other than those of hydrogen and so-called "hydrogen-like" systems -- those with only one outer electron to produce the radiation, such as certain positive ions. It was clearly not the last word. It is an interesting fact that Bohr, like Planck before him, did not believe that the light itself was quantized, until he was finally convinced, many years later, by direct experimental evidence of collisions between light quanta and electrons (the Compton effect).

WAVE/PARTICLE DUALITY

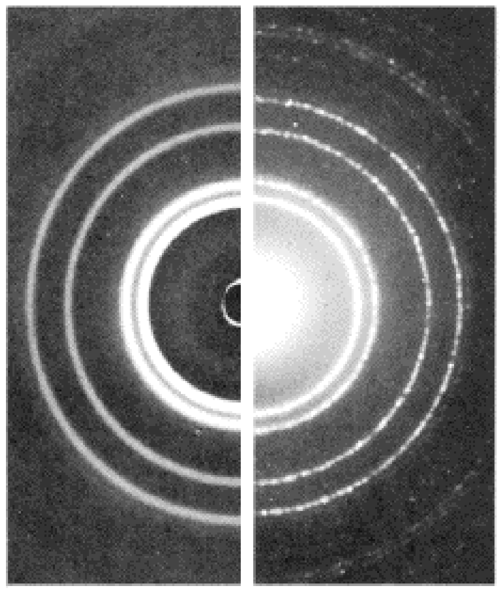
We have seen how people's ideas about the nature of light oscillated between a particle model and a wave model. It had seemed axiomatic that these two models were mutually exclusive. Certainly the wave properties of light could not be denied. But then, early in the 20th century, experiments were made on the photoelectric effect -- the ejection of electrons from metals by light -- that were consistent with Einsein's proposal that the energy of light was emitted and absorbed in minute packets -- *quanta* -- that came to be called *photons*. In other words, light had properties that embraced those of both particles and waves. This was a totally new idea.

Then, about 20 years later, Louis de Broglie (1892-1987) went one step further, and made the complementary suggestion that electrons, which had been unequivocally accepted as particles, might have wave-like properties, with a wavelength equal to h/p, where h is Planck's constant and p is the momentum mv. Within a few years this, too, was confirmed. Electrons of a specific energy were diffracted by crystal lattices in just the same way as x rays (Fig. 5). In other words, our accepted categorization of the basic elements of the physical world ceased to apply at the atomic level. In fact, at this level our ordinary language, with all its customary associations, simply broke down. It was necessary to accept a photon or an electron simply for what it was, defined not by words of our own making but by its behavior.

Before long it was discovered that every kind of physical object that had been labeled as a particle -- neutrons and protons and every kind of neutral atom or molecule -- also had this wave property, with a wavelength given by de Broglie's formula.

THE WORLD OF QUANTUM PHYSICS

The randomness of radioactivity and the wave/particle duality could simply not be fitted into the framework of classical physics, yet it was clear that the classical picture worked very well for many purposes. What was to be done? The answer was soon provided by two brilliant theorists, Werner Heisenberg (1901-1976) and Erwin Schroedinger (1887-1961). In 1925-26, using very different approaches, which were not at first recognized as equivalent, Heisenberg and Schroedinger created the new science of *quantum mechanics.*



X-rays ....electrons

Fig. 5. A pair of photographs showing the diffraction of electrons and x-rays of similar wavelength. These ring patterns are obtained when a beam of electrons or x-rays passes through a thin foil made up of small crystals of a material (aluminum) oriented randomly in all directions. The diffracted waves (particles) are received on a photographic plate on the other side of the foil. (After A. P. French and Edwin F. Taylor, Introduction to Quantum Physics, New York: W. W. Norton. 1978.)

The approach taken by Schroedinger is the easier one to appreciate, and builds directly on the wave/particle duality we have just described. By accepting the wave character attributed to particles by de Broglie, Schroedinger was able to construct an equation that led to the solution of a vast range of atomic problems. (This version of quantum mechanics is called *wave mechanics*.) There were strong similarities to acoustics. We know that, in the open air, sound of any wavelength or frequency can be transmitted, but in an enclosed space, such as the interior of a room or the body of a wind instrument, only certain wavelengths and frequencies are possible. Similarly, in empty space electrons of any wavelength are possible, but the interior of an atom is like an enclosure, with rather soft walls defined by the attraction of the positive nucleus for the electrons. Electrons of less than a certain energy cannot escape, and such electrons are restricted to certain discrete energies. The results of Bohr's theory of the hydrogen atom emerged naturally and automatically from this model, and it was applicable to many other atomic systems.

There remained a basic question: What are these waves? This question has most often been discussed in the context of an analog of Thomas Young's first two-slit experiment on the interference of light. One can imagine a similar experiment being done with electrons (in fact, 35 years after wave mechanics was invented, such an experiment was performed). Whether the experiment is done with light or electrons (or other particles) the main features are the same.

Let us discuss it in terms of light, since this is universally accessible, whereas electron beams are not. If the intensity of the light is high, one gets a classical wave interference pattern, with smooth variations of intensity between maxima and minima as measured, for example, on a photographic light meter. But if the intensity of the light is reduced to an extremely low level, and if the light meter is replaced by an extremely sensitive device that can detect individual photons (a photoelectric multiplier tube) then an amazing result emerges. The experiment can be done under such conditions that only one photon passes through the apparatus at a time. It arrives at a particular point on the detector screen -- that is, it is detected as a particle. Its point of arrival on the screen is completely unpredictable. However, if millions of photons pass successively through the system the distribution of the individual impacts builds up to the classical interference pattern. The key point is that each photon, in some sense, is passing through both slits of the apparatus and interfering with itself; that, at least, is the simple-minded way of accounting for the results of the experiment. Does this mean that the photon literally divides? The answer is no; something more subtle is involved.

If one tries to discover which slit the photon passes through, the interference pattern disappears. To describe such phenomena, Bohr introduced the concept of what he called *complementarity*. The wave and particle aspects of photons are complementary. Photons are detected as particles, at a particular point, but their motion from source to detector is described by a wave equation. It was Max Born (1882-1970) who proposed that Schroedinger's waves are waves of probability (or, to be more exact, of probability amplitude, the square root of a probability). Despite many subsequent developments, this interpretation has stood the test of time. It is a strange result that raises many questions, as every physicist acknowledges. Among other things, it points to the very close association between physics and mathematics -- a phenomenon that was the subject of an essay entitled "The Unreasonable Effectiveness of Mathematics in the Natural Sciences" by the distinguished theorist Eugene Wigner (1902-1995).

One further comment is appropriate here. Phenomena such as radioactivity and the double-slit interference experiment show that individual events on the atomic scale can have a random property. Does this mean that physics has ceased to be an exact science? The answer is "No"! The development of classical physics had led us to believe that all kinds of individual events are subject to strict causal laws. Quantum phenomena have forced us to recognize that this is not true. But it remains true that the statistical behavior of large populations of identical atomic systems is rigorously predictable. This is not in itself a novel idea, although its importation into basic physics is new. We are all familiar with the fact that the properties of large populations of humans are amenable to precise descriptions and predictions, although what happens to individuals may not be. Thus, for example, insurance companies can base their business on a very well defined knowledge of the distribution of human lifetimes, although the fate of a single person is completely unpredictable. But the statistical predictions of quantum physics are more exquisitely precise than anything in human affairs.

INSIDE THE NUCLEUS

We have long been familiar with the fact that the basic constituents of atomic nuclei are what are called *nucleons* -- protons and neutrons. The proton, the nucleus of a hydrogen atom, had been known since about 1910. The existence of its partner of approximately equal mass, the neutron, was suggested by Rutherford in 1920 and was established experimentally by James Chadwick (1891-1974) in 1932. Shortly after this the new field of nuclear theory came into existence and proceeded to grow at a rapid rate. It was quickly recognized that a hitherto unknown type of force was involved. It is rather astonishing to realize that, until nuclear forces were introduced, all of the physical phenomena known up to that time were explainable in terms of only two basic kinds of force -- gravitational and electromagnetic. Gravity, intrinsically an extremely weak force, becomes important only when exerted by very large bodies, such as the Earth. All other forces could be described in terms of electric and magnetic interactions. Nuclear forces are of extremely short range -- their effect scarcely extends beyond the boundary of an atomic nucleus and so plays no role at all in the interaction between different atoms. It is only in circumstances completely beyond our own experience -- at the centers of stars and, even more, in such objects as neutron stars, consisting of close-packed nucleons -- that nuclear forces play a central role. It came to be recognized that there are two types of nuclear force, labeled simply as *strong* and *weak*. The strong force is what holds the protons and neutrons in a nucleus together, against the electrical repulsion of the protons; the weak force is the agent behind some forms of radioactive decay. We shall not consider either of these forces in any detail here; it is enough to know that they exist.

Once the picture of nuclear structure in terms of neutrons and protons was well established, the attention of many physicists turned to the next step down the ladder -- the possible internal structure of the nucleons themselves. The quest entailed the construction of bigger and bigger particle accelerators, acting as sources of more and more energetic particles -- such as electrons -- as probes. A primary reason for this need for ever increasing energies resides in the de Broglie relation: wavelength equals Planck's constant divided by momentum. Modern particle accelerators are like microscopes for the study of objects smaller by many powers of l0 than anything that can be examined in an optical microscope. To do this requires wavelengths smaller than that of visible light by a similar factor, and the only way to achieve this is to increase the momentum and hence the energy of the probing particles. This research at first generated what seemed like an unlimited list of new and exotic (and short-lived) particles, most of which were clearly not basic building-blocks of nuclear matter. But then, in l964, the proposal was made that nucleons were composed of triads of *quarks* -- a name given to them by their inventor, Murray Gell-Mann (1929 -). The consequences of this theory were far-reaching, and extended well beyond the internal constitution of nucleons. Essentially all the known "heavy" particles (i.e., other than the electron and its relatives, such as the neutrino) could be pictured as combinations of either two or three quarks. Sophisticated symmetry arguments were involved in all this analysis, which led to the prediction of a previously unobserved particle, a kind of excited state of a nucleon. Successful prediction such as this is, as we have said before, an important criterion for a good theory.

THE REALM OF CONDENSED MATTER

There is, of course, much more to physics than the search for new fundamental particles. Indeed, the number of people doing research in this area is probably quite small compared to the number who have been engaged in various aspects of what goes under the name of *condensed matter physics* -- primarily the physics of solids. Until the invention of quantum theory, the properties of solid materials -- for example, whether they were transparent or opaque to light, whether they were electrical conductors or insulators -- were just a matter for empirical study. This does not mean that the field was largely unexplored. Indeed, for crystalline solids in particular the use of x-rays had led to a very detailed and accurate picture of the arrangements of the atoms. But the reasons for their physical properties were largely a mystery. The application of quantum ideas changed all that.

The first calculations in quantum mechanics had been of the energy states of electrons in individual atoms. The next step was to consider how those energy states would be changed as assemblies of similar atoms were brought more and more closely together. It was discovered that, when this was done, some fraction of the electrons would no longer be attached to a particular atom but would be shared over the whole extent of the assembly. In some cases this would mean that the assembly would become a good electrical conductor, in others it would be an insulator. And there were intermediate cases -- the *semiconductors*. It was realized that these properties were controllable through the addition of other types of atoms -- what is called *doping*. Out of this came the transistor, and then the whole science of solid state electronics, which now dominates our communications and computer technology. The transistor was invented in 1947 by John Bardeen (1908 - 1991), Walter Brattain (1902-1987) and William Shockley (1910 - 1989).

Another important area of condensed matter physics is that of low temperatures. Whereas the nuclear and particle physicists were concerned with exploring the properties of matter at higher and higher energies, the low-temperature physicists have been interested in phenomena at the lowest attainable energies, down into the region of millionths of a degree above absolute zero. In terms of energy per particle, this is a factor of about l0 (l0,000,000,000,000,000,000,000) less than the highest energy achievable by modern particle accelerators. Under less extreme conditions, but still in the low temperature range (up to about 100 degrees above absolute zero) much research has been done on the phenomenon of electrical superconductivity, in which the electrical resistance of certain materials falls to zero. The practical possibilities presented by this behavior are immense, especially if materials can be found for which the superconducting property can be pushed up close to room temperature.

MASERS AND LASERS

We have described how the theory of solids developed from the consideration of what happens when large numbers of atoms are brought into close interaction with one another through their electrons. A comparable although different situation concerns large numbers of atoms interacting through the exchange of quanta of radiation. This can take place in the condensed solid state but also in gases at low pressures -- even in the near vacuum of interstellar space -- and the controlled exploitation of it made possible the invention of the laser. This is another noteworthy example of how fundamental physics can lead to major contributions to technology.

Once again the story begins with Einstein. In 1916 he developed a new way of deriving Planck's formula for the spectrum of radiation from a hot object. It was already accepted that a quantum of radiation would be spontaneously emitted by an atom in an excited energy state when it fell to a state of lower energy. It was also accepted that an atom in the lower state could be raised to the higher state if a light quantum of the correct energy fell upon it and was absorbed. To this, Einstein added a further possibility -- that the transition of an atom from its exited state to its lower state would be enhanced if it were struck by a photon of the same energy as it would emit spontaneously -- a process of *stimulated emission.* This process would lead to the appearance of two quanta of a certain energy where there had only been one before, so that if one could start with a large population of atoms in the excited state there would be the possibility of a sort of chain reaction; a single incident photon of the right energy could give rise to a big burst of radiation of the same frequency and wavelength. This was the laser concept.

It was first turned into reality in 1953 by Charles Townes (1915 -) and his students, using radiation of about l cm wavelength emitted and absorbed by ammonia molecules. This is in the range of electromagnetic radiation called microwaves, and they decided to call their invention a *maser* -- Microwave Amplification by Stimulated Emission of Radiation. Seven years later a similar device using visible light was created by Theodore Maiman (1927 -) The word "microwave" was replaced by "light" in the acronym devised by Townes and his colleagues, and thus the *laser* got its name. Its most obvious feature is the amazing purity of its emitted light -- that is, the extremely small range of wavelengths in its emitted light compared to light from the same atomic transition in an ordinary light source. Along with this goes the possibility of producing a beam of light of very high intensity and very small angular divergence so that, for example, it has been possible to place reflectors on the Moon and observe the light returned by them to the position of a laser source on the Earth.

PLASMAS

Although this topic does not involve any fundamentally new concepts, no survey of physics would be complete without at least a brief mention of what are called plasmas. A plasma is essentially a gas raised to such a high temperature that a large fraction of its atoms have lost an electron, thereby becoming positive ions. The negative electrons remain in the system, so that it is electrically neutral as a whole. A fluorescent light is a familiar example of a plasma. It may not feel hot to the touch, but its electrical temperature, as measured by the energy of the free electrons in it, may correspond to tens of thousands of degrees.

Plasma has been called "the fourth state of matter." Although (except for natural phenomena such as lightning bolts and the aurora) special steps must be taken to create it on Earth -- primarily electric discharges in gases --

most of the visible matter in the universe is in the plasma state. Virtually the whole volume of a normal star is in the plasma state, with temperatures up to tens of millions of degrees. That is why it is important to include plasmas in any discussion of the physical world. However, the particular interest of plasmas for us on Earth is the possibility of using them to generate "clean" energy. The idea is to achieve this by creating a plasma of certain light elements -- in particular the hydrogen isotopes of atomic mass 2 and 3 -- and make the system hot enough to produce nuclear fusion reactions. Work in this direction has been going on for about 50 years. Success has often seemed tantalizingly close; the view now appears to be that useful power from plasma fusion may be achieved by the middle of the 21st century.

THE GOAL OF UNIFICATION

The preceding account has pointed out that physicists have come to recognize four different types of force: gravitational, weak nuclear, electromagnetic, and strong nuclear. (Arranged this way they are in order of increasing strength.) The dream of many theoretical physicists has been to find some basis for combining all these in a single unified theory of forces. Einstein worked fruitlessly for many years, right up until his death in 1955, in an effort to combine gravitation (which was the subject of his general relativity theory) with electromagnetism. Others then took over. One major achievement, in 1967, was a theory that united the electromagnetic and the weak nuclear interactions; this was done (independently) by Sheldon Glashow (1932 -), Abdus Salam (1926 - 1996) and Stephen Weinberg (1933-). At the time of writing (1996) there has been no clear advance beyond this point. There have been interesting suggestions that the strong nuclear force was fused with the weak and electromagnetic forces at an early stage in the birth of our universe, when (according to the "big bang" model) the temperature was higher by a huge factor than any that exists today. The gravitational force, despite many efforts, has remained outside the framework of the other three forces, but perhaps it, too, will be brought into a unified scheme one day. It is so incredibly weak compared to the other forces that its very existence is a mystery.

CHAOS: CLASSICAL PHYSICS RECEIVES ANOTHER SHOCK

We have pointed out that the study of quantum phenomena forced upon us a revision of our beliefs about the predictability of individual atomic events. But it continued to be an article of faith among most physicists that the laws of strict cause and effect allow us to predict, in principle, the course of all events above the atomic level. The great French physicist Pierre Simon de Laplace (1749-1827) articulated this belief in a famous statement:

"An intelligence which, at a certain instant, knew all the forces of nature and also the situations [positionsand velocities] of the entities in it, and which furthermore was capable of analyzing all these data, could encompass in the same formula the motions of the largest bodies in the universe and those of the lightest atom; to it [this intelligence] nothing would be uncertain, and the future would be as clear to it as the past."

This faith was based on a feature that we mentioned earlier; the power of mathematics to describe the physical processes of nature. It was recognized that certain problems (for example, turbulent motion of fluids) were in practice so complicated that they defied formal mathematical analysis. Nevertheless, it was believed that this was just a practical limitation, not a fundamental one. Another great French scientist, Henri Poincaré (1854 - 1912) realized, however, that there was more to the situation than this, that -- even with strictly causal mathematical equations -- there were fundamental limits to predicting the long-term history of certain types of physical systems. The key feature was the existence of so-called non-linear terms in the equations of motion. Before the advent of modern electronic computers, the behavior of such systems could not be adequately explored, because -- for example in periodic motions such as the motion of a pendulum -- it would have been prohibitively time-consuming to follow the motion through thousands or millions of cycles. But this is the kind of work -- so called "iterative calculations" -- for which modern computers are ideally suited. What they do can be called experimental mathematics; the equations are well defined, but their implications can be followed out only if one can repeat a numerical program over and over again. And the results were startling. It had previously been believed that a very small change in initial conditions would produce correspondingly small changes in the final outcome. But it was discovered that the final outcome might be so sensitive to the initial conditions that the long-term situation was in effect unpredictable, that totally different outcomes might be possible*.

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* This has suggested such fancies as that the beating of a butterfly's wings might change the world's weather pattern!

This is what Poincaré realized. The phenomenon is called *deterministic chaos*; it differs from the intrinsic failure of causality in quantum systems, but its consequences are in some ways similar.

The exploration of chaotic systems has become a major field of mathematical physics. Although its chief physical application has probably continued to be in fluid mechanics, it has found applications in solid state physics, acoustics, plasma physics, elementary particle physics and astrophysics, as well as in biology and chemistry.

CONCLUDING REMARKS

If one looks at the development of physics throughout time, it is a story of a continuing effort to push back the frontiers of our knowledge of the universe. Much of this advance has consisted in the extension of the range of our knowledge in terms of distance and time. When Man was limited to the use of his natural faculties, he could not see anything smaller than a speck of dust -- say about l/l000 cm in diameter. At the other extreme, although he could see the stars and realize that they were very far away, finding the distance of anything farther away than the Moon (about 400,000 km) was beyond the scope of his abilities. Now we have specific knowledge of distances as small as 10^{-18} m and as large as 10^{+15} m. With regard to time, the eye could not separate events occurring less than about 1/50 s apart, and a human lifetime set an upper limit of about 10^{+9} s to the duration observable by any one individual, although of course a sense of history would have permitted people to have some awareness of times up to perhaps a few thousand years*.

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* And, of course, 19th-century geologists envisaged time scales of hundreds of millions of years without the benefit of well-defined measurements of time.

But contrast that with what has become possible today through physical measurements. The marvels of modern electronics permit the study of times as short as about 10^{-15} s, and the combination of observation and inference enables astrophysicists to talk with some confidence about times as long as billions of years (10^{17} s). So, with respect to both space and time, physics has now given access to phenomena over a range embracing factors of more than 10^{32}. And the attempts to extend these ranges continue.

Our knowledge of how the various components of matter interact with one another to produce the immense (and increasing) variety of specific physical phenomena is not quantifiable in this way, but there can be no doubt that the ability of physics to detect, explain and control them is an ongoing process. So also is its reach. It has even been suggested that the traditional goal of seeking a minimal number of fundamental principles is in the process of being replaced by a program of using these well established principles to explore an ever expanding catalogue of specific applications.

The truth, I think, is that both processes are at work, and will continue to be. The expansionist part of the program is undoubtedly being aided by the power of modern computational methods, and impinges on other sciences also. All of chemistry can, at least in principle, now be explained in terms of electromagnetic forces and quantum theory, and biology is beginning to derive valuable insights from the application of basic physical principles. This is not to suggest that physics is in any way superior to those other sciences; anyone who looks at the astonishing achievements of chemists and biologists, especially in the 20th century, will quickly be disabused of any such idea. Nor would I wish to suggest that the fate of chemistry and biology will be to become part of physics. Certainly the complexity of biological systems, with which both chemists and biologists are concerned, is so great that it calls for a qualitatively different approach from that of the physicist. The special status of physics is simply that, in a universe built of elementary particles and their interactions, it has been the task of physics to understand these things at the most primitive level. That sentence, in fact, epitomizes what it has been the purpose of this article to explore.

I wish to thank Professor E. L. Jossem for reading this article in draft, and for making a number of valuable suggestions.

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Section B1, *The Nature of Physics* from: Connecting Research in Physics Education withTeacher Education

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The physicist's toolkit

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(Received 27 August 1986; accepted for publication 23 January 1987)

A physicist's "toolkit" might include mathematical, diagrammatic, and modeling tools, including such models as a crystalline solid, a harmonic oscillator, or an inverse square law of interaction. The notion of a toolkit provides a meeting ground for scientists, philosophers, and teachers for appreciating what scientists do. For doing science may be thought of as a craft, skillfully employing a kit of tools.

I. INTRODUCTION

We may think of scientific work as a craft with an associated toolkit, practiced in guild. The number and kind of tools and practices can be seen as small, teachable, and specifiable. (See Table I for such a kit.) Taking physics "toolishly," physics has nature under its command if it has an effective toolkit and craft of practice.[1] Physicists carefully choose and formulate their problems so they can work on them using their kit of tools. As we shall see, they persist in picking out the linear or at least linearizable situations (including the seemingly nonlinear ones). And they invent good ground states to hide the nonlinearities. Physicists explain their capacity to encompass nature by giving an account of the hierarchies of forces (and the monotonicity of a temperature scale) and of the stability of matter. Then their linear perturbative approach should "work," since at each level in the hierarchy one has a stable base from which to work.

Toolishness provides us with a powerful way of understanding and describing what scientists do. We may describe just what is in the physicist's toolkit and the skills and judgment needed for effective practice. We account for how a scientific theory is effective, in that it provides the right tools for doing the work and justifies that work as the appropriate work to be done. Now, in general, a craft may selectively borrow and adapt tools from other crafts. And so, for example, physics and mathematics, or physics and engineering, borrow from each other. So toolishness may suggest why mathematics works in physics.

The notion of a toolkit is attractive because it gets around the conventional separation of theory, hypothesis, and idea - versus experiment, testing, and instruments. All of these might be taken as tools. The traditional questions about scientific truth, knowledge, or belief do not disappear, but they now allow for a rather more concrete approach.

In Sec. II, I describe how physicists conceive of themselves as having a toolkit, and what tools are. Next I shall exhibit a kit's general structure, aiming for comprehensiveness rather than detail. (The reader interested in the contents of a physicist's kit can skip to Sec. III immediately.) The kit I describe is suited for the paper-and-pencil conceptualizing, explanatory, and problem - solving work of a physicist. The toolkit is contemporary, a particle physics and field theoretic one, congenial with modern views of condensed matter. It is drawn from texts, exams, and handbooks. Finally, in Sec. IV I elaborate on some of the consequences of taking physics toolishly.

II. PHYSICISTS AND TOOLS

Physicists like to think of themselves as possessing a set of tools, and contemporary writing about science has taken that claim seriously. Fermi was notorious for approaching problems in a simple fashion, using a small number of models -

Table I The physicist's toolkit.

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1. Mathematical tools

- a. Counting and approximation
    - combinatorics, statistics, asymptotics

  b. Pattern
    - geometry, symmetry, conservation laws

  c. Linearity and limits
    - calculus, optimization procedures, linear representations

2. Diagrammatic tools

- a. Geometric and spatial
    - vectors and graphs

  b. Algebraic and symbolically patterned expressions
    - canonical forms

3. Rhetoric

- a. Tools:

- (1) Media:

  space-time vacuum, hydrogen atom, crystal, continuous elastic medium, fluid, gas
- (2) Objects:

  particles and excitations, oscillators, fields and waves; linear operators including

  differential equations and groups; correlations; properties including energy,

  momentum, and translation operators
- (3) Interactions:

  objects with objects and with media (potentials, particle exchange, force field,

  scattering), Interaction Lagrangian, response functions

b. Approaches:

- (1)Strategies:

  good vacuum or ground state, equilibrium, conservative potentials; analogy

  and heuristic, homology of equations and solutions; $n \log n$ vs n^2

  (2) Commonplaces:

  qualitative methods (e.g., Migdal): become friendly with nitty-gritty material like Coulomb wave functions; look for big contributions, the physics lies in the poles; use a classical picture, supplemented by quantum rules; things fall off, but asymptotics are important; know about potential wells, oscillators, one- particle transitions, polarizable media,...

(such as electromagnetism) and adapting them as needed. Back of the envelope calculations and order of magnitude estimates are part of the legends of physics. Pais begins his recent study of Einstein with a one_sentence scientific biography: "Better than anyone before him, he knew how to invent invariance principles and make use of statistical fluctuations." Landau's course of theoretical physics, "the theoretical minimum," is well known. Less well known is the talismanic or emblematic list of his "Ten Commandments," his most useful formulas and models, engraved in stone, given to him by his students on his 50th birthday. Feynman's diagrammatic methods were tools for expressing the physics and for doing the calculational work. Peierls gives a list of the standard models in physics which include: hypothetical, phenomenological, approximate, simplified, instructive, analogical, and Gedanken models. Kenneth Wilson has described a new set of tools based on computation and computer science.[2]

Physicists also readily offer coaching advice about choosing a problem to work on, the right level of difficulty to start out with, or where to search for new laws. For example, Dyson following Bragg: "Don't try to revive past glories. Don't do things just because they are fashionable. Don't be afraid of the scorn of theoreticians."[3] As means of guidance and caution Peierls describes surprises in theoretical physics, surprises in that initial intuitions and approaches proved incorrect.[4] A. B. Migdal has written an advanced text in quantum mechanics that aims to expose the student to how-to-do-it qualitatively, like a real pro. Comprehensive and explicitly a toolkit, I summarize some of its guidance in Table I [items 3b(2)] under "Commonplaces."[5]

A physicist's toolkit might be divided into three parts: mathematical, picturing or diagrammatic, and descriptive or rhetorical. As can be seen from Table I, the kit includes models of media such as a crystal, models of objects such as a particle, and models of interactions such as a collision. And the practice includes strategies and commonplaces, such as looking for equilibrium states. Using a toolkit requires technical skill for adept manipulation of mathematical and diagrammatic expressions. It also requires judgment, for assessing and deciding which tool or model is appropriate to a situation, or when a strategy is likely to be effective.

A. **Tools in general**

Tools are things we use for doing our work. Tools feel objective and are literally shareable, while skills are personal and imitated. A toolkit of seemingly abstracted or objective tools comes along with a practice of tool-using - how to work and how the work is organized, and a sense of what it is the craftsperson is doing. Carpenter's toolkits surely have hammers and chisels, but carpenters use nails and work with wood, they know how to swing a hammer, they work during regular hours along with other crafts, and they are in the business of constructing something. The toolkit's contents and practices depend on the historical time, where the work is being performed, the kinds of material being worked on (wood, metal, atoms, condensed matter), and what is being constructed. There are standard tools, as well as personal and jerry-built devices. The term "toolkit" suggests a small number of versatile tools meant to work together.

Tools can be notional, as in Kuhn's description of exemplary or standard problems and paradigmatic practice. Ravetz explicitly develops the tool model in great detail, describing tools as multifunctional, robust, designed, standardized, and so forth.[6] In a recent history of contemporary particle physics, field theorists are described as having an interest in exploiting their tools and expertise, and the coming of a suitable problem as allowing them to go to work. Earlier they were "mechanics without tools" for calculating low-energy quantum chromodynamics, where particle properties were well known already.[7] And Hacking treats particles as probes, means of intervening in the world that cause well-defined and measurable effects. He says "Long-lived theoretical entities, which don't end up being manipulated, commonly turn out to have been wonderful mistakes."[8]

Another, more literal and materialist, version of "instrumentalism" is becoming important. Scientists encourage national commitments to the material devices vital to their work, such as telescopes and synchrotrons. They present their research as device driven, rather than people or idea driven. Greater emphasis is being placed on the importance of craft and of instruments, and their limits and capacities in scientific investigation. Particular features of instrumentation, and the interpretation of what those instruments produce (data), are being shown to play a subtle role in the making of science. And anthropologists, using the framework of cultural and material anthropology, show how tools such as accelerators and detectors organize the culture and production of science. [9]

We might discern two traditions for describing tools, the objective and the situational.

In the objective tradition a tool is an object, such as a hammer or microscope, possessing certain capacities. A trained person picks up a tool and uses it to do something. Such a tool may be made by a toolmaker and when it is done it is then available for use. In modern times, making and use are for the most part separated, although it is well known that effective craftspersons will modify a tool for particular uses or to suit their own idiosyncracies. A tool here is for the most part passive, objective, and modular.[10]

Skills are capabilities for using tools, and those skills come to be automatic and unnoticed. But different users of what we take as the same tool have different skill and practices. Crystallographers and elementary particle physicists use group theory, but in different ways. Still it is taken as the same tool. One becomes more skillful in using tools through practice, say doing many integrals, and more versatile, say solving a harmonic oscillator as an $F = ma$ differential equation, as an Euler-Lagrange problem, or in action-angle variables.

In the situational tradition tools are defined in terms of the work to be done. They are ways of getting ahold of the world and manipulating it, taming its many degrees of freedom and getting a handle onto it. We discover tools as such, as abstract objective things, when they do not work.[11] We notice the hammer when its head flies off. We have to pay attention to an asymptotic expansion when it blows up. In this tradition a world *is* as handled, tools exist *in* practice, practice is learned and commanded *in* specific environments and for specific tasks.

The two traditions are complementary, and each tradition inherits a complementary problem. The objective tradition must give an account of how tools are used and are versatile, an account of play. The situational tradition must account for how tools come to be seen as objective, separable and disengaged from their original contexts, and as universal, available to all. Still, both traditions agree that a tool is something that can be seen as objective and shareable, that it is affected by how it is used, that the world we discover and make is intimately related to the tools we use. Tools are versatile and depend on their users .[12]

Masters of a craft employ tools in more inventive and subtle fashions and produce finer than usual objects.[13] Their products are masterpieces, but not so distinctive or difficult they cannot be produced by others once they see how.

Those of us who were fortunate enough to watch Enrico Fermi at work marveled at the speed and ease with which he could produce a solution to almost any problem in physics brought to his attention. When he had heard enough to know what the problem was, he proceeded to the blackboard and let the solution flow out of his chalk. He kept in trim by doing a lot of problems, either for the courses he taught, the talks he gave, or the papers he wrote. Most frequently, he worked out his own solutions to problems he heard about, in seminars, or in discussions with those who came to talk physics with him. Fermi's solutions were almost simpler and easier to understand than the ones obtained by the person who raised the question in the first place. [14]

Fermi's style and methods were appreciated, learned, and then taught to several generations of physicists. His lecture notes became texts, his approach repeated by his students to their own.

A toolkit and a craft are successful if there is important work they can do.[15] A guild succeeds because its craftspersons find both work to do and a market for their products. It is within a context of tools and craft that a practice is orderly, clear, natural, and simple. And it is in terms of tools and craft that a personal style is realized.

III. THE TOOLKIT

A fairly straightforward version of a physicist's toolkit would include specific model systems such as crystalline solids or a heat engine, specific objects such as Newtonian particles or Maxwellian fields, and specific modes of attack such as linearization, potential theory, phase space formulations, and least-action principles. There is, for example, as Peierls describes them, a small number of frequently used gaseous or atomic models, or kinds of interparticle interactions. [16]

Here I shall describe the toolkit somewhat more schematically (See Table I). I suggest that the physicist's toolkit and skill consists of a trivium: (1) mathematics, (2) picturing or diagrammatic, and (3) description or rhetoric corresponding roughly to number and structure, picture and pattern, and language and argument. Tools (3a) including the model worlds or media [3a (1)] we employ in doing physics, the model objects [3a (2)] that populate each medium, the model interactions [3a (3)] among the objects themselves and with the medium, and the strategies [3b (1)] for formulating and working on a problem.

I want to describe briefly the mathematical and diagrammatic parts of the toolkit, and then discuss the descriptive or rhetorical part in some detail.

Mathematics is perhaps most apparent as a skill and set of tools. I hazard a synoptic description of the scope of such skill: A physicist has to be able to count and make approximations (Table I, item la), and hence in the toolkit there are tools of combinatorics, statistics, and asymptotics. One has to master patterns (1b), and hence there is geometry and the calculus of variations, symmetry principles and conservation laws, and rules of propagation for waves and boundary influences. And there is a mastery of the principles of linearity and limits and stability (1c): in the calculus, in optimization procedures, and in linear representations.

Assuming that physics itself might explain why the mathematics is useful, one might begin to justify the mathematics as follows. Physically, counting and approximation (la) are usually about fluctuations and perturbations and their smallness, which is true for many of the situations physicists concern themselves with. Patterns (lb) are about the small number of good classifications in nature, again as physicists concern themselves with it. And linearity and limits (lc) are about the fact that there is a hierarchy of well-separated forces, measured in terms of their strengths, and that there are stable objects which may be linearly (or almost so) perturbed. Built into this subset of mathematics are the deepest principles of the world as physicists understand it. And so mathematics naturally seems to apply to physics.

A second set of tools are picturing or diagrammatic tools (Table I, item 2), figures that represent the world, and from which we may "write down" and "read of" the physics. These figures might be seen as either geometric and spatial (2a), or algebraic and symbolically patterned (2b) . Vector diagrams, Feynman graphs, and boundary condition pictures are of the first sort, while covarient expressions and canonical forms of equations are of the second. Of course, diagrams have to be interpreted correctly. A symmetric Lagrangian can have an asymmetric ground state (as in freezing); parallelism on a sphere is not the same as on a plane.

Again assume that physics itself might explain the diagrammatics. We might say that diagrammatic (2) expresses the fact that physics literally accounts for nexuses and flows, and so there can be conservation laws. Vectors and the like, and covariant expressions, are tools for expressing the flows and conservation laws more or less automatically. And physics is also a story of symmetries and systematic categories, such as groups, for organizing phenomena. The various patterned symbolisms are set up to do this work.

The third skill (Table I, item 3) is a mastery of the descriptive or rhetorical tools of the craft, or modeling, what might be called "the art of addressing nature," as Rabi puts it.[17] The tools here are the models invoked when we encounter a situation, models that make nature something we can talk about. They include models of media [3a(1)] objects [3a(2)], and interactions [3a(3)]. There are also more explicit strategic skills [3b(1)] such as searching for conserved quantities, and using commonplaces [3b(2)] such as those Migdal suggests.

What is distinctive about this mode of description or rhetoric is that the various media, objects, and interactions are nicely separable, and they may be combined in seemingly arbitrary ways - x medium with y object with z interaction mechanism. Nature for a physicist comes in almost isolable yet combinable parts. States of matter are separated by sharp phase transitions; particles have well-defined properties; and there is a hierarchy of fundamental interactions.

A. Physical tools and skills

When physicists approach a situation as physicists they immediately take it *as* a physical world or a *medium* . The media [Table I, item 3a(1)] include: the space-time vacuum; an atom or a solar system; an orderly crystalline solid; continuous elastic media (including liquid drops and drum surfaces); and fluids and gases.

The media are often treated as sequences tending to greater symmetry and higher temperature (for example, solid/liquid/gas or atom/nucleus/quark). As the temperature rises each medium "melts" into one of the next ones and so unfreezes some degrees of freedom. There are "phase transitions" between them. In each of these media there is fluctuation, and generally those fluctuations increase with temperature. High fluctuation or susceptibility (at phase transition) alternate with the smooth and highly damped stable states.[18] This heuristic picture of media is inspired by current models of the early universe and of elementary particles, as well as those of condensed matter.[19]

While settling on the medium the physicist immediately identifies the things in that medium, using models such as particles. Calling these things *objects,* what seems crucial about objects [3a(2)] is that each object is individual yet addable - typically, linear and superpositionable - even if it, itself, is made up of much more complicated stuff. Objects are demographic. The total effect of a group of objects is a matter of adding up their individual marginal effects. Often there are conservation rules, so that it does not matter how you do the adding up. If it proves impossible to do such demographic addition, one then looks for normal modes, eigenstates, and quasiparticles that do allow for such addition.

Objects may be things or motivating entities. (We will get to the latter shortly). As things there seem to be particles, oscillators, and fields and waves. Conspicuous in their absence are actual structures, such as levers and beams. Their substantiality and extension delegate them to the realm of engineering, where effects of scale and nonlinearity are taken into account.

A medium can be an object in another medium, so a gas of electrons can fill a crystal. And there are modes of transformation among the objects. A particle can come to be seen as a wave; or a wave becomes an oscillator. A crystal taken as an N-body symmetric field is seen as being a space populated by particles such as phonons. Because those transformations are not only at a single scale, but between scales, an atomic hypothesis tells us "look more closely."

While my description of the toolkit is schematic, in actual usage tools are taken quite specifically. A crystalline solid is likely to be cubic, an atom will be the hydrogen atom, a gas will be ideal or van der Waals, a field will be Maxwell's electromagnetic one, and an interaction may be inverse square.

Media and objects *interact,* eventually perhaps changing from how they started out. Interaction [Table I, item 3a(3)] requires actors, means, and resolution. Objects may interact with each other in a medium (two electrons in a vacuum), an object may interact with a medium in which it is embedded (an electron in a crystal); or an object may interact with a medium taken as an object (an electron bouncing off a crystal, both in a vacuum). Interactions may be expressed as forces and influences (in contact, propagated through a medium, or at a distance), as exchanges of information, as energies, or as probing feelers and responses in polarizable medium. Eventually interaction may be seen to have expended itself. The now-interacted and perhaps changed objects and medium may once more go along independently - until the next episode of interaction. This is expressed by the scattering matrix, by the existence of constants of motion as in action-angle variables, and by stable quasiparticles representing a "sum" of most interactions.

Motivating entities are means for interaction, conveying the media and objects toward each other, and eventually freeing them from each other. Differential equations "move" objects around, or push them forward in time. Group theory shows how they might be combined. Correlation or transfer functions relate what happens in one part of a medium to another. Conserved properties, such as energy or angular momentum lead to translation operators [exp($-iHt$), exp($-ipx$), exp($-iJ$)] that take a world into a similar world at a different time, place, or orientation. Motivating entities, expressed as linear operations, are combined and added to get nature going, just as objects are in general combined to make up nature. But unlike objects as things, the space these objects occupy is explicitly mathematical or formal.

Populating a medium with interacting objects brings all the tools to bear to a situation. However, a physical explanation requires using those tools effectively. One needs a mode of addressing nature.[20]

There are a number of such *strategies* of address [Table I, item 3b(1)]. The most crucial is to find a good ground state or vacuum, such as a crystal lattice or quasiparticles in that lattice, the physical space-time vacuum, Cooper pairs in a Bardeen-Cooper-Schrieffer (BCS) ground state, a singlet S state hydrogen atom, or an ideal gas. A study of the ground state's perturbations or excitations is fruitful in finding out about its structure. It may be possible to find conservative potentials, such as electrical or thermodynamic ones, which characterize how it changes quasistatically. If you have to invent new particles, such as a neutrino, or new quantities, such as entropy, to get good conservation laws, it may well be worth it.

Two other strategies should be mentioned. The first is that of analogy and heuristic. If you can get away with treating a black body as an ideal gas, or light as a particle, or nuclear forces as potential forces, do it. Also, recall that the same equations have the same solutions, and that there are physical analogies behind this.[21]

A second strategy concerns what might be called the restricted plenitude of nature.[22] When you address nature, do not be surprised if a "good" stable world is not always the best of all possible worlds, but rather the one that simply is quite popular or orderly. Statistically, equilibria have many macroscopically equivalent microscopic states, combinatorically, some structures are more stable and self-reinforcing than most others. Gases, markets in economics, and the macroscopic inverse square law, are examples of this cunning of nature or of the invisible hand.[23]

We might summarize the strategies as follows: Get ahold of something that will mostly stay put and that will allow for simple yet productive investigations. Use all you know about one situation to investigate another that seems to be like it. And assume that the world is tractable, one way or another, to your understanding.

In creating this schematic toolkit I have slighted some crucial tools. Diagrams are often of pieces of apparatus, rather than vectors or algebra. Thermodynamics conceived of in terms of heat engines, electricity in terms of resistors and capacitors, and optics conceived of as mirrors, lenses, and light rays, may be fit into this kit, but they do not quite belong. In part, this kit concentrates on the microscopic world. And in part this toolkit, and the set of skills and strategies for employing it, are concerned with paper-and-pencil problem-solving activities.

When the problems are derived more directly from experiment and empirical investigation, we might imagine additions to the kit. There would be both tools of inquiry and of recognition.[24] For inquiry, there are logical tools, such as electronics or filters, for picking out events; amplifiers for making them more prominent; and stimulators or probes, to search for and bring out the cases of interest. For recognition there are tools and skills of simulation or empathy, in order to figure out how, say, an electron might act in an apparatus; tools to manage dissimulation, for dealing with how chance and fakery produce events; and tools for emulation, to set up situations so that they are the same, so as to provide for reproducibility and stable outputs (namely, good data). In a good toolkit the problem solving and the experimental tools are intimately connected, so that, as Hacking suggests, a particle had better be a probe, and filters and amplifiers had better be interaction mechanisms.

IV. TAKING PHYSICS TOOLISHLY

These tools and skills give us a version of nature that is additive, smooth, and dumb or deanimated. Nature is a "sum" of its parts; the parts interact smoothly as in the calculus, and discontinuities may be shown to disappear, say in a higher dimension; and the tools are objective and independent of context, they have no memory or will of their own, only we craftspersons do.[25] The modularity of the toolkit is a mirror of pictures of modern society composed of individuals.

Physics, taken as a craft possessing a toolkit, is true because the toolkit works and leads to interesting work. It focuses on reproducible and explainable phenomena, within a historical tradition that gives to the craftsperson an idea of what it means to work and to be interesting. When the toolkit does not work or becomes of limited interest, new tools and practices need to be invented, new probes, filters, and models created. The new tools may be seen as adaptations of the old, even if they are used rather differently from them. For example, modern electroweak theory is taken as just another step in the tradition of Maxwell's equations for electromagnetism.

A description of a toolkit begins to be adequate if it fairly encompasses standard texts, exams, and handbooks. The reaction of practitioners of the craft and members of the guild to such a description is also important. It should strike a chord of recognition. The description should seem familiar and right, to be an "of course." Now the pervasive belief in a toolkit and the admiration for masters in using it, means that if a toolkit is offered and it seems roughly adequate, it is likely to strike the appropriate chord. It occasions debate about its specific details and its articulation, and it is just in that debate that the adequacy of the proposed toolkit is judged.

The proposed toolkit and set of skills can be made more comprehensive. How does such a kit actually vary in different institutions and nations and eras, and how have tools entered and left the kit? (A nice problem would be to study the fate of the harmonic oscillator in the last several hundred years.) Does it help to look at the division of labor - instrument making crafts and performing or user crafts - in the doing of physics?[26] What is the role of style and fashion in tool use?[27] Are there corresponding toolkits for chemistry, biology, or geology?

How does coaching take place? And how is training not only substantive but behavioral? How do masters pick their disciples?[28] What are the examples and counterexamples that are brought up when a point needs to be made? How is error and surprise treated?[29]

One of the interesting developments in physics in the last few decades has been the large research team and the bureaucracy it becomes, the concomitant rise of the use of standardized detectors, and the growth of symbolic manipulation programs. What was once crafted is now manufactured.

How does the work of science change in the age of mechanical reproduction?[30]

Scientific work is a skillful craft. A physicist's toolkit begins to describe just what it is that scientists do, how they do it, and how that is related to the structure of nature as they discover it.

ACKNOWLEDGMENTS

I began this paper at the National Humanities Center and at the Van Leer Jerusalem Foundation. More recent work was supported by the Exxon Education Foundation through a Science, Technology, and Society Research Fellowship at the Massachusetts Institute of Technology, and by the Russell Sage Foundation.

FOOTNOTES:

[1]Tools, of course, are not restricted to carpentry or physics. Tools in computer science include "software tools" that are used to build and organize large programs, and recursion and data structures (say as embodied in LISP); literary studies nowadays use classical rhetoric and so-called "deconstructionist" strategies; and lawyers and physicians will speak of professional skills and tools. But not all fields lay claim to their tools as tools. Much of political theory and the humanities see themselves as in opposition to tools or methods. [See S. Wolin, Am. Poll Sci. Rev. **63**, 1062 (1969).] So it is interesting that physics sees itself as having a toolkit.

[2] E. M. Purcell, Am. J. Phys. **51**, 11 (1983); P. B. James and J. S. Rigden, Am. J. Phys. **50**, 1069 (1982); G. Holton, *The Scientific Imagination* (Cambridge U. P., Cambridge, 1973); A.Pais, *"Subtle is the Lord..." The Science and Life of Albert Einstein (* Oxford U. P., New York, 1982); A. Livanova, *Landau: A Great Physicist and Teacher (* Pergamon, Elmsford, NY, 1980); R. Peierls, Contemp. Phys. **21**, *3 (* 1980); *University of Chicago Graduate Problems in Physics With Solutions,* edited by J. A. Cronin, D. F. Greenberg, and V. L. Telegdi (Addison-Wesley, Reading, MA, 1967).

[3] F. Dyson, *Phys. Today* **23,** 23(September 1970); R. P. Feynman, *The Character of Physical Law* (MIT Press, Cambridge, MA, 1965).

[4] R. Peierls, *Surprises in Theoretical Physics* (Princeton U.P., Princeton, NJ, 1979).

[5] Migdal's methods reflect a situation in which computers are comparatively unavailable. Wilson has argued for a theoretical science based on computation, with a different set of tools or models. A. B. Migdal, *Qualitative Methods in Quantum Theory* (Benjamin, Reading, MA. 1977): K. Wilson, *CERN Courier* **23**, 172 (June 1983).

[6] T. S. Kuhn, *The Structure of Scientific Revolutions* (Univ. of Chicago Press, Chicago, 1970); J. Ravetz, *Scientific Knowledge and Its Social Problems* (Clarendon, Oxford. 1971); M. Heidegger, *Being and Time*

(Harper and Row, New York, 1962). See also, on skills, M. Polanyi, *Personal Knowledge* (Univ. of Chicago Press, Chicago, 1958). Heidegger employs tool-using as a central image in his work; Wittgenstein uses craft practice in the initial parts of the *Philosophical Investigations* (Macmillan, New York, 1968). "Tools" and "craft" are the metaphors of a philosophy concerned with function versus essence, with practice versus ideas, with technology versus nature.

[7] A. Pickering, *Constructing Quarks* (Univ. of Chicago Press Chicago, 1984); see also, J. T. Cushing, Synthese **50**, 5 (1982).

[8] I. Hacking, *Representing and Intervening* (Cambridge U. P., Cambridge, 1983), p.. 275.

[9] M. Harwit, *Cosmic Discovery* (Basic, New York, 1982); D. D. Price, Nat. Hist. **93**, 49 (January 1984); B. Latour and S. Woolgar, *Laboratory Life (* Sage, Beverly Hills, 1979); H. Garfinkel, M. Lynch, and E. Livingston, Philos. Social Sci. **11**, 137 (1981); P. Galison, Rev. Mod. Phys. **55**, 477 (1983); S. Traweek, in *Les Savoirs dans les Pratiques Quotidiennes,* edited by C. Belisle and B. Schiele (Editions du Centre National de la Recherche Scientifique, Paris, 1984).

[10] Kuhn, Ref. 6; Ravetz, Ref 6; A. H. Dupree and H. W. Dupree, "Performer Crafts and Instrument Maker Crafts: The Persistence of Craft Traditions in Industrial Transformation." Mimeo, 7 May 1979.

[11] Heidegger, Ref. 6; A. R. Luria, *Cognitive Development: Its Cultural and Social Foundation* (Harvard U. P., Cambridge, MA, 1976).

[12] See Ref. 6, and for example, M. Harris, *Culture, People, and Nature* (Harper and Row, New York, 1980).

[13] See, e.g., R. P. Feynman, R. B. Leighton, and M. Sands, *The Feynman Lectures in Physics* (Addison-Wesley, Reading, MA 1964). On Feynman's practice, see F. Dyson, *Disturbing the Universe* (Harper and Row, New York, 1979).

[14] *Physics Vade Mecum,* edited by H. L. Anderson (American Institute of Physics, New York' 1981).

[15] G. Kubler, *The Shape of Time (* Yale U. P., New Haven, CT, 1962).

[16] Peierls Ref. 2.

[17] I.I. Rabi, *Columbia Today,* **6**, (Winter 1977).

18 Strictly speaking, this is an account of second-order phase transitions.

19 Henry Adams tells a similar story in "The Rule of Phase Applied to History (1909)" in *A Henry Adams Reader,* edited by E. Stevenson(Anchor, Garden City, 1958).

20 I should note that I have paralleled my description of the toolkit to descriptions of rhetoric, the classical art of address, For in addressing nature we are as well producing persuasive demonstrations for ourselves and others. Media corresponds to genres, objects to tropes, interaction to plot, strategies to modes of address, and qualitative methods to commonplaces.

21 Feynman, Ref. 3. And just because two systems have the same equations does not mean they are the same - the approximations used in getting those equations may be different.

22 A. Lovejoy, *The Great Chain of Being (* Harvard U. P.. Cambridge, MA, 1936).

23 H. Simon, *The Sciences of the Artificial* (MIT Press. Cambridge, MA, 1969); S. Kirkpatrick, C. D. Gellatt, Ir., and M. P. Vecchi, Science **220**, 671 (1983).

24 See Hacking, Ref. 8, on representing and intervening, and Cushing, Ref 7 for an alternative vision in S-matrix theory.

25 The rational economic man in neoclassical microeconomics is similarly smooth, adaptable, and objective. A. Marshall in his *Principles of Economics* (Macmillan, London, 1890, 1920) states this in terms of a "Principle of Continuity." See also, M. H. Krieger; J. Poll. Anal. Management **5**, 779 (1986). Another example of making the world suit the physicist is the recent interest in "chaos," a way of studying aspects of formerly intractable "nonlinear" phenomena in a form physicists can handle conventionally.

26 Dupree, Ref 10.

27 M. H. Krieger, Fundam. Sci. **2**, 425 (1981).

28 S. Traweek has described this process for the field of elementary particle physics in both the US and Japan. See her forthcoming, *Particle Physics Culture* (Harvard University Press).

29 Peierls, Ref. 4; C. Bosk, *Forgive and Remember* (Univ. of Chicago Press, Chicago, 1979).

30 W. Benjamin, *Illuminations* (Schocken, New York, 1969).

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HISTORY AND PHYSICS [1]

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INTRODUCTION

Physicists always have valued their history. Libraries are replete with books on the history of physics written by physicists, from Ernst Mach's historical-critical studies on mechanics, heat theory, and physical optics [2] , to Abraham Pais's history of matter and forces (Pais, 1986), not to mention Max Dresden's biography of H.A. Kramers (Dresden, 1987) and the many other biographies and autobiographies written by physicists [3] . Journal articles and chapters of books, obituary notices of Fellows of the Royal Society and of members of the National Academy of Sciences add to the vast body of historical literature written by physicists. The allure is great; physicists continue to contribute to the historical literature at a high level, and a substantial number of historians of physics began their careers as physicists.

Physicists also have fostered historical studies by others. In some instances, historians of physics could not have secured a scholarly niche in colleges or universities without the support, both intellectual and financial, of physicists. The American Institute of Physics Center for History of Physics was established by physicists concerned about the preservation and study of their intellectual heritage, and the Center's nuclear physics, astrophysics, and solid-state physics projects, as well as the earlier Sources for History of Quantum Physics project, could not have succeeded without the full involvement and support of the physics community. Sections devoted to the history of physics have been created within the American Physical Society and the European Physical Society. Clearly, the history of physics continues to strike a deeply resonant chord among physicists.

The main attractive force is unquestionably the intellectual appeal of the history of physics. Every physicist who has written a review article or browsed in a good library and comes across a seminal article or book written by a physicist of an earlier age knows the thrill of historical discovery and experiences the desire to learn more about the life and times of its author. The link with the past is a powerful one. Far from the stereotypical image of the narrow scientist confined to his or her laboratory, many physicists, perhaps a majority, have broad intellectual interests, one of which traditionally has been the history of their own discipline.

It comes as no surprise, therefore, that physicists have been vocal and staunch proponents of the idea of introducing history of physics into physics courses. Some have furthered their conviction by writing textbooks from a historical point of view [4] . Others have helped to organize conferences on the role of history in physics teaching [5] .

Still others - - the vast majority - - have found ways to use the history of physics in their physics courses for pedagogical purposes. In 1948, at a meeting of the History of Science Society, P.W. Bridgman expressed his rationale for doing so as follows:

it seems to me that the one most important thing to realize about science is that it is a human activity, and this can only mean the activity of individuals.... If science is taught with a large admixture of history this point of view will automatically be stressed. In so doing a purpose will be served that is increasingly important in our present day, namely to impart an adequate appreciation of the fundamental conditions under which science flourishes. (Bridgman, 1950, 66- 67; 1955, 346-

The historian, said Bridgman, would be compelled to show that scientific development seldom follows a purely logical course, and he then added:

The insight that the progress of science is often illogical is perhaps more important to the scientist himself than to the layman, and constitutes one of the reasons why the scientist is concerned with his history. This suggests that perhaps one of the most important fields of service of history of science is to the scientist.... Whatever concern the scientist has already had with history must often have disclosed to him the illogical progress of science in the errors of the past and the retraced steps. (Ibid., 70; 354- 355)

Bridgman has not been alone in seeing value in the history of science. In 1936 Lord Rayleigh lamented the loss of historical perspective when original memoirs are turned into textbooks, masking the personalities and lives of their creators. (Rayleigh, 1936, 217) Studying original memoirs of great scientists carries other benefits as well. In 1971 Peter Kapitza argued that it helps a group leader to learn how to "assess the creative potential of youth," (Kapitza, 1980, 275) while ninety years earlier Arthur Schuster felt that it might uncover a "faint prophetic glimmering of a modern theory," thus stimulating the researcher and also driving home the lesson that the acceptance of a theory depends as much on its audience as its creator. (Schuster, 1881, 20) "The young man who begins life with the idea of making a name as a scientific discoverer," wrote Schuster, "is like the little girl in Punch who intended to become a professional beauty. They may both be successful, but if so, it will depend as much on the ready appreciation of their contemporaries as on themselves." (Ibid., 23)

Students thus might learn a certain amount of humility: "Every age," Henri Poincaré observed, "has ridiculed the one before it, and accused it of having generalized too quickly and too naively.... No doubt our children will some day laugh at us." (Poincaré, 1946, 127) "For me, personally," said Anthony P. French, a recent Oersted Medalist of the American Association of Physics Teachers, "one of the most powerful reasons for injecting some history into a physics course is the very basic one of getting students to appreciate that physics does have a history.... [We] can at least convey a sense that physics is a living, growing subject and that it is the product of the accumulated endeavors of humans just like ourselves - though generally much smarter!" (French, 1989, 588) Louis de Broglie perhaps summarized it best when he wrote that, "A well-rounded education will be incomplete without the history of science and of scientific achievement." (Quoted in Seeger, 1964, 621)

These are eloquent testimonials, and they could be multiplied [6] . Yet, an objective observer would agree, I think, with Max Jammer's rather blunt assessment:

Most teachers of physics at all levels of instruction fully acknowledge the desirability of including the history of physics in their teaching but, when actively engaged in their teaching, show a strong antihistorical bias so that their performances belie their declared convictions. (Jammer, 1972)

We are therefore confronted with something of a paradox: On the one hand, there is a natural intellectual alliance between physicists and historians of physics and their respective disciplines. On the other hand, the actual extent to which physicists and historians of physics join together to improve the teaching of physics seems remarkably small, despite sentiments to the contrary. I will try to analyze this paradox here, much in the spirit in which Niels Bohr grappled with paradoxes in physics, believing that through their analysis progress becomes possible. And just as Bohr found the resolution of some paradoxes in physics in his principle of complementarity, I too will argue that the same principle can serve as a guide for understanding the paradoxical behavior of physicists and historians of physics.

THE PHYSICIST'S POINT OF VIEW

Physicists teaching today in colleges and universities have never been under more professional pressure. Quite apart from the demands of research, pressures to improve the teaching of physics have mounted in recent years. More young people, and especially more young women and minorities, must be attracted to physics as a career. In part to meet these challenges, there has been a substantial effort in the United States under the auspices of the American Association of Physics Teachers to reexamine the calculus-based introductory physics course. To me, however, as a historian of physics, the most remarkable feature of this entire effort has been its complete neglect of the history of physics. It appears that the history of physics will come into play only as it always has in the past, namely, anecdotally. The message seems clear: In designing a physics course, logical and not historical considerations dominate [7] .

It could hardly be otherwise. Physics is problem oriented, from the most elementary to the research level, and when seeking a solution to a particular problem the novice taking an examination knows as well as the experienced research physicist that logic should pay off while history probably will not. There simply is no substitute for logical analysis. Professor Iain Stuart once compared a research problem to a fortress surrounded by defensive weapons of all kinds, and suggested that it is up to the researcher to determine logically how best to attack it, perhaps by striking at its foundations or its points of weakness, perhaps by drawing its defenders out onto unfamiliar ground, perhaps by a full-scale assault using every available weapon [8] .

The ultimate goal is to gain deeper understanding of the physical universe by reducing that understanding to the smallest number of physical laws possible. The quest of the physicist, in other words, is one for simplicity. As Martin J. Klein put it:

It is, I think, characteristic of the physicist to want to get at the very essence of a phenomenon, to strip away all the complicating features and see as clearly and directly as he can just what is really involved. That is why we prize simple conceptual models so highly.... (Klein, 1972, 16)

The watch words of the physicist are logicality and simplicity.

THE HISTORIAN'S POINT OF VIEW

The historian's task is very different. In the military metaphor above, the historian's job is to survey the battlefield, selectively examining fallen bodies in an effort to reconstruct the battle that took place some time ago. The remains - the historian's sources - include published books and articles, and unpublished correspondence, notebooks, and diaries - anything that can be found long after the event. And these remains reveal not only the victor, but the many skirmishes as well, the illogical progress of the battle, as Bridgman might say. Hermann von Helmholtz, who emerged victorious time and again, offered another analogy:

I must compare myself to a mountain climber, who without knowing the way climbs up slowly and laboriously, must often turn around because he can go no further, discovers new trails, sometimes through reflection, sometimes through accident, which again lead him forward a little, and finally, if he reaches his goal, finds to his shame a Royal Road on which he could have traveled up, if he would have been clever enough to find the right beginning. (Helmholtz, 1892, 54)

The gaining of the summit is there for all to see, but the false byways and retreats along the way are not, and uncovering them is at the center of the historian's craft. "I see the main purpose of historical studies," wrote Otto Neugebauer, "in the unfolding of the stupendous wealth of phenomena which are connected with any phase of human history and thus to counteract the natural tendency toward oversimplification and philosophical ignorance." (Quoted in Klein, 1972, 16- 17) The watch words of the historian are illogicality and complexity.

COMPLEMENTARITY

The physicist and the historian thus have very different objectives in their research, use very different sources, employ very different analytical tools, and are guided by very different principles in their search for solutions to their research problems. In all of these respects, research in the two disciplines seems complementary, almost mutually exclusive, like wave and particle [9]. A scholar cannot be constrained by logic and strive for simplicity and at the same time give full weight to illogicality and strive to portray complexity. The logical skills so essential to research in physics can not be relied upon to yield an accurate historical picture.

The complementary nature of research in physics and history enables us to understand why the results often are so different when physicists and historians write history. Physicists tend to follow the Royal Road from the base of the mountain to its summit - the more or less linear path from one historical event to another, as seen in retrospect. Such history, sometimes pejoratively called "Whiggish history," [10] is by no means valueless in my opinion; it often serves, for example, as a useful guide in identifying achievements of crucial significance in a particular development. Still, few would deny that such history is inadequate - that by failing to follow the false trails, a misleading historical picture emerges. To uncover them requires a desire to master historical skills, and a willingness to devote the time required to locate and analyze all of the available documentary evidence, both published and unpublished. These qualities are not too common among scholars who see themselves primarily as scientists. As the organic chemist and Nobel laureate Richard M. Willstäter once remarked, "I have noticed that my fellow scientists, who determine melting points conscientiously to half a degree, apply a much less stringent standard to their historical writing." (Willstätter, 1965, 181 [11]) Of course, historians are not infallible; they can make scientific or historical errors themselves; they also can be mislead if they lack sufficient scientific intuition to distinguish good work from bad.

The tendency of physicists to write linear history - - which meshes so well with their logical skills - has certain consequences. One is that physicists generally confine themselves to the history of theoretical ideas or experimental developments - "internal history" in the historian's jargon. Physicists often discuss social or "external" questions in private, but they hesitate to discuss them in public or in print. A prevailing feeling among physicists seems to be that social influences on physics, whether institutional, economic, or political, tend to adversely affect its quality. Consequently, the less said about them the better.

The community strictures imposed by physicists upon themselves are even more stringent in regard to personal matters. Most physicists would acknowledge, I believe, that the personal life of a physicist can influence his or her research, although precisely how and why is difficult to say. Abraham Pais recalled, for instance, that Hermann Weyl once remarked to him that Erwin Schrödinger "did his great work during a late erotic outburst in his life." (Pais, 1986, 252) We now know what Weyl meant from Walter Moore's revealing biography of Schrödinger. (Moore, 1989) But most physicists, although they are willing to discuss such questions privately, rarely discuss them in public or in print, even when the subject has been dead for many years. A prominent exception is Max Dresden's courageous biography of H. A. Kramers. (Dresden, 1987) In general, because physics is a strongly hierarchical discipline in which one physicist knows pretty accurately the position occupied by another (with those at the very top being objects of great admiration, even awe), it is difficult for one physicist to write candidly about another; it is far easier to emphasize objective scientific results and to underplay subjective personal factors, even when writing biographies or obituary notices. Personal matters are felt to be irrelevant at best and in bad taste at worst, the net result in either case being that they are not usually discussed in print. I. I. Rabi remarked with tongue in cheek that before the second world war he used to tell his friends and students that *the history of a physicist's life was very simple. He was born; he became interested in physics in some way...; he wrote his thesis and received his Ph.D. degree; he died. The rest and the essential part of this biography could be read only in the scientific journals.... (Rabi, 1960, 1- 2)*

There are two common ways in which physicists use history of physics. First, some textbook authors include historical introductions or chapters, the intention being to give the reader, usually an undergraduate student, some appreciation for the effort that went into establishing the subject under discussion and to stimulate interest in it [12] . Second, physicists while lecturing often tell anecdotes, for example about physicists who have had an equation or effect named after them. The fundamental question - to which I will return below - is whether these common uses of history by physicists do physicists more harm than good.

HISTORY OF PHYSICS IN PHYSICS EDUCATION

According to some recent data, in the United States, of the 3,000,000 high school seniors per year only about one- fifth (623,000) take physics and less than one- tenth (275,000) go on to take an introductory physics course in a college or university. At that point the attenuation is really startling: Of that one-tenth or 275,000 students, less than 2 percent or only 5,300 go on to receive bachelor's degrees in physics, and a mere 0.4 percent go on to receive doctor's degrees in physics. (Neuschatz, 1989, 35 [Figure 5]) Put another way, only 0.04 percent of the high school seniors in the United States eventually acquire first- hand experience in physics research at the doctoral level. A truly overwhelming 99.96 percent of the high school seniors graduating each year in the United States, and consequently almost the entire future citizenry of the country - even the educated citizenry, including lawyers, politicians, and businessmen - have no direct acquaintance whatsoever with physics at a creative, research level. This state of affairs has enormous implications for the future welfare of the nation and for the continued support of physics. My focus, however, will be much narrower; I wish to discuss the image of physics and physicists that is gained by the 275,000 students each year who actually do take an introductory course in physics but then for the most part do not go on to become professional physicists.

Part of that image is formed by the history of physics these students learn, and this is my principal concern here. Both textbooks and teachers typically treat the history of physics in the linear fashion noted above - a more or less straight-line development from one theoretical or experimental high point to another, the high points being associated with some of the greatest names in the past. Such linear history implicitly conveys at least two messages to students. First, it suggests that physics progresses in an almost programmed fashion: start the machine at any time, and in the near future it will have produced a new discovery; nothing can stop or impede it. Second, such linear history suggests that physicists are people - mostly white males, of course - of superhuman intellectual capacities; physics is not a discipline for ordinary mortals such as young and inexperienced students [13]. These two messages combine to send a third: Physicists, those superhuman beings, can accomplish anything, can make any discovery - just feed them some money, point them at a target, and in no time at all they will score a bull's eye. That this public perception, at least in the United States, is not too wide of the mark may be gathered from the rapidity with which its citizens, from the president on down, became captivated by that futuristic fantasy, the Strategic Defense Initiative or Star Wars.

I hasten to add that linear history taught in introductory physics courses was probably not the only factor contributing to Star Wars. Nevertheless, such history does contribute to the public perception of physics and physicists. Certainly, it would be healthier if the public had a more accurate picture of the nature of scientific discovery, as encapsulated for example by the physical chemist Frederick Soddy:

though you may foster in a general way the discovery of new knowledge,... you cannot command the discovery of any new knowledge in particular. The attitude of the man of science is not that of the technologist or engineer. He sets forth into an unknown land not to discover anything definite, anything of use to anyone, but to discover what there is in the unknown to be discovered, however apparently commonplace and unimportant it may seem. The grander the discovery, the more trivial and utterly useless it often appears at first sight. (Soddy, 1920, 55)

Other benefits also would follow from an accurate historical portrayal of physics and physicists. I will give a few examples of what I have in mind. First, consider Albert Einstein's light-quantum hypothesis and its principal experimental supports, Robert A. Millikan's photoelectric effect experiments and Arthur Holly Compton's X-ray scattering experiments. The standard textbook and lecture account is that Einstein proposed his light-quantum hypothesis in 1905 as an explanation of the photoelectric effect, that Millikan's experiments of 1915 provided the first proof of Einstein's hypothesis, and that Compton's experiments of 1922 established it beyond doubt. The linearity and brilliance of this account are clear: The greatest physicist of the twentieth century boldly proposed an interpretation of a puzzling experimental result, a decade later an extraordinary experimentalist confirmed the prediction, and yet another seven years later another extraordinary experimentalist put the icing on the cake. There is not much room in this story for ordinary mortals or mistakes.

An accurate historical account would present a rather different picture [14]. Einstein did not arrive at his light-quantum hypothesis in 1905 in response to an experimental puzzle, but from general theoretical considerations grounded in the statistical interpretation of the second law of thermodynamics; the photoelectric effect was only one of three possible experiments that promised confirmation. By 1915, following a long series of experiments, Millikan and his students finally confirmed the predicted linear relationship between the frequency of the incident radiation and the maximum energy of the ejected photoelectrons. However, Millikan categorically rejected Einstein's light-quantum hypothesis as an interpretation of his experiments - despite his own words to the contrary in his later, self-aggrandizing autobiography. (Millikan, 1950, 101- 102) Compton in fact began his postdoctoral career in 1916 in an atmosphere of virtually universal skepticism toward Einstein's light-quantum hypothesis. His struggles over the next seven years built partly upon the work of well known people such as C. G. Barkla, but also partly upon that of lessor lights such as D.C.H. Florance and J. A. Gray. Then, as Compton's own X-ray scattering experiments progressed, he rejected one interpretation after another, misread his experimental data, then read it correctly, and in general struggled on his own to the extent that Einstein's name does not appear once in Compton's published papers. In the end, moreover, Compton was nearly scooped in his discovery by Peter Debye, who by contrast was directly influenced by his knowledge of Einstein's light-quantum hypothesis.

Hearing this story instead of the standard account, students would receive a rather different impression of physics and physicists. First, they would learn that the relationship between theory and experiment in physics is far from simple and depends upon the particular historical circumstances at a given time. They would see physics as an open-ended quest for knowledge, a lesson whose importance has been emphasized by Yehuda Elkana. (Elkana, 1970, 32) "A great discovery," said J. J. Thomson, "is not a terminus, but an avenue leading to regions hitherto unknown." (Quoted in Rayleigh, 1942, 264) Second, students would see that even an experimental physicist as great as Millikan could be dead wrong in his theoretical views - and then could try to mask his error much later in life by presenting a patently false historical account in his autobiography. Third, students would learn that progress in physics depends upon a great many people, and not simply upon the giants of a particular age. Fourth, they would see that even Compton, one of the greatest experimentalists of this century, could misread his experimental data and could propose incorrect theoretical interpretations of it - an insight that has come as a great relief to students when I have talked about this story. Finally, students would come to understand that research in physics is highly competitive, and consequently that simultaneous discoveries are not so uncommon and do not imply, for example, any unethical behavior such as plagiarism.

This example deals largely with "internal" history of physics; a second one, involving an intense controversy between researchers in Cambridge and in Vienna during the 1920s on the artificial disintegration of elements, brings in psychological and institutional factors as well [15]. Here there really is no standard textbook or lecture account; instead, there usually is just the bald statement that Ernest Rutherford in 1919 (just before leaving Manchester for Cambridge to succeed J. J. Thomson as Cavendish Professor of Experimental Physics) bombarded nitrogen with alpha particles, producing an isotope of oxygen and a proton, thereby proving for the first time that he had artificially disintegrated the nitrogen nucleus. From a historical point of view, this statement represents quite a remarkable compression of events, entirely eliminating almost a decade of history that offers great insight into the nature of scientific activity.

In the first place, Rutherford did not believe in 1919 that he had produced an isotope of oxygen; instead, he believed that the incident alpha particle struck and expelled a proton circling like a satellite inside the nitrogen nucleus, leaving an isotope of carbon behind. This satellite model guided Rutherford and James Chadwick's researches at the Cavendish Laboratory throughout most of the 1920s. However, both Rutherford and Chadwick's experiments and Rutherford's satellite model were attacked strenuously by two physicists working in the Institut für Radiumforschung in Vienna, Hans Pettersson and Gerhard Kirsch. Pettersson and Kirsch concluded from their own experiments that instead of alpha particles being able to disintegrate only some light elements, as Rutherford and Chadwick believed, they could disintegrate all of them. Furthermore, instead of expelling proton satellites, they argued that the incident alpha particle triggered an explosion inside the target nucleus, thereby releasing protons. This controversy - which pitted researchers in two prominent laboratories against each other - was not resolved until the end of 1927, when Chadwick visited Vienna and discovered that Pettersson and Kirsch had subtly biased their assistants who were actually observing the scintillations that were being produced by the disintegration protons - they had fallen prey to a psychological effect, as in the earlier and more famous case of René Blondlot and his N Rays. (Nye, 1980; 1986, 33- 77) This finally brought home to Rutherford and Chadwick and their contemporaries the necessity of replacing human observers with electrical counting techniques. Ironically, while Rutherford and Chadwick triumphed in their controversy with the Vienna researchers, within a year Rutherford's theory came under attack once again, this time by George Gamow wielding the weapon of quantum mechanics, and Rutherford was indeed forced to abandon it.

Students learning about this episode in the history of physics might glean several insights from it. First, they would see that even Rutherford, who is often regarded as the greatest experimental physicist of this century, was deeply concerned with theory and in fact never divorced theory from experiment in his own mind - an outstanding illustration of just how intimately theory and experiment are bound up with each other [16] . Second, students would learn that competition can be a powerful motivating force in physics, and that not only individual reputations but also institutional reputations can be strongly affected by the outcomes of intense scientific controversies. Third, this story shows that subjective psychological factors can play a role in scientific observations and lead to error. Fourth, students would learn that progress in physics is strongly tied to technical innovations, in this case techniques for counting charged particles, and that one goal of physicists is to make these as objective and reliable as possible.

A final example offers still other insights into the nature of scientific activity. To understand how it was possible for Lise Meitner and Otto Robert Frisch to interpret Otto Hahn and Fritz Strassmann's discovery of nuclear fission correctly in December 1938 on the basis of the liquid-drop model of the nucleus, I examined the development of that model in detail. (Stuewer, 1994) I found that it occurred in two distinct stages, from 1928- 1935 as a result of work by George Gamow, Werner Heisenberg, and C. F. von Weizsäcker, and from 1936- 1938 as a result of work by Niels Bohr and his collaborators. The earlier stage focussed on the application of the liquid-drop model to mass-defect calculations - static features of the model - while the later stage focussed on its application to nuclear excitations - dynamic features of the model. Meitner was embedded in the former tradition in Berlin, while Frisch was embedded in the latter tradition in Copenhagen. Then, in July 1938, Meitner was forced to flee Berlin, and over the Christmas holidays in late December 1938 she met her nephew Frisch in Kungälv, Sweden, thus bringing these two traditions together during their discussions and producing an entirely new application of the liquid-drop model - the correct interpretation of nuclear fission.

In the first place, this story could convey to students something of the nature of scientific creativity. We recall Arthur Koestler's analysis of the creative act, in which he argued that it lay in the merging of what he called different "matrices" of thought. (Koestler, 1964, 207) It appears that something of this sort occurred here: Meitner and Frisch brought to their meeting very different conceptual frameworks pertaining to a particular nuclear model, and they found that they could combine them in an entirely novel way. Second, as in the earlier examples, students could learn here about the extraordinary personal lives of some physicists. Third, this story shows just how strongly political events can influence the development of science, because both Frisch and Meitner were forced into exile by the brutal racial policies of the Nazis, Frisch soon after the promulgation of the Nazi Civil Service Law in April 1933, Meitner soon after the Anschluss of Austria in March 1938. Students, as future citizens, should understand that the laws, policies, and actions of their government can impinge directly on the scientific health of their country: Science, in common with all of the highest cultural achievements of a nation, cannot be taken for granted but is a delicate plant that requires constant nurturing and support.

COMPLEMENTARITY REVISITED

The complementarity of objectives, sources, tools, and principles of the physicist and the historian in research thus carries over to teaching. The physicist designs and teaches courses based upon logical considerations; he or she primarily teaches results - the principles, laws, and concepts that are the culmination of centuries of intellectual effort. The historian designs and teaches courses that focus primarily on the intellectual, social, and political contexts in which those principles, laws, and concepts were discovered, and on the personalities and lives of their discoverers. The physicist is more or less constrained to reduce history to vignettes or anecdotes. The historian also enjoys vignettes or anecdotes, but is not satisfied with the picture of physics and physicists they convey.

Thus, students who receive their only exposure to physics and physicists through physics courses as commonly taught will gain an image of physics and physicists that departs significantly from reality. History of physics, accurately taught, can serve as a powerful corrective force: Through history, students can acquire an understanding of the nature of physics, as practiced by real physicists. Teaching in physics and in history also seem complementary; they are to a great extent mutually exclusive, but both are necessary, I would argue, to give students a full understanding of the nature of physics as an intellectual and human activity.

IMPLICATIONS

Everyone's best interest is served by promoting an accurate understanding of science. In particular, physicists are best served by promoting an accurate understanding of physics among non-physicists - a point convincingly made in a recent survey of high school physics teachers in the United States. That survey supported the finding of other studies, "that broadening physics literacy among all students and preparing future professionals for further work in the field are complementary rather than competing goals," that is, "there is a synergistic effect between physics education for the mass of nonscience students and physics education for future scientists." (Neuschatz, 1989, 34- 35 [17]) The better the one, the better the other; the better citizens in general understand physics, the better will be the cultural climate for physicists. Erwin Schrödinger years ago lamented the "tendency to forget that all science is bound up with human culture in general, and that scientific findings, even those which at the moment appear the most advanced and esoteric and difficult to grasp, are meaningless outside their cultural context." (Schrödinger, 1952, 3; 1984, 478)

Science is the most powerful and pervasive force affecting countries of the world today - their economic health, political stability, and cultural vitality. But force is exerted in both directions; physicists depend upon governmental support for their research and livelihoods. "We are in real danger," Carl Sagan warned, "of having constructed a society fundamentally dependent on science and technology in which hardly anyone understands science and technology. This is a clear prescription for disaster." (Sagan, 1989) Frederick Soddy put it more pithily when arguing that scientists should always be aware of the societal context in which they work: "Most fish," he wrote, "probably remain utterly oblivious to the existence of water until rudely hauled into the upper air." (Soddy, 1920, 3)

Physicists and scientists in general also would benefit if the public and their representatives in government thoroughly understood the profound difference between scientific fraud and error - to pick another topic of current concern in the United States. Physicists have a particular stake in clarifying this distinction because fraud in physics is virtually unknown [18] . Error, by contrast, has been rather common, and indeed often has led to progress. But there is little room for honest error in a linear history of physics. Only if students and the general public come to understand that the course of physics is charted through many false byways will they come to appreciate the positive role played by scientific error.

The history of physics also offers lessons in another direction [19] . In democracies there is a strong commitment to egalitarianism, to the belief that people deserve equal treatment as human beings no matter what their position in life might be. At the same time, class distinctions do exist among people occupying jobs of different social status. In this situation it might be well to point out that a good many physicists began life in humble socio-economic circumstances and yet reached the very pinnacle of their profession - one thinks immediately, for example, of Michael Faraday, J.J. Thomson, or Ernest Rutherford. The history of physics also shows that progress often has depended upon the close cooperation of technicians and physicists. Thomson and Rutherford, for example, thoroughly appreciated what every experimental physicist knows, namely, that the knowledge and skills of technicians are essential for success, and that when physicists and technicians work together toward a common goal a deep mutual respect develops. A physics laboratory, in some sense, is a microcosm of an egalitarian, democratic society, and as such might be an object of study by those who are concerned with the dynamics of human dignity.

The general public, of course, views physics and physicists radically differently. E. E. Fournier d'Albe captured that public image in a biography of William Crookes published as long ago as 1924:

to the general public the man of science is a man of mystery, a man of inhuman and somewhat unaccountable tastes. Not everyone goes so far as to maintain that he is a freak because he indulges in an activity "with no money in it." But it seems to be generally agreed that the "scientist" is a being living outside ordinary human spheres, not amenable to ordinaryhuman standards, a being who is usually harmless but may quite conceivable become dangerous.... (Fournier d'Albe, 1923, 2)

Norbert Wiener asserted in 1950 that to the average man in the street

the scientist is exactly what the medicine-man is for the savage; namely, a mysterious ambivalent figure, who is to be worshipped as the carrier of recondite knowledge and the agent of recondite powers; and who is at the same time to be feared, even hated, and to be put in his place. The medicine-man may be a power, but he is a very acceptable sacrifice to the gods. (Wiener, 1950, 215)

Spencer R. Weart has shown just how persistent the image of the physicist as a mad scientist has been. (Weart, 1988a, 1988b)

This image could hardly be otherwise if physics students and the general public learn nothing substantial about the personal lives of physicists in lectures or textbooks owing to a feeling that it is somehow improper to discuss such matters. It is hardly surprising, but quite remarkable nevertheless, that despite their high accomplishments and aesthetic sense, only rarely have physicists been portrayed as central figures or heroes in novels, while artists, lawyers, doctors, and politicians, for example, figure prominently in them. Even though physicists often have been compared to detectives [20] , the number of physicists portrayed in popular literature is vanishingly small compared to the number of detectives. Novelists and writers apparently view people in many professions as sympathetic members of the human race, but physicists rarely qualify for inclusion; they are seen as coldly logical thinkers, unmoved by ordinary human emotions and passions. The history of physics reveals that this is hardly the case. "The life of a great scientist in his laboratory," wrote Marie Curie, "is not, as many may think, a peaceful idyll. More often it is a bitter battle with things, with one's surroundings, and above all with oneself." (Curie, 1926, 144)

CONCLUSIONS

History and science, and in particular history of physics and physics, I have argued, are complementary - they are to a considerable degree mutually exclusive, but both are necessary for students to understand the nature of physics. If there is some validity to my argument, the central question becomes how to bring the two together constructively. This is a difficult question, and one that has been around for a long time. I can offer no easy answers, but I can at least offer some observations.

Almost five decades ago, I. Bernard Cohen presented a paper entitled "A Sense of History in Science" at a meeting of the American Association of Physics Teachers in which he began with much the same premise as I have begun, namely, that history and science are words that are "often thought to be connotative of extremely different, if not mutually exclusive, disciplines." (Cohen, 1950, 343 [21]) A principal goal of Professor Cohen's paper was to bridge the two disciplines by acquainting physicists with books and articles in the history of physics, and offering pointers on how to distinguish the good ones from the bad. This was a valuable service, and a necessary one, because the history of science as a discipline was then in an embryonic stage: Professor Cohen could point to only three colleges or universities in the entire United States that then offered full-time employment in the history of science. (Ibid., 344) Five decades ago, about the only way to acquaint physicists with sources in the history of physics was through the written word.

Physicists today have an easier task. The history of physics has grown significantly as a discipline, and although the number of historians of physics in the universe is still small compared to the number of physicists, the former nevertheless are to be found today on the faculties of a fair number of colleges and universities, where they are available to provide information on historical sources, both published and unpublished, or answers to historical questions. It is quite possible today, as A. P. French urged in 1983, for physics teachers "to make use of scientific history as unearthed by professional historians." (French, 1983, 216) This points to an essential precondition for progress: Physicists and historians themselves have to be brought together in constructive ways to provide opportunities to develop mutual respect for each other as teachers and scholars. At times, professional isolation and even professional arrogance can impede communication, but these are expensive luxuries, and should not be encouraged. In some instances, historians have been appointed as members of physics departments, establishing a solid institutional basis for cooperation - by jointly teaching undergraduate and graduate courses, arranging historical colloquia, and the like. In other instances, physicists and historians have cooperated across departmental boundaries. In still other instances, physicists themselves - following a venerable tradition - have become expert in the history of physics. In general, just as Max Planck in 1909 mistakenly felt that accepting Einstein's light quanta meant rejecting Maxwell's electromagnetic waves, (Planck, 1909) so physicists and historians today should not make the mistake of rejecting each other. History and physics, although seemingly complementary disciplines, might be merged in ways that would greatly benefit students and ultimately the general public.

FOOTNOTES

[1] This is a revised version of a paper first presented at a conference in Bielefeld, Germany, and published in (Misgeld & al., 1994, 41-68).

[2] Editions I have readily at hand are (Mach, 1896, 1908, 1921, 1925, 1942).

[3] See for example the bibliography (Heilbron and Wheaton, 1981).

[4] Two well-known textbooks that immediately come to mind are (Taylor, 1941) and (Holton, 1952 [1973]).   For a more complete list, see for example (Brush, 1972, Part I, 64-65). Professor Holton reflected on his teaching experiences in (Holton, 1971).

[5] The proceedings of some conferences that have been organized during the past quarter century are (Brush & King, 1972), (Bevilacqua & Kennedy, 1983), (Thomsen, 1986), (Blondel & Brouzeng, 1988), (Herget, 1989), and (Misgeld & al., 1994). Another conference was held at the first meeting of the History of Physics Group of the European Physical Society, St. John's College, Cambridge, August 28- 30, 1990.

[6] See, for example, some of the statements related by Professor French in (French, 1989), as well as (Kondo, 1955).

[7] For a discussion of the "logical" and "historical" methods, see (Brush,1969); see also (Brush, 1974).

[8] Private discussion while both of us were visiting professors in the Institute for Theoretical Physics of the University of Vienna, April 1989.

[9] In 1972, Martin J. Klein responded to remarks by Max Jammer with the words: "I agree that the methods of the scientist and of the historian are completely different, but I'm not so sure this creates a gap that needs to be filled; I don't see a conflict between them. In Bohr's terminology, these are complementary approaches." (Klein, 1972, 25) Clearly, I agree completely.

[10] From the famous essay (Butterfield, 1973[1931]).

[11] In a similar vein, Richard J. Weiss remarked that during a diversion in his life as a physicist some years ago he turned from physics to playwriting, and it was then that he "became aware that scientists make poor historians. They tend to focus in their hindsight on their own scientific achievements and less on matters of interest of historians (who are after the bigger picture, i.e. how do the interactions of people and ideas turn into history)." (Weiss 1987, 29)

[12] One of the best- known examples is (Richtmyer, 1928) and its subsequent editions written with various coauthors.

[13] When he was Director of the American Institute of Physics, Kenneth W. Ford pointed out negative effects when students receive the message that physics is an unusually difficult subject.(Ford, 1989)

[14] The account that follows is based especially upon (Klein, 1963) and (Stuewer, 1975).

[15] The following account is based upon (Stuewer, 1985).

[16] This point is brought out well in (Badash, 1987).

[17] For a more complete report, see (Neuschatz & Covalt, 1988).

[18] For pertinent remarks, see (Franklin, 1986, 226- 243).

[19] I became fully aware of the concern I discuss here while serving as a member of a study group on vocational- technical education convened by Professors George Copa and Robert Beck at the University of Minnesota between October 1988 and January 1989. This project was sponsored by a grant from the Office of Vocational and Adult Education, U.S. Department of Education.

[20] Two examples are (Einstein & Infeld, 1938, 4-5) and (Peierls, 1956, 15-16).

[21] See also (Cohen, 1952).

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Section B3, *History and Physics* from: Connecting Research in Physics Education with Teacher Education

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INTRODUCTION TO SECTION C

LauranceViennot
SectionEditor

This Section of the book is devoted to students' knowledge and learning. This is a topic which has been documented by what is probably the largest number of studies during the last two decades. The investigations have shown that before instruction on a given topic children and students usually hold a set of ideas and ways of reasoning in stark contrast to accepted physics, and that these ideas are often extremely resistant to instruction. Needless to say, only a part of these findings can be discussed here.

Learners' ideas in mechanics and electric circuits are the two topics that have been the most extensively investigated. The two first chapters, one by L.C. McDermott and the other by R. Duit, review the main results concerning each of these two domains. Both authors suggest ways of teaching that, given these findings, they think appropriate to improve the effectiveness of the teaching-learning process. A third chapter (by myself) concerns the common views of learners on some phenomena involving heat and temperature. Although devoted to thermodynamics, this chapter emphasizes some trends of reasoning that are transferable among various areas of physics, and are referred to as "linear causal reasoning", an extension of the "sequential reasoning" introduced in a preceding chapter. This reviews ends with an analysis of possible teaching goals concerning phenomena in thermodynamics and, more generally, multivariable problems.

Thus these three chapters illustrate to different extents the two approaches that may be adopted when investigating the commonly held views of learners: collecting common ideas on a particular topic, and seeking more general ways of reasoning. They also put forth some hypotheses, based on research results, about what might be elements of effective teaching from the perspective of making the learners as active as possible in the construction of their own knowledge. However, it is only with detailed evaluations of such suggestions that one can assess their relevance, a point discussed in Section E of this book.

A fourth chapter, by R. Millar, deals with students' understanding of scientific enquiry. It discusses similar elements of information, but faces the additional difficulty that there is no consensus in the scientific community about what is meant by "the scientific method". Investigations of students' understanding of scientific enquiry are grouped according to the views of their authors on the scientific approach, a model is proposed to improve the ability of students to carry out scientific investigations, and (sub)teaching goals are identified.

Note that an important aspect emerges from all these studies on learners' common understanding: one cannot investigate students' ideas in a given domain of knowledge without reexamining this knowledge, a process which may lead to new teaching goals. Content analysis and investigation of learners' common understanding are two necessarily interrelated approaches.

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Section C, *Introduction* from: Connecting Research in Physics Education with Teacher Education

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STUDENTS' CONCEPTIONS AND PROBLEM SOLVING IN MECHANICS

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INTRODUCTION

Results from research on student understanding in physics indicate that certain incorrect ideas about the physical world are common among students of a wide variety of national backgrounds, educational levels and ages. There is considerable evidence that university students often have many of the same conceptual and reasoning difficulties that are common among younger students. There is often little change in conceptual understanding before and after formal instruction. Moreover, students are often unable to apply the concepts that they have studied to the task of solving quantitative problems, which is the usual measure for student achievement in a physics course.

The number of empirical studies on student understanding in mechanics exceeds the number in all other domains combined. We have not attempted to summarize all the research that has been done. An important criterion for the choice of studies has been the degree to which the findings are directly applicable by university faculty to the preparation of teachers. In making this judgment, we have drawn on many years of experience in preparing elementary, middle and high school teachers to teach physics and physical science. Another consideration that has entered into the selection of references has been their relative accessibility to physicists in all countries. Physics publications have been given preference over less readily available references. Because of the rapid growth in the research literature, we have limited this review mostly to studies conducted among students at the university level, including prospective and practicing teachers. The findings, however, apply equally well to high school students and, in some instances, to children in the elementary grades.

INVESTIGATION OF STUDENT UNDERSTANDING

In this section, we give a brief overview of the current state of research on conceptual understanding and problem-solving ability in mechanics. Although instructors had long been aware that this material is difficult for students, the extent of the problem was generally not recognized until physicists and science educators began to conduct systematic investigations and document the results.

CONCEPT DEVELOPMENT

An earlier review of research on conceptual understanding in mechanics identified certain features that should be taken into account in interpreting the results of research (McDermott, 1984). The characteristics of an investigation that can affect the outcome include: the nature of the instrument used to assess understanding; the degree of interaction between student and investigator; the depth of probing; the form of the data; the physical setting; the time frame; and the goals of the investigator.

Kinematics

A study conducted among students taking introductory physics at a large university probed student understanding of the concepts of position, velocity and acceleration in one dimension by examining whether students could apply these concepts correctly in interpreting actual motions of real objects (Trowbridge and McDermott, 1980; Trowbridge and McDermott, 1981). During interviews, students observed two motions and were asked to compare velocities and accelerations. After instruction, about one-fifth of the students confused the concepts of speed and position. Virtually every failure to make a proper comparison could be attributed to the use of a position criterion to determine relative velocity. Confusion between the concepts of velocity and acceleration was even more common. Many of the 200 students who participated lacked even a qualitative understanding of acceleration as the ratio *v/*t.

Another study examined 'spontaneous' reasoning in kinematics among 700 first and fourth-year university students and 80 eleven-year old children (Saltiel and Malgrange, 1980). The students were asked to solve paper and pencil exercises involving uniform motion in Galilean reference frames. Analysis of their attempts to describe the motion revealed that many students were inappropriately using a causal model (i.e., invoking forces or other 'causes' of motion).

In a study of student understanding of two-dimensional motion, diagrams of trajectories of moving objects were shown to five students in an introductory university course and to five physics faculty (Reif and Allen, 1992). The participants were told whether the objects were speeding up, slowing down or moving with constant speed and were asked to draw the acceleration vectors at specified points. The novices did very poorly at these tasks; even the experts had some difficulties. A detailed analysis of how the two groups approached these tasks enabled the investigators to identify the underlying knowledge and skills required for successful performance.

Researchers from several countries participated in another study in which high school and university students were interviewed on their understanding of displacement, velocity, and frames of reference (Bowden et al., 1992). The results demonstrated the contextual nature of learning and showed that, as problems become easier to solve in a quantitative manner, it becomes more difficult to differentiate among students on the basis of their level of understanding of basic concepts.

Some investigations have focused on student understanding of the graphical representations of motion. A descriptive study that extended over several years and involved several hundred university students helped identify a number of common difficulties encountered by students in making connections between the kinematical concepts, their graphical representations and the motions of real objects (McDermott et al., 1987). Another study identified specific difficulties that students have with the graphical representation of a negative velocity (Goldberg and Anderson, 1989).

The persistence of certain difficulties in mechanics has been demonstrated not only through detailed studies conducted on a small scale but also through widespread administration of instruments designed to assess conceptual understanding. These have proved valuable for helping faculty become aware that many students who do well on quantitative examination questions may have serious conceptual difficulties. The tests noted in this chapter have been published in widely accessible journals.

An assessment instrument has been developed for testing the ability of students to interpret graphical representations of motion: the Test of Understanding Graphs in Kinematics (TUG-K) (Beichner, 1994). Test questions on the drawing and interpretation of motion graphs are also included in the Force and Motion Conceptual Evaluation (FMCE) (Thornton & Sokoloff, 1996).

Dynamics

Results from research have repeatedly demonstrated that students often emerge from introductory physics courses with many of the same incorrect beliefs that have been found to be prevalent before instruction. Misconceptions about the relationship between force and motion have been extensively studied. Less well documented are difficulties students have in interpreting the relationships between force and more complex concepts, such as work, energy and momentum. Below is a small sample of investigations on student understanding of dynamics.

Prior to instruction, more than 100 students in an introductory university mechanics course were given a short-answer test on concepts of force and motion (Champagne et al., 1980). The test used a technique abbreviated as D.O.E. (demonstration, observation, explanation). The results revealed that the students, who had previously studied physics, had many incorrect ideas: a force will produce motion; a constant force produces constant velocity and the magnitude of the velocity is proportional to the magnitude of the force; acceleration is due to an increasing force; and in the absence of forces, objects are either at rest or slowing down. The results of another study also indicated that both before and after an introductory course in mechanics many students seem to believe that motion implies a force (Clement, 1982). The study involved written tests and interviews about a pendulum and a coin tossed in the air.

The subject of another investigation was the extent to which individual students consistently applied alternate concepts of force (e.g., 'motion implies a force') in different contexts (e.g., bodies moving and bodies at rest) (Finegold and Gorsky, 1991). Over 500 university and high school students in Israel attempted written tests, while 35 students participated in interviews. The test consisted of questions about the forces acting on various objects such as a book at rest on a table, a pendulum bob, a cannonball in flight, etc. For questions concerning objects in motion, the authors found that students who included a force acting in the direction of motion only included this force in some situations. The belief that no forces act on an object at rest was prevalent.

A study was conducted among European students drawn from the last year of secondary school through the third year of university (Viennot, 1979). Responses to paper-and-pencil exercises on situations such as a mass oscillating on a spring were analyzed. The results indicated that many students assume a linear relationship between force and velocity.

In a study involving curvilinear motion and trajectories of moving objects, about fifty undergraduates were asked to trace the path that a pendulum bob would follow if the string were cut at each of four different positions along its path (Caramazza et al., 1981). Only one-fourth of the students gave an essentially correct response. About 65% drew a line straight down for the case when the string was cut at the equilibrium position.

Some studies have examined student difficulties with situations involving gravity. A study of several hundred first-year university students in Australia involved the use of simple lecture demonstrations related to gravity (Gunstone and White, 1981). For example, students were asked to compare the time it would take equal-sized steel and plastic balls to fall from the same height. On this task, three-quarters of the students predicted different times. Most believed that the heavier object would fall faster. A tendency to "observe the prediction" was noted. Common incorrect answers, illustrated with student quotes, are discussed in detail in the paper that reports on this study.

Another Australian study was based on questions on a multiple-choice, end-of-high-school examination in physics taken by 5500 students (Gunstone, 1987). The test items were based on situations involving gravity that had proven revealing in previous, smaller-scale studies (see above). Certain incorrect ideas were found to be highly prevalent among this population. One test item concerned an Atwood's machine with two weights initially at rest at the same height. The students were asked to predict what would happen if someone were to lower one weight to a new location, hold it there, and then release it. More than half of the students predicted that the weights would then move. When this task was repeated in an open-ended format, a majority of students who answered incorrectly expressed the belief that the weights would return to their 'equilibrium' position.

In a study of student understanding of the Atwood's machine, it was found that many students had serious difficulties with the acceleration, the internal and external forces, and the role of the string (McDermott et al., 1994). The same research group had also investigated student difficulties with applying the work-energy and impulse-momentum theorems to the analysis of actual motions (Lawson and McDermott, 1987). After studying the relevant material, most of the students were unable to relate the algebraic formalism learned in class to the simple motions that they observed.

The Force Concept Inventory (FCI) is a multiple-choice test developed to assess student understanding of Newtonian dynamics (Halloun and Hestenes, 1985; Hestenes et al., 1992). This test is intended to determine whether students are able to distinguish between correct Newtonian answers and popular but erroneous "commonsense" beliefs. The same authors have developed another multiple-choice test, the Mechanics Baseline Test (MBT), which covers a greater range of topics in Newtonian mechanics than does the FCI (Hestenes and Wells, 1992). In a survey of 6,000 high school, college and university students, who had taken the FCI before and after instruction in mechanics, it was found that the largest increase in scores occurred among students who had been interactively engaged in activities that yielded immediate feedback through discussion with peers or instructors (Hake, 1996). This report has been submitted for publication.

Although the results obtained with the assessment instruments described above are encouraging, they should be interpreted with care. It is impossible to tell in any multiple-choice test when a correct answer is given for the wrong reasons (Sandin, 1985). Such tests can be used as indicators of the initial state of individual students. However, as McDermott and her colleagues in the Physics Education Group have discussed, good performance on these tests should be viewed as a necessary but not sufficient condition for the attainment of a proper conceptual understanding (O'Brien Pride et al., 1997).

PROBLEM-SOLVING ABILITY

It has been in the domain of mechanics that the ability of students to solve physics problems has been most thoroughly investigated. Problem solving has been used by cognitive psychologists and cognitive scientists as a context for examining thought processes. Research on problem solving that has direct relevance to the teaching of physics has been discussed in a comprehensive review (Maloney, 1994). In the studies discussed below, the process through which individuals at different stages of expertise in physics attempt to solve problems in dynamics is examined and analyzed.

A study attempted to identify differences in the ways that experts and novices solve physics problems (Chi et al., 1981). The subjects included undergraduates who had completed a single course in mechanics, an advanced undergraduate physics major, a physics graduate student, and a physics professor. Among the findings were the tendency for experts to categorize problems according to "deep structure" while novices tended to categorize according to surface features.

In one study, problem solving was analyzed in terms of three main stages: description and analysis of the problem, construction of a solution, and testing of the solution (Reif, 1983; Reif, 1995). An analysis of these stages indicated that the components of problem solving are too complex to be learned through examples and practice. The ability to solve problems depends not only on the learning of procedures but also on the ability to draw on appropriate ancillary knowledge (Reif, 1985).

APPLICATION OF RESEARCH TO INSTRUCTION

A major motivation for conducting research on student difficulties is to use the results to guide the development of curriculum that matches the needs and abilities of students. The results from all of the studies discussed above are consistent with a perspective on teaching and learning that can be broadly categorized as "constructivist." Two important elements of the constructivist view of how scientific knowledge is acquired can be summarized as follows:

All individuals must construct their own concepts, and the knowledge that they already have (or think they have) significantly affects what they can learn. The student is not viewed as a passive recipient of knowledge but rather as an active participant in its creation. This view of learning is in sharp contrast to the transmissionist view in which it is assumed that information can be delivered directly to students in a usable form, if only it is stated clearly enough. The implication is that listening to lectures, reading the textbook and practicing problem-solving should enable them to develop a functional understanding of physics, i.e., the ability to do the reasoning needed to apply appropriate concepts and principles in situations not previously memorized.

Below are some examples of instructional strategies and materials that reflect a constructivist approach. Although taken from curriculum that has been developed in the United States, the examples have much wider applicability. The examples illustrate the application of research to instruction and are also relevant to teacher preparation.

CONCEPT DEVELOPMENT

Instructional materials have been specifically designed to help prospective and practicing teachers develop the conceptual understanding and reasoning skills necessary to teach science as a process of inquiry (Rosenquist and McDermott, 1987; McDermott et al., 1996). This conceptual approach to teaching kinematics engages students in structured laboratory-based activities designed to help them develop a qualitative understanding of instantaneous velocity, constant acceleration and the distinction between these two concepts. There is an emphasis on helping students develop the ability to translate back and forth between actual motions and their graphical representations. These materials have been developed through an iterative process of research, curriculum development and instruction (McDermott, 1991). In addition to systematic research, the initial design of the materials drew on the insights of an experienced instructor who had examined student understanding in less formal ways (Arons, 1977; Arons, 1994).

A study was conducted to examine the disparity between the precise use of technical terms by scientists and the indiscriminate use by students. The results suggest a general instructional strategy for minimizing linguistic complications in the teaching of mechanics. (Touger, 1991).

Ongoing research in the classroom guided the development of an instructional strategy to address the difficulty that students frequently have in acknowledging that a stationary surface can exert a normal force on an object with which it is in contact (Minstrell, 1982). In this approach, the normal force exerted by a table on a book is made plausible by having students consider the book in a series of similar physical situations that are more intuitively acceptable (e.g., on a hand, on a spring, on a flexible surface, etc.). In a related curriculum development project, analogies have been used as a bridge between students' incorrect beliefs and Newtonian ideas (Clement, 1993).

A general instructional strategy for helping students overcome some common conceptual difficulties involves the use of microcomputer-based laboratory activities (Thornton and Sokoloff, 1990). For example, in kinematics, the students create real time position, velocity and acceleration versus time graphs of motions, including their own. The instant feedback helps make explicit the connections between motions and their graphical representations. These and other microcomputer-based activities have been incorporated into an introductory course that is entirely laboratory-based (Laws, 1991). Evaluation of the curriculum by pretests and post-tests indicates that learning and retention are significantly better than in courses taught by traditional methods. In a different type of laboratory-based approach students perform simple experiments that are designed to form a basis for a Socratic dialogue (Hake, 1987; Hake, 1992).

Interactive lectures have been increasingly used in introductory physics courses as a means of engaging students intellectually. In one new curriculum, the instructor conducts interactive lectures during which students analyze physical situations with the help of worksheets (Van Heuvelen, 1991a; Van Heuvelen, 1991b). The students' first encounter with a topic is qualitative; quantitative analysis follows. Peer instruction is another approach that has been used to secure the active involvement of students in large lecture-based courses (Mazur, 1996). At several points during a lecture, the instructor presents a qualitative question and multiple-choice responses that together are designed to reveal common conceptual difficulties. After recording their response, the students are asked to converse with their neighbors and to revise their answers if they choose.

Carefully sequenced qualitative questions for use in small group tutorials and in interactive tutorial lectures have been developed to supplement the lectures, textbook and laboratories that characterize traditional instruction (Shaffer and McDermott, 1992). Research has been used as a guide throughout the development of this supplementary curriculum, which has been designed to promote the growth of conceptual understanding and reasoning skills. To foster conceptual change, the materials often make use of an instructional strategy in which the tendency to make a particular error is first deliberately exposed and then explicitly addressed. The procedure may be summarized as a sequence of steps: elicit, confront and resolve (McDermott, 1991).

The process through which students can be encouraged to make a conceptual change has also been examined from several theoretical perspectives. One model for learning describes conceptual change in terms of conflict between the learner's existing conceptions and new conceptions (Hewson and Hewson, 1984). It is suggested that the learner may agree to adopt a new conception if it is 'intelligible, plausible, and fruitful.' There are a number of other factors that are important, including the degree to which an individual student is committed to internal consistency.

It has been suggested that processes of conceptual change can be organized into three types: 'differentiation,' 'class extension,' and 'reconceptualization' (Dykstra, 1992). In differentiation, new concepts emerge from more general ideas (e.g., velocity and acceleration from motion). In class extension, concepts considered different are found to be the same (e.g., rest and constant velocity). In reconceptualization, a significant change takes place (e.g., force implies motion becomes force implies acceleration).

In another model, student knowledge is described in terms of pieces or 'facets' that may be related to content, strategies or reasoning (Minstrell, 1992). An example of a facet is the notion that 'heavier objects fall faster,' an idea that is usually incorrect but may be valid in certain contexts. In this model, instruction is seen as an effort to help students modify existing facets and add new facets. Instruction is viewed as a process of helping students incorporate existing and new facets into a correct conceptual framework.

PROBLEM-SOLVING ABILITY

Curriculum has been developed specifically to improve students' problem-solving competence. A series of studies investigated the abilities needed for understanding a relation such as a definition or a law (Reif et al., 1976; Reif, 1981). An instructional strategy was developed to teach the general method of acquiring an understanding of such a relation. An explicit problem-solving strategy, involving the application of the relation was taught. The results of a study on the effects of knowledge organization on task performance suggest that a hierarchical presentation of information improves the ability of students to solve certain types of problems (Eylon and Reif, 1984).

A strategy for teaching problem-solving skills using cooperative groups has been developed in which problem-solving sessions have taken the place of standard recitations as a supplement to labs and lectures (Heller et al., 1992; Heller and Hollabaugh, 1992). Context-rich problems are assigned for group work. These problems differ substantially from end-of-the-chapter problems in traditional textbooks. They place the student in a real situation in which physics must be used to devise a solution to a problem. The information provided to the students may include irrelevant facts and may be incomplete. Tests of the approach helped identify a number of factors that are important for its effectiveness, including the structure of the groups and the training provided for teaching assistants.

Another type of instructional strategy for problem solving was designed for use in large lecture classes. Students are taught to begin the solution of a problem by writing a qualitative description. The students identify the relevant concepts and principles and justify the selection they have made. They then describe how to apply the concepts and principles to find a solution (Leonard et al., 1996).

COMMENTARY

Some of the experimental studies discussed above have focused entirely on the identification and analysis of student difficulties, while others have included the design and testing of instructional strategies that address these difficulties. The results from all of these studies, taken together, support the following generalizations on learning and teaching (McDermott, 1993).

Facility in solving quantitative problems is not an adequate criterion for functional understanding.

Questions that require qualitative reasoning and verbal explanations are essential.

As course grades attest, many students who complete an introductory physics course can solve standard quantitative problems, such as those at the end of the chapter in a typical textbook. Success on such problems, however, does not ensure that students have developed a functional understanding, i.e., the ability to do the reasoning needed to apply appropriate concepts and principles in situations not previously memorized. For many students, solving such problems is a relatively passive experience. Problems that require qualitative reasoning and verbal explanations demand a higher level of intellectual involvement. There is evidence from research that students who have had experience in solving qualitative problems do as well, and often better, on quantitative problems than those who have spent more time in traditional problem-solving (Shaffer and McDermott, 1992; Thacker et al., 1994). More importantly, students who have worked through qualitative problems do much better on such problems than other students and are able to give much better physical explanations.

This result suggests the following sequence of instruction. The study of a new topic should begin by helping students develop a qualitative understanding of the material from direct experience or observation when possible. Mathematics is often introduced very early in the typical presentation. Unfortunately, once equations appear, students tend to avoid analyzing situations qualitatively. Mathematical formalism should be postponed until after students have had some practice in qualitative reasoning about the phenomena under study. Moreover, students should be asked to synthesize the concepts and mathematics and articulate the relationship in their own words.

A coherent conceptual framework is not typically an outcome of traditional instruction.

Students need to participate in the process of constructing qualitative models that can help them understand the relationships and differences among concepts.

Concept development is an iterative process, one of successive refinement. The first encounter with a new concept should be closely tied whenever possible to the observations and experience of students. Successive refinement should take place in a spiraling fashion as students recognize the need to account for new phenomena.

Certain conceptual difficulties are not overcome by traditional instruction.

Persistent conceptual difficulties must be explicitly addressed by multiple challenges in different contexts.

In instances in which it is known from research or teaching experience that students will have certain difficulties, it is important that the tendency to make a particular error be deliberately exposed and then explicitly addressed. Once an error is elicited through an appropriate task, the student can be helped to recognize and confront the difficulty. At that point, it is crucial that the instructor insist that the difficulty be resolved. If this is not done, the difficulty is likely to remain latent and arise later in a different context.

Research and experience in preparing teachers have demonstrated the need for special courses for teacher preparation (McDermott, 1990). Two generalizations are especially relevant to the preparation of teachers. Both are strongly supported by research and teaching experience.

Teaching by telling is an ineffective mode of instruction for most students.

Students must be intellectually active to develop a functional understanding
and

Most teachers tend to teach as they have been taught.

Teachers should be given the opportunity to learn the content that they will be expected to teach in the manner that they will be expected to teach .

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COMMENT ON C1: STUDENTS' CONCEPTIONS AND PROBLEM SOLVING IN MECHANICS (L.C. McDermott)

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This chapter is very useful because it provides the means to find, in the research literature, many results concerning common students' and trainee teachers' ideas concerning mechanics. Numerous now classical tests as well as the main predictable errors can therefore be collected by the reader.

Moreover, a viewpoint which is compatible with research findings is stated and proposed as a basis for teaching strategies: the learner should be in a position of being as active as possible in the building of his or her own knowledge. There is now a large consensus among researchers on that point, as is widely shown in this book.

On that basis, the author recommends emphasizing, in teaching and teachers' training, the following aspects: qualitative analysis, explicit addressing of common ideas, debating, and this *à propos* of open situations of problems in various teaching contexts.

With these elements of information and of reflection, the reader has a decision to make. Will she/he make the predictable difficulties and errors explicit one by one, test by test, one situation being considered at a time? On the contrary, will the learner be informed of the "logic" which seems to underlie a set of common ideas. In the latter case, which scale should we adopt in the grouping of ideas, which ones should we account for together. Available elements to guide this choice seem contradictory.

On the one hand, a dependency of common errors with respect to the type of situation is observed. For instance, some questions very frequently raise a classical error, i.e. to assume a linear relationship between force and velocity, whereas other questions which are at first sight in the same domain very rarely give rise to the same error (Viennot 1979).

On the other hand, striking similarities exist between answers concerning physical situations which are usually dealt with in different chapters. For example, propagation of sound and motion of a projectile are commonly analyzed in a similar way: a dynamical "supply" due to the source seems to act as a permanent cause all along the progression (of the projectile or of the sound), to get lower in case of an opposing agent, and to determine at every time the velocity of the projectile or that of the sound (Maurines 1992).

Scattered knowledge on the one hand, unifying links on the other hand: in fact, common ideas do not "coagulate" according to the domains defined by traditional chapters. They can be accounted for to a large extent assuming ways of reasoning in which causality and time are central elements (Driver et al. 1985, Andersson 1986, Rozier and Viennot, 1991, Gutierrez et Ogborn 1992, Viennot 1993).

The main features of these reasonings are the following: linear character of causal analysis (one cause for one effect), ascribing of a cause (which is an undifferentiated amalgam of our physical concepts) to the object in evolution (and/or the "storage" of an initial cause in this object), temporal shift between cause and effect (Viennot 1996).

On this basis, one can understand why it is so often (wrongly) believed that the force exerted by a wrestler on his adversary is larger than its reciprocal at the time of his victory (Viennot and Rozier 1994), or why the pressure inside a gas is not taken into account by children unless this gas is provoking a motion (Séré 1985).

Considering these aspects of reasoning leads one to see "common ideas" and "problem solving" as intricate domains (Fauconnet 1984), and to interpret the existence of the "facets", using Minstrell's format (see chapter), in a less scattered way.

Anyhow, the way we make common ideas explicit is to be adapted to the particular students and teaching contexts. According to the cases, it may be useful to limit oneself to the surface features of common reasoning, situation by situation, or, on the contrary, to try and show its deeper roots.

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LEARNING AND UNDERSTANDING KEY CONCEPTS OF ELECTRICITY

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Introduction

This chapter has two major aims: First, to summarize briefly findings on students' pre- and post-instructional conceptions in the domain of electricity and on their double role in teaching and learning processes, namely to be impediments of learning and also to be the necessary building blocks for students' processes of constructing understanding. Second, to employ the case of learning difficulties in electricity to point to more general aspects of the role of students' pre-instructional conceptions in learning physics.

Electricity is one of the basic areas of physics which are important at all levels of physics teaching. At the primary level young children already gain experience with simple electric circuits. At the following levels electricity is systematically taught and is a significant topic in all kinds of schooling. For reasons of a compressed description this review will not focus on the evolution of students' conceptions with age and over the different levels of education. Instead of this, the different conceptions will be listed and described in a loose sequence

Students' conceptions of current, voltage and resistance

Everyday meanings of current

Everyday talk about electricity and electrical appliances is markedly different from physics electricity talk; the basic physics terms of electricity, current, voltage and resistance, for instance, are also used in everyday talk, but in significantly different meanings than in physics. As there are certain differences between languages with regard to the meanings given, for instance, the mentioned basic terms of electricity, it is not possible to provide a conclusion that holds across languages. But it is possible to state that the meanings of words for current in European languages generally are nearer to the meaning of energy than to current as used in physics. In other words, the term current in everyday language includes a broad spectrum of meanings with a certain dominance of energy ideas. Misunderstandings in physics classes, therefore, are likely if the teacher is not aware of these differences between his or her way and the students' way to talk about electrical phenomena.

Linear causal effect between batteries and bulbs

For children at the primary school level who have not received any formal instruction it is suggestive to ask them for a circumscription of their concepts of electric processes. But it is possible to analyze how the children handle batteries and bulbs and which explanations they give in relation to their actions as was done by Tiberghien and Delacôte (1976). The result of this study is that children use very general explanations for the functioning of a simple electric circuit. Usually, they establish a causal connection between the battery and the bulb and explain that there is an agent moving between the battery and the bulb. The agent may be called electricity or electric current. Electricity or current is stored in the battery and may "rest" in wires. The agent is consumed in the bulb, i.e., there is no idea of conservation of electricity among these children. The linear causal effect between battery and bulb does not imply a closed circuit. A significant number of children namely think that one wire between battery and bulb suffices and that the second wire to be found in working circuits in everyday life simply serves to bring more current to the bulb. There are also findings that two kinds of current travel both from the battery to the bulb; sometimes they are called "plus" and "minus" current (see below). In the bulb there is a clash of the two currents, a notion which has been called "clashing current" (Osborne, 1983), or there is some sort of (chemical) reaction that leads to the light the bulb provides.

Research has shown that the consumption of current idea does not vanish through formal instruction. This idea and other students' conceptions may be discussed by means of a test which was administered in five European countries to more than 1200 grade 10 students after instruction in secondary schools (Shipstone et al., 1988). The overall result of this test is that despite different school systems and languages -- approximately the same pattern of learning difficulties is found in these countries.

Consumption of current

The conception that current is consumed remains attractive to students even after instruction. Consumption comprises the two aspects of devaluation and diminution of the electric current. In one of the tasks which refer to the consumption idea three statements are presented to students (in connection with a bulb connected to a battery and the bulb is lit up), and they are asked to indicate the statements as true or false. The result was that only a minority of the whole sample agreed to the conservation of current (statement 3):

1: "The bulb uses all of the electric current. "

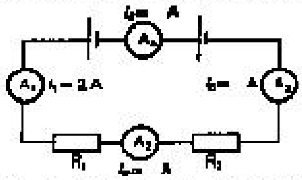
2: "The bulb uses up a little of the electric current."

3: "All of the electric current. from the battery to the bulb goes back to the battery."

Hence the consumption of current is still attractive since for many students the conservation of current is at variance to the fact that the battery must become "empty ".

In another task (figure 1) the students were asked to compare the readings of several ammeters. The result was that only about *50%* of the students gave the correct answer: I = const = 2A.

In the circuit drawn below the resistances R_1 and R_2 are different.



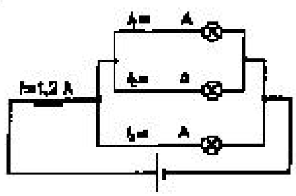
There are four ammeters in the circuit. A_1 shows a reading of 2A. Write on each of the other meters what you think it will read.

Figure 1

Local reasoning

Local reasoning describes the fact that students focus their attention upon one point *in* the circuit and ignore what is happening elsewhere. An example of local reasoning is that many students are regarding the battery as a constant current source and not as a constant voltage source. The battery as a constant current source delivers a constant current, independent of the circuit which is connected to the battery.

In the circuit shown below all the bulbs are of the same type.



Complete the currents I_1, I_2, and I_3 in the wires.

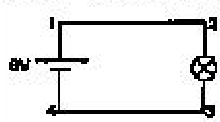
Figure 2

In the task of figure 2 local reasoning is related to the concept of current. About 60% of the sample hold that I1 = 0.6A, and 12 = 13 = 0.3A. The currents are divided up at every junction point in the circuit in two equal parts. This division is not influenced by what is lying ahead in the circuit. The students argue that "the current does not know in the junction points what happens afterwards in the circuit". The unusual graphical representation of that task makes clear that many students show a tendency to argue on currents only. The current in a single branch is not perceived as a consequence of the voltage across the resistance in that branch.

Voltage in closed circuits

One of the most difficult concepts in basic electricity is the concept of voltage or of potential difference. Before instruction voltage is related to "strength of a battery" or "intensity or force of the current". Even after instruction students use the voltage concept as having approximately the same properties as the current concept. The next task (figure 3) shows the lack of differentiation between the two concepts.

Look at the following circuit:



Insert the values of the voltages across the points
1 and 2: ....V, 2 and 3: ....V, 3 and 4: V

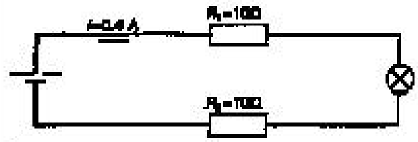
Figure 3

About 40% of the sample expect the voltage of 6V across all the pairs of points in the circuit and do not differentiate the two concepts voltage and current in the presented situation.

Sequential reasoning

If in a circuit an element such as a resistor is changed, a special kind of reasoning called sequential reasoning becomes manifest. Sequential reasoning means that the students analyze a circuit in terms of "before" and "after" current "passes" that place. A change at the "beginning" of the circuit influences the elements after, whereas the change "at the end" does not influence the elements situated before. The information of change is transmitted by the electric current. The current in a circuit is influenced by a resistor when it comes to this element and transmits this information in the direction of flow and not in the opposite direction.
A task for showing sequential reasoning is presented in figure 4. About one third of the sample shows sequential reasoning, also in similar and more elaborated tasks. Even students at the university level use sequential reasoning in other situations (Closset, 1983).

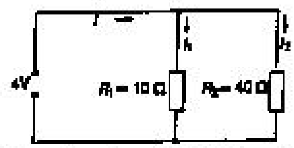
In the circuit drawn below the current is 0.4 A.



Now the resistor R_1 and afterwards the resistor R_2 are exchanged by resistors of 20Ω. Compare the current after the first change with the initial current and put a tick in the box with the correct answer...

Figure 4

Look at the following circuit:



The resistor R_2 = 40Ω will be replaced by a resistor of 50Ω.
Put a tick in the box with the correct answer.
a) The electric current I_2 increases. ( )
The electric current I2 stays the same. ( )
...

Figure 5

Resistance

Some difficulties in connection with the concept of resistance may be discussed according to a task with two branches in parallel (figure 5). The influence of changing the resistance R2 on the different currents I1 12, and I turns out to be extremely complicated for most of the students: Only 20% detect that I1 stays the same and the other currents decrease. 12% use an inverse relation between resistor and current and believe that an increase of R2 leads to an increase of 12. 20% consider the source as a constant current source and tick off that 12 decreases, I1 increases and I stays the same. About 10% use sequential reasoning and predict that all the currents stay the same since the resistor R2 is placed "at the end" of that branch and the change of R does not influence the currents "before" the resistors.

The complicated mixture of incorrect argumentation in the last task denotes that instruction generally leads not to a well defined representation of the concepts used in physics. Often, we find even after instruction elements of pre-instructional conceptions loosely connected to some elements of the concepts taught. Beyond that, research has generally shown that students' conceptions are context specific, i.e., they depend on the concrete task which is presented. If the situation changes from a first exercise to a similar (from the physicist's point of view) exercise, and students' may employ substantial different conceptions to solve the task.

Conceptions may overrun empirical evidences -- on the confirmation bias

It is a well known general finding of research on students' conceptions that the conceptions students hold very much influence what they actually see in experiments. Further, students usually are not "willing" to change their conceptions if their prediction is challenged in just one experiment (Chinn & Brewer, 1993).

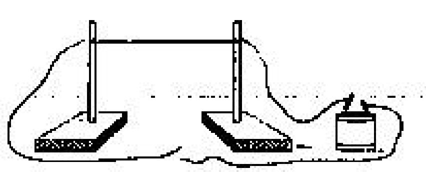


Figure 6: Where does the wire starts glowing first when the circuit is closed?

Schlichting (1991) provided a striking example of how students do not see what actually is to be seen but what their conceptions allow them to see, so to speak. He presented the experimental setup shown in Figure 6 to a grade 10 class and asked where the thin wire starts glowing when the circuit is closed. There were three different predictions. (1) The wire will glow first at the left or the fight side depending of the assumption of direction of current flow taken as current enters the wire there. (2) The wire will glow up First in the middle as two kinds of current (see above) will come together in the middle. (3) The wire will simultaneously glow up at all places (the correct view). After the prediction the experiment was carried out. Almost everybody saw what he or she expected.

As mentioned above many stu(Figure 6: Where does the wire starts glowing first when the circuit is closed?)rding to students' views) to the battery. Gauld (1989) challenged that conception by the experiments shown in figure 7. After a quite difficult and painstaking process he succeeded in convincing his class of about 14 year old students that the same deflections of the ammeters may be best explained by the physics view of current conservation. Three months later he interviewed his students on their conceptions of current flow. Most of them did not use the physics conceptions they obviously had achieved in instruction any more. Asked for the readings of the meters a number of them said that they were different, at least a little, although they all had seen and had agreed upon that the deflections are equal three months before.

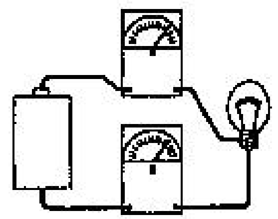


Figure 7: Ammeter readings challenge students' current consumption idea (from Gauld, 1989)

Students' learning processes

Many studies like the above summarized European survey on students' conceptions of electricity (Shipstone et al., 1988) have shown that success of physics instruction on achieving the physics point of view usually is limited (see the list of around 280 studies on learning electricity in Pfundt & Duit, 1994). Most studies draw on data after instruction or on comparing data before and after instruction. But there are also some learning process studies available that allow to follow the details of learning processes of individual learners (see the contributions in Duit, Goldberg, & Niedderer, 1992; for a learning process study in the field of electricity see Schwedes & Schmidt, 1992, in that volume). It becomes obvious in such learning process studies that the learning pathways students follow are very complicated: There are forward and backward movements, there are parallel developments and there are dead end streets also. Usually a development towards the science view becomes visible only after a long time, conceptual development towards the physics view, e.g., of electricity, is a strenuous long lasting process. The studies also reveal that there are often developments that go just in the opposite directions than intended by the teacher.

In a study by Niedderer and Goldberg *(1995),* for instance, a group of three college students approaching the physics ideas of the above discussed simple electric circuit in a kind of guided inquiry approach was involved. These students first had many difficulties to connect a bulb to a battery in the correct way. It took them around 30 minutes to solve that task. The intention of the teacher was to provide students with concrete experiences to allow them to establish ideas about the electric circuit. The students developed a conception well know from other studies and presented above. They viewed current as a kind of fuel that flows from the battery to the bulb and is consumed there. They referred also to previous knowledge taught in science class on positive and negative charge. They merged these two conceptions (the consumption idea and the notion of plus and minus current) in such a way that they achieved a framework that provided fruitful explanations to them. The teacher initially supported their view and did not become aware that the students' ideas developed in a direction he had not intended and that actually hampered further development towards the physics view. These students were unwilling and unable to change their view which had proven very fruitful and plausible for them. In other words, the guidance and support given by the teacher led them to a conception that happened to be a more serious impediment for further learning than their initial everyday ideas.

Teaching electricity taking students' learning difficulties into account

Of course, research in the field of learning electricity has not been restricted to bringing learning difficulties to light but also to address these difficulties in order to improve teaching and learning. A substantial number or studies have been carried out in which new learning and teaching approaches have been evaluated. It is not possible to provide a comprehensive review of the approaches here. Only some remarks on general findings may be given (see the list of referring studies in Pfundt & Duit, 1994).

Conceptual change

Learning in the research domain under review here generally is seen as an active construction process on the side of the learner on the basis of the already existing knowledge. What the learner already knows has proven *the* key factor in learning of whatever domain. The sketched view of learning is usually called "constructivist" (Tobin, 1993) denoting that knowledge acquisition is a construction process of the individual within a certain social setting. The term "conceptual change" which is widely used and often stands for constructivist ideas of learning in general denotes that learning science usually involves fundamental restructuring of the already existing, pre-instructional knowledge (Vosniadou, 1994). In other words, the term stands for the fact that usually students pre-instructional, everyday ideas about science phenomena are in stark contrast to the science concepts and principles to be learned.

The term conceptual change is not well chosen as it may be misunderstood. Change does not stand for *exchange* (or even extinction) of the pre-instructional conceptions for the physics concepts. Research has shown that this is not possible and it has also proven that this is not desirable. As outlined above students usually learn at best a kind of hybrid idea that merges facets of pre-instructional conceptions and physics views. Further, many students' pre-instructional conceptions have proven powerful frameworks in daily life context. This is true, for instance, for the conceptions of electricity presented above. In most daily life concerns they provide sufficient guidance to deal with electrical appliances and they allow fruitful everyday discourse about most electrical issues. The view of exchanging students' pre-instructional everyday conceptions therefore has to be exchanged by a context dependency view: A certain coexistence of both views has to be tolerated; students have to learn in physics classes that the physics view provides more powerful frameworks *in certain situations and contexts.*

Conceptual change and conceptual change supporting conditions

Conceptual change in the above sense, i.e., in terms of students' learning pathways from certain issues of their pre-instructional conceptions towards the physics concepts has proven to include rational (logical) as well as emotional issues. There are many cases known from the literature that students understand the physics view but do not believe it (Jung, 1993). Conceptual change, therefore, has to be embedded into conditions that support the development of students' ideas. Among these supporting conditions are a classroom climate that allows students to voice their ideas and to exchange their views with other students, and where students' ideas generally are taken as serious attempts to make sense of a certain phenomenon by the teacher. Also students interests and motivation play a key role.

In a study on teaching and learning the basic concepts of electricity (Grob et al., 1994) the significance of the mentioned factors became evident. Girls and boys use a different access to learning physics. The girls tend to distance themselves from physics because their interest is low. This does not mean that they do not learn physics. In the female group of those students who show a steady learning behavior intrinsic motivation is a determinant factor for learning physics. Intrinsic motivation is not subject matter dependent and indicates that these students are generally bright students. The boys find an emotional access to physics via interest and they prove to be good and continuous learners as long as their effort depends on interest.

Discontinuous and continuous learning pathways

Students' pre-instructional conceptions of the electric circuit are undoubtedly in stark contrast to the referring physics concepts. In many new teaching and learning strategies available in the literature instruction starts with elicitation of students' ideas and with establishing their experiences with the phenomena in question. As is the case in the constructivist teaching scheme of the CLIS (Children's Learning in Science) project (Driver, 1989), but in many other approaches also, students carry out experiments (for instance, with batteries and bulbs), and develop and exchange their views of the phenomena investigated. From such a basis the teacher tries to guide students towards the physics view in a step by step procedure. Challenging students' ideas is a crucial part in this period, in other words, cognitive conflicts play a major role. Gauld's (1988) strategy briefly discussed above may be taken as a paradigmatic example. Afterwards the physics view is applied to a number of novel situations. Much emphasis also is given students' reflection of their own learning process in order to make students aware in which way their initial everyday ideas are different from the new physics views. These strategies may be called discontinuous as they deliberately draw on cognitive conflicts.

Cognitive conflict strategies, though generally superior more traditionally oriented approaches (Guzetti & Glass, 1993), bear a number of difficulties. The most important is that it is often difficult to make the students see the conflict. Also it may happen that elicitation and long discussion of students' pre-instructional view may strengthen just this view. Therefore, there is the search for strategies that avoid cognitive conflict, i.e., that start from facets of students pre-instructional conceptions that share at least some basic issues with the physics view already, and from this kernel of conformity proceed towards the physics view via a basically continuous pathway. One kind of such strategies may be called "reinterpretation" (Jung, 1986). Grayson (1996) provides the following example for this strategy (her term is "concept substitution"). Instead of challenging students' view of current consumption as sketched above she provides the following reinterpretation: The view that something is consumed is not wrong at all -- if seen in terms of energy. Energy actually is flowing from the battery to the bulb while current is flowing and is "consumed", i.e., transformed into heat and light.

There are other possibilities of continuous pathways towards the physics view of electric concepts. In these cases instruction initially bypasses students' pre-instructional conceptions of the electric circuit and starts with certain more general schemes or with drawing analogies to domains already familiar to students. The most popular strategy of this kind is to draw on analogies to water circuits of manifold kinds. The problem of this standard analogy of physics instruction is that it may lead to severe misunderstandings if not handled with care. Research namely has shown that students hold basically the same conceptions (which have to be termed wrong from the physics point of view) in both the electric circuit and the water circuit (see Schwedes, 1996, for an approach that addresses these problems).

Student oriented structure of science content

Of course, in all new conceptual change approaches for teaching and learning electricity there are attempts to change the structure of physics content in such a way that the learning difficulties revealed in the many studies available may be adequately addressed. There appear to be three key concerns:

(1) Current flow and energy flow have to be clearly differentiated from the very beginning in order to address students' idea of current consumption which has proven to withstand instruction in a very serious way.

(2) Current and voltage have to be differentiated from an early stage on in order to provide students with a view of the phenomenon of current flow that includes the idea of a flow of something in a circuit and the idea of a driving "force" of that flow but that also allows to distinguish these issues.

(3) In order to address the above discussed "local" and "sequential" reasoning dominating students' views of current flow it is necessary to guide students to a "system view" of the electric circuit (Härtel, *1985)* , from an early stage on. Whenever there is a change of some sort in one point of the circuit there are simultaneously changes in other points also. An adequate model would not draw on individually moving charges (or particles) but on a view where all particles are intimately interconnected.

Concluding remarks

The domain of electricity is the field where most research on students' learning difficulties is available. Results of this large body of research clearly show that students' pre-instructional conceptions deeply influence or even determine learning. Most of students conceptions have proven impediments of learning as they are in stark contrast to the physics concepts to be learned.

As students pre-instructional knowledge necessarily has to be the starting point of every learning process the impediments have to be overcome in certain intelligent ways. Also here research has provided valuable approaches tat may lead to more efficient and more pleasing physics teaching and learning for teachers and students alike in the domain of electricity and beyond. Much has been done so far, many valuable ideas are available, yet much more still has to be done.

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COMMENTS ON C2: LEARNING AND UNDERSTANDING KEY CONCEPTS IN ELECTRICITY

(**Reinders Duit** and **Christoph von Rhöneck)**

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This chapter by Reinders Duit and Christoph von Rhöneck provides an overview of much of the research that has been conducted on student understanding of electricity. The emphasis is on simple DC circuits that consist of batteries and bulbs. The authors describe some common conceptual difficulties that have been identified among pre-university students, citing several studies. There is also ample evidence that university students who have studied introductory physics have similar conceptual difficulties (McDermott and Shaffer, 1992). Included in this group are elementary, middle and high school teachers, both those teaching now and those who plan to teach. Since electric circuits are part of the pre-university curriculum, it is important that teachers overcome their difficulties with this material and also become familiar with effective instructional strategies that they can use to help their students.

The authors of this chapter comment briefly on how to help students improve their understanding. Below, we extend this discussion by giving a specific example of an instructional sequence designed on the basis of research. The laboratory-based approach that is used has been shown to be effective in addressing many of the difficulties mentioned in the chapter (Shaffer and McDermott, 1992). The curriculum in which this example is embedded is readily available (McDermott, L.C. & the Physics Education Group, 1996).

Example of Application of Research to Instruction

The students are guided through the process of constructing a conceptual model for electric current from direct experience with simple circuits consisting of batteries and bulbs. They perform experiments, make observations and draw inferences through which they formulate the basic concepts of current and resistance. They use both inductive and deductive reasoning to synthesize these concepts into a qualitative model for electric current. As they apply the model to circuits of increasing complexity, the need for other concepts becomes apparent. Below we outline the logical progression through which students develop a conceptual model that they can use to predict and explain the behavior of simple resistive circuits.

The students begin the process of model-building by trying to light a battery with a bulb and a single wire in as many ways as possible. They find that there are four possible arrangements in which the bulb will light. They are asked to compare these with arrangements in which the bulb will not light. They note that for the bulb to light, each of its terminals must be connected to a different terminal of the battery through a continuous conducting path. The students formulate the concept of a complete circuit and realize that all four arrangements can be represented by a single diagram. They investigate the brightness of different configurations of bulbs connected to a single battery. Their observations make plausible the following two assumptions that provide the basis for initial development of the model: (1) a flow (identified as electric current) exists in a complete circuit and (2) bulb brightness indicates the amount of current.

The students next investigate the behavior of series and parallel circuits in a systematic manner. The dimming of a light bulb that occurs when a second identical bulb is added in series to it provides a basis for introducing the concept of resistance. The students recognize that the equal brightness of the two bulbs implies that current is not "used up." They determine that neither the direction of the current nor the order of the elements affects bulb brightness. When they observe that individual bulbs connected in parallel directly across an ideal battery are as bright as a single bulb connected in the same way, they realize that their intuition that the battery is a constant current source is not correct. They are forced to conclude that the current through the battery depends on the configuration of the circuit. The concept of equivalent resistance is introduced. The students find that this quantity depends on the configuration and not merely on the number of elements or branches. The students then investigate the behavior of different configurations of bulbs and observe that changes made anywhere in a circuit often result in changes at other points. They find that the model that they have developed enables them to predict the relative brightness of bulbs in a variety of circuits, but not in all situations.

Only qualitative reasoning has been required for construction of the model thus far. The experience is therefore particularly suitable for students in elementary and middle school and for their teachers, whose mathematical skills are often not strong. For high school students and their teachers and for university students, the development of a conceptual model should not stop with the concepts of current and resistance. The need to extend the model becomes clear through a series of experiments in which the students examine the effect of adding batteries in series in a circuit. The students note that bulb brightness increases with each addition. This effect suggests the idea that the battery is the agent that "drives" current through the circuit. The concept of potential difference is introduced. With the aid of an ammeter and voltmeter, the students develop operational definitions through which they quantify the concepts of current, potential, potential difference and resistance. They formulate Kirchhoff's first and second rules and determine the relationship between current and potential difference for ohmic materials (Ohm's law).

The model that the students have developed enables them to predict relative brightness when bulbs in a circuit are identical but not when their resistances are different. The students conclude that neither current, nor resistance, nor potential difference alone is sufficient to determine brightness. When the model is extended to include the concept of power, the students can make predictions for non-identical bulbs. Experiments that demonstrate that batteries have a finite lifetime help the students to identify energy as the quantity that is dissipated. They can now reconcile their formal knowledge that current is conserved with their intuitive belief that something is "used up" in a circuit.

Generalization

This chapter serves a useful purpose in calling the attention to findings from research on student understanding of electric circuits. However, the identification of difficulties is only part of the contribution that research can make to the improvement of instruction. Of equal importance is the use of the results to guide the development and assessment of curriculum. The specific example described is an illustration.

ACKNOWLEDGMENTS

The research and curriculum development on which the comments in this paper are based are the results of an ongoing, collaborative effort by many members of the Physics Education Group at the University of Washington. Support from the National Science Foundation is also gratefully acknowledged.

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EXPERIMENTAL FACTS AND WAYS OF REASONING IN THERMODYNAMICS: LEARNERS' COMMON APPROACH

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INTRODUCTION

In the large number of studies about learners' conceptions that have been conducted during the last twenty years, the topics of interest were first defined in terms of the traditional topics of accepted theory. Heat and temperature were among the first topics documented by researchers, followed by pressure in gases and the particulate structure of matter. It soon appeared that similar features of reasoning were involved in pupils' answers concerning very different topics, and more recent research at the university level was focused on these transferable aspects of reasoning. After an outline of the results concerning children's ideas about heat and temperature, these general ways of reasoning will be illustrated with examples in thermodynamics, and some implications for the choice of teaching goals will be discussed.

PHENOMENA INVOLVING HEAT AND TEMPERATURE: A FRAMEWORK FROM A PHYSICIST'S POINT OF VIEW

In the accepted theory of physics, "heat" refers to a type of transfer of energy between two systems, for instance by conduction, and designates the energy transferred in that way. The other way of transferring energy from one system to another is work: for instance, mechanical or electrical work. Processes such as convection or radiation can be referred to these two fundamental types of transfer - heat and work - although in a non trivial way. In fact, in considering energy transfers, we need a proper distinction between heat and work only when entropy is considered. This will not be the case in this chapter, therefore I will not analyze in detail the actual processes of transfer. I will only say "transfer of heat " (although it would be less ambiguous to say: "transfer of heat-type"), or "work".

Temperature is one of the quantities that characterize the state of a system. Its theoretical definition is somewhat complex. But in situations where classical thermodynamics holds, this intensive quantity is simply related to - in fact is proportional to - the mean particulate kinetic energy.

Since energy can be transferred simultaneously by several means, and since particulate energy is not only kinetic, a transfer of heat to a system does not necessarily entail an increase in temperature of this system. For instance, a transfer of heat may cause a change of state, and this occurs without any change in temperature (then it is the potential energy of particles that changes), or a change in temperature may occur during an adiabatic expansion of a gas, i.e. an expansion without any transfer of heat. A transfer of heat may even occur from a "cold" source to a "hot" source (which means, respectively, "colder", or "hotter", than the other source), as in refrigerators.

In this complex domain, a restricted category of phenomena allows simpler predictions : those in which only a transfer of heat occurs, with only the mean particulate kinetic energy varying in each system. Then, it is correct to claim that energy goes from the hotter system to the colder one, until these systems finally reach the same temperature. It is worth noting that in this "restricted category", one might without any trouble identify "heat" with "thermal energy", transferred as well as stored. Then, the difference between heat and temperature would be only that temperature is an intensive quantity, while in the case of energy it is not. In fact, as shown above, the conceptual gap between the two quantities is much more important. In this very brief summary, two conceptual fields are encountered, which extend beyond the topics of heat and temperature: the particulate structure of matter (see chapter E3 of Meheut, and Lijnse and al., 1990), and the concept of energy. These two very important topics cannot be dealt with as such in the limited scope of this chapter. What follows is focused on learners' ways of reasoning about physical phenomena which involve heat and temperature.

CHILDREN'S IDEAS ON SOME THERMODYNAMIC PHENOMENA

It is now widely accepted that a knowledge of learners' common conceptions and ways of reasoning is of crucial importance in designing teaching strategies.

This section describes conceptions held by 10 to 16 year-old adolescents before, during or after teaching, with a particular stress, in the latter case, upon the difficulties that remain after teaching. The findings reported here are mainly drawn from review articles (Erickson 1985; Tiberghien 1985; see also Tiberghien 1984), in which more detail can be found.

-What heat and temperature are said to be

In most pupils' comments, heat seems to be simply something hot that heats other things. As Erickson (1985) wrote, this "something" is equated either with a hot body or with a kind of substance given off by a heat source.

These responses have been obtained during an investigation concerning 12-16 year-olds asked to "say in a couple of sentences what heat is" (Engels 1982):

"Heat is warm air";

"Heat is a warming fluid or solid...when you touch it it feels hot-if anything has got the heat in it".

Still a third of the older pupils in this study gave these types of responses, in contrast with others where "heat" is defined in terms of energy and transfer: "Heat is energy; when it heats something up it will transfer the heat energy to what is heating up.

According to Erickson (ibid.), "up to the age of 12-13 pupils are familiar with the term temperature and are able to use a thermometer to assess the temperature of objects, but they actually have a fairly limited concept of the term and rarely use it spontaneously to describe the condition of an object".

As for the difference between heat and temperature, when children were asked directly about this point, "the most common type of response (accounting for more than 25% at all age levels) is that there is no difference between them". Erickson quotes other typical responses (Engels 1982) in which temperature seems to be either "a measurement of heat" or "the effect of heat":

"Temperature is the amount of heat in that space...it tells you the hotness of the water".

-How are phenomena analyzed?

This being said, researchers agree on focusing their attention on children's comments and predictions concerning phenomena involving heat and temperature, rather than on purely declarative aspects of knowledge.

From a physicists' point of view, the phenomena put into play in these studies can be classified in two types: the "restricted category" defined above (i.e. with only a transfer of heat and only mean particulate kinetic energy varying) on the one hand, and changes of state on the other.

-Phenomena of the "restricted category"

In the "restricted" category is the experimental fact that all objects in prolonged contact reach the same final temperature. This idea is not obvious to pupils. Researchers report on some answers that seem to deny the existence of a thermodynamic equilibrium between the objects involved.

For instance, when asked if two plates situated in the same room, one of metal and one of plastic, are at the same temperature, most of pupils even after teaching think that this is not the case (Engels & Driver 1985). Tiberghien (1985) also reports that "different materials (flour, nails, water) placed for several hours in an oven at 60^{o}C are at different temperature for the majority of pupils. Typically, flour is at less than 60 ^{o}C because flour does not heat up very much, nails are at more than 60 ^{o}C because iron heats faster, and water is at 60 ^{o}C because it takes the temperature of the surroundings".

Along the same lines, it is not obvious to adolescents that heating any material will result in an increase of this material's temperature. Thus, still quoting Tiberghien, "before teaching, only about a third of the pupils think that the temperature of sand, sugar and water increases when they are heated. Many of them predict that sand will not be hot "because sand cannot heat", whereas water can heat up. For them, the ability to be heated is a "natural" property of particular substances. After teaching, more than 50 per cent of the pupils recognized that the temperature of these three substances increases when they are heated, but it remains a difficult concept for them."

All these difficulties do not appear in the case of homogeneous mixtures of liquids. The existence of a unique final temperature is well accepted by pupils. The focus is a qualitative or quantitative prediction about this final value. Various investigations (Stavy & Berkovitz 1980, Driver & Russel 1981, Strauss 1981, Engels 1982) used mixing experiments with amounts of water at same or different initial temperature. In both cases, qualitative and quantitative predictions were asked. The case of identical initial temperatures are seen as easier to cope with, and quantitative questions are more difficult than qualitative ones. Strategies consisting of adding or subtracting the initial temperatures are still observed at the age of 16 (Engels 1982).

Finally, still in the "restricted" category (only heat transfer occurring and only kinetic energy varying), some questions bear on which materials are good for the thermal insulation of different objects. To produce a correct answer in this case, one needs to consider a property of a given material -being a good or a bad conductor - with a focus on the idea of transfer between two other systems. This idea of transfer also enters into the difficult issue of tactile sensations produced by various materials at same temperature.

Not surprisingly, most of pupils' explanations for such problems rely on a property of the material. But in many of these, the property of the object is asymmetrically linked to one or the other of the categories "hot" or "cold", as if a particular situation had been used to ascribe an intrinsic link between the material and one particular end of the hot-cold continuum.

Most of these explanations seem to take into account the material under consideration and only one of the other involved systems: the body to be insulated or ambient air, with or without the mediation of "heat". Tiberghien (1985) quotes some examples of such explanations:

(to insulate a cold ball bearing), "the aluminum keeps cold better" (11 year-old);

(to insulate a hot drink), "the glass wrapped in cloth will be hotter than the others since it is wrapped in cloth" (11 year-old);

"metal cools things, metal is cool" (12 year-old);

"I think that (metal) will keep (the ice) frozen most easily, because that (cotton) is hotter and keeps the heat better" (12 year-old).

These explanations are predominant before teaching and can be gradually replaced, after teaching, by others which suggest no asymmetry with respect to "hot" and "cold", such as (Tiberghien ibid.): "The material transmits heat more or less quickly; heat propagates, moves in the material, more or less quickly." Saying simply "the material is a conductor or an insulator"" doesn't guarantee that the problem of transfer is properly understood. For instance, the following comment was given by a pupil who had chosen aluminum foil to keep a ball-bearing cold (Tiberghien ibid.):

"because the metal keep the cold, the aluminum is a conductor.

Yes because it will take the temperature of the marble... and it will keep it for a long time." (12 year-old).

The question of symmetry of role between the interacting systems (the "hot" and the "cold" source) is one of the most critical, a point that will be discussed below.

Changes of state

Turning now to changes of state, it appears that the stability of temperature during a change of state is not known before teaching, and that it causes a real surprise when observed. After teaching, this point seems to be widely accepted, although such a stability over time is often considered as affected by the rate of heating, as shown in two studies (Driver & Russel, 1981, Andersson 1979).

It also seems difficult for students to accept that, once the change of state is over, the new phase will behave normally, i.e. will have its temperature increased when heated. Tiberghien (1984, 1985) reports that, asked to explain why a piece of zinc placed in an oven at 1000 ^{o}C had successive values of temperature 30^{o}, 70^{o}, 200^{o}, 420^{o}, 420^{o}, 420^{o}, about 20% of a group of pupils answered, after teaching about changes of state, that "it is the highest possible temperature for zinc". Concerning the values of temperature to be expected later on, 70 per cent of the pupils said that "the temperature always stays at 420^{o} ". Swedish students also often think that 100^{o} C is "the maximum temperature of water" (Andersson 1979).

I propose the following hypotheses:

This reluctance to admit a normal behaviour for the phase resulting from a change of state might be phenomenon-dependent. In particular, children would probably admit that heating an ice cube results first in its melting, then in an increase of the temperature of the resulting water.

It might be partly due to the fact that very high and very low temperatures are difficult to imagine. Extreme values, indeed, cannot be connected with ordinary personal experience of a range of temperatures.

It might also be due to a rupture in a way of reasoning. The change of state forces one to leave aside the rule that holds in the "restricted category" of phenomena, i.e.: if a body is heated, its temperature increases. This may seem arbitrary to children and discourage them from coming back to this rule when they consider the phase resulting after the change of state.

In the absence of any experimental support, it is not possible to say much more about these hypotheses. But, from a teaching-learning perspective, the last remark suggests that we take all the more seriously Erikson's plea (Erikson 1985) for presenting pupils with explanations - for instance concerning the boiling point of water:

"...This understanding would seem to require some explanation of what is happening to the liquid, at the molecular level, in order for temperature invariance to make sense."

Thus, concerning simple heat transfers as well as changes of state, simply "learning the facts" seems insufficient to reach a coherent understanding of the concepts involved. This idea consistently leads one to analyze the types of reasoning that commonly appear in this domain.

COMMON WAYS OF REASONING CONCERNING SYSTEMS

-Transferable aspects of reasoning: first hints

One of the main results concerning children's ideas about heat and temperature is that when they analyze a heat transfer children have difficulty in taking into account both the hot and the cold source. Somewhat similar is the reluctance of children to consider both sides of a moving piston when they analyze the forces due to pressures which are acting on this object (Séré 1985, Méheut 1997). It seems as if two causes were too much for a given effect. At the end of their book on children's ideas in science, Driver et al. (1985) conclude that: "These recurring ideas....tend to derive from a linear causal reasoning with a single action producing an effect". Andersson (1986), and Gutierrez & Ogborn (1992) also pinpointed the simple causal structure commonly observed in learners' reasoning.

Transferable with respect to specific content as it is, this trend of reasoning is likely to be all the more resistant to teaching (Viennot 1993a). Indeed, concerning heat transfer along a metallic rod, university students were found (Rozier 1987, Viennot 1996) to use a "sequential reasoning" - which is also extremely common in electricity (see chapter C2 of Duit and v.Rhöneck) i.e. they reason as if heat was something starting from the hot source along the rod, irrespective of what is situated downstream. Like children, they have the greatest difficulties in taking into account on the same footing both the "starting" (hot) area and the "arrival" (cold) area of heat in a transfer.

In fact, Rozier (ibid.) observed, at the university level, the enormous resistance to instruction of common trends of reasoning that she referred to as "linear causal reasoning" and that she analyzed as follows.

The quasistatic analysis of systems

It is useful to recall first some major features of the accepted theory. The analysis of systems, indeed, puts into play several physical quantities. When multivariable systems are transformed, they can, under certain conditions, be analyzed in a quasistatic way. This means that the quantities that characterize the state of the system evolve simultaneously under the permanent constraint of simple laws. "Simple" excludes laws of propagation from one side of the system to another. In other words, "quasistatic" and "propagative" are two exclusive adjectives. For instance, in thermodynamics, a quasistatic transformation of a perfect gas is such that, at any time, the relation $pV = NRT$ (with classical notations) holds as if the system was permanently in thermodynamic equilibrium. This type of analysis can be contrasted with the trends of reasoning described below, with instances in thermodynamics.

Reducing the number of variables

A most general and well known tendency in coping with multivariable problems is to ignore some relevant variables. This is illustrated in particular by a test given to university students (Rozier, 1987, Rozier & Viennot, 1991). An adiabatic compression of a perfect gas is presented. It is said that "pressure and temperature both increase". The question is "can you explain why in terms of particles?" About half of the students in various levels at university gave answers such as:

"The volume decreases; therefore there are more molecules per unit volume and the pressure increases"

"The volume decreases, therefore the molecules are closer to each other; therefore there are more collisions and the pressure increases"

These responses may be outlined in the following way:

V decreases > n increases > p increases

Concerning pressure, they mirror an exclusive link of this quantity with particle density (n). The other relevant factor, namely the mean square speed of particles is ignored. This constitutes a preferential association between pressure and particle density, at the expense of the kinetic aspect. In this way, the role of temperature is ignored. Méheut (1996) also observed that students have more difficulty in understanding the relation between pressure and "force of collisions" than between pressure and particle density.

Reasoning with such linear chains about multivariable problems leads in fact to ad hoc arguments and to inconsistencies. For instance, one cannot "explain" at the same time the lower pressure at higher altitudes by the implication "particle density (n) decreases > pressure p decreases" and the way a hot air balloon works by the link "hot air inside the balloon > particle density (n) decreases", without a contradiction concerning the pressure inside the hot air balloon, which obviously is not lower than the external one. In both cases, when using the $pV = NRT$ relationship (holding for perfect gases), it is necessary to specify what happens to the third relevant variable, i.e. the absolute temperature T. The implication - "particle density (n) decreases > pressure p decreases" - only holds at constant temperature. At a higher altitude, both n and T are lower than at sea level, whilst in a hot air balloon, n is lower but T is higher than in the external air, which explains why the internal pressure p is not lower than outside the balloon.

Another common way of reducing the number of variables actually considered is to combine two variables as if they were only two facets of the same notion. "Thermal motion" is one of these notions often used by learners as well as by textbooks' writers as a kind of conglomerate of the speed of particles and mean distance between them. Statements such as "particles need more room to move faster", "in solids particles cannot move", "thermal motion is more intense in gases", are very commonly found (Rozier & Viennot, 1991). In fact, "thermal motion", if intended as the mean particulate kinetic energy, is only a function of temperature (when classical thermodynamics holds), and therefore the mean distance between particles is not a relevant parameter in that respect. At thermodynamic equilibrium between gas and liquid, for instance, temperature and therefore "thermal motion" are the same in the two phases.

Causality and chronology: the linear causal reasoning

Another aspect of common reasoning is presented by Rozier (ibid.). Students were asked to "explain" the increase in volume resulting from the (quasistatic) isobaric heating of a gas. About 40% of various samples of university students gave answers of the following type:

"The temperature of the gas increases. Knowing that pV = NRT, therefore at constant volume, pressure increases: the piston is free to slide, therefore it moves and volume increases."

The linear structure of this response is manifest: supply of heat > T increases > p increases > V increases

More surprising is the contradiction apparent between this answer and the statement of the problem, where pressure is said to be constant.

This seemingly contradictory statement can be understood if the described events are not supposed to be simultaneous (as in a quasistatic analysis).

Some students, indeed, clearly stipulate that there are two steps in this argument:

First step: supply of heat > T increases > p increases, with the volume being kept constant.

Second step: p increases > V increases, the piston being now released.

This suggests a reconsideration of the status of arrows in linear arguments such as those outlined above. These arrows do not mean only "therefore", but also "later". The totally ambivalent word "then" (or equivalently the words "alors" in French, "entonces" in Spanish) favors this melding of these logical and chronological levels.

To sum up Rozier's findings, a "linear causal reasoning" is often observed. Its structure is that of a chain: F1 > F2 > ...> Fn , in which each phenomenon F is specified by only one quantity, and where the causality referred to by an arrow has both a logical and a chronological content. As a whole, such arguments look like stories with simple events and successive episodes.

Permanence: a forgotten case

Understanding phenomena as successive consistently leads one to seeing them as temporary, or at least it obscures reasoning in terms of permanence. This is indeed what is observed by Rozier. An argument commonly observed to explain an increase of temperature in adiabatically compressed gases, "collisions between molecules produce heat", is almost never spontaneously confronted, neither by students nor by teachers, with the long term outcome of this assumed phenomenon, i.e. an explosion. Steady states of disequilibrium, for instance in a green-house or in a bolometer, often raise comments such as : "more energy gets in than out, so the temperature is higher". The result from unbalanced flows in the long term, again an explosion, is not envisaged. This implicit focus on a aspect of change hinders a check of validity which relies on an analysis of the long term evolution of the system (see also Viennot 1993b).

The importance of rates of change in learners' reasoning is also emphasized by Kesidou & al. (1995). They report the case of 15- to 16-year-old students who deny temperature equalization for a piece of metal at 20^{o}C placed into water at 80^{o}C, arguing that the rates of temperature changes are different for the two bodies in contact. This shows how difficult it may be to reconcile views on changes and the idea of a final permanent state.

In brief, it is common to explain steady states with arguments implicitly focused on a particular aspect of change, or to focus on an aspect of change without consistently considering the end of the story. Consequently, the part played by time often seems to be totally blurred in learners' arguments. We can, for instance, review the comment quoted above: (in an oven at 60 ^{o}C) "nails are at more than 60^{o}C because the metal heats faster".

Clearly (in the authors' opinion), the pupil who gave this answer focused on a rate of change with no clear distinction between this topic and that of a final (permanent) state of equilibrium.

CONCLUDING REMARKS: SOME GUIDELINES FOR THE CHOICE OF TEACHING GOALS

The main features of "linear common reasoning" analyzed above seem to be widely shared by university students and children. However, reasoning consistently with accepted thermodynamics requires two essential components that are opposed to these common trends of reasoning.

1- identify the relevant systems as well their relevant characteristics in order to predict transfers of heat, instead of simply ascribing to objects a property intrinsically linked with only one of the categories "hot" or "cold"; more generally consider several causes for one effect, contrary to the linear causal reasoning.

2- clearly sort out what concerns changes on the one hand, permanent states on the other.

It is all the more important, when designing a teaching sequence, to specify very precisely the corresponding conceptual goals.

Of course, these goals should be compatible with the analysis of phenomena implied in accepted physics. But this compatibility is to be looked for at a level which remains to be defined. Teachers are therefore confronted with making choices.

The question of the explanations to be proposed to learners is a crucial problem. Given the complexity of the thermodynamic phenomena, we suggest that the following attitudes be adopted. (Rozier & Viennot 1991):

One has to be extremely careful with the degree of "explanation" actually expected, and to specify what the proposed argument fails to explain. For instance:

"Solids expand when heated (or contract when cooled), but we cannot (yet) explain why. Knowing that "thermal motion" (mean particulate kinetic energy) increases (or decreases) in such a case is not enough to explain why this makes the solid expand. Indeed the particles might vibrate more intensely, and stay around the same place without drifting."

One can also work with "soft" explanations which are focused on one predominant variable, but without hiding the dangers of their careless extension to other cases. For instance, the idea that "at high altitude, there are fewer molecules, therefore pressure is lower" requires the addition: "This reasoning works only if the molecules have (more or less, admittedly) the same mean speed in the two situations being compared."

This "harder" qualitative reasoning may be considered too demanding for a given population, but in fact the required degree of consistency can be chosen from a continuum which ranges from factual knowledge to accepted theory. For instance, it may be considered appropriate, for a given population of children, to teach the fact that at sea level, water boils at 100 oC, and this without the least explanation. But if one clearly introduces some factors which do not affect the boiling temperature, such as the amount of water and the rate of heating, this already constitutes the beginning of a multivariable reasoning.

In the same perspective of a realistic adaptation to learners, the goal of aiming at a clear distinction between heat and temperature may be debatable. But if one decides to take this challenge, it is useful to decide which of the following conceptual targets are aimed at: the intensive character of temperature and the extensive character of heat, the identification of relevant systems and parameters, the distinction between phenomena of "restricted category" (only heat transfer and only kinetic energy varying) and others (for instance, changes of state).

Moreover, the attitudes suggested above concerning explanations and corresponding reservations are intrinsic components of scientific modeling.

When selecting the goals for teaching, it may be decided, or not, to make explicit the question of modeling. The reader will find in chapters E3 (Méheut) and E4 (Psillos) of this book some reports on experiments concerning teaching sequences explicitly focused on modeling. They constitute a necessary complement to the present chapter.

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SectionC3, *Experimental facts and ways of reasoning in thermodynamics: learner's common approach* from: Connecting Research in Physics Education with Teacher Education

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Comments on C3: Experimental Facts and Common Ways of Reasoning in Thermodynamics: Learners' Common Approach
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This chapter draws attention to two quite different kinds of teaching and learning issues. The first concerns the difficulties which many learners have in coming to terms with the scientific understanding of thermal phenomena. The second is the challenge posed by reasoning about situations where more than one factor simultaneously influences an outcome, with a set of interrelated effects happening together and not in sequence.

The research evidence for students' difficulties in grasping the scientific view of temperature, heat, and internal energy is considerable. Researchers' findings echo the more informal observations of teachers in the classroom. Perhaps the principal value of research is to draw attention to the basic ideas which learners appear to struggle with, yet which can appear so obvious to the teacher that they may not be explicitly taught at all. We need to be reminded that younger students need to be helped to understand that all materials, if left for long enough in a fixed temperature environment, reach the temperature of that environment, regardless of the material they are made from; that they need to be taught that the temperature of all materials can be raised by heating them; and so on.

Basic thermodynamics is, however, one of those topics where the number of articles in the science education literature about learners' difficulties is matched by those arguing that the treatment in many textbooks is inaccurate and at odds with the actual scientific understanding of the topic. In particular the use of the noun 'heat' has been questioned, with some suggesting that we should always talk instead of the process of 'heating'. Viennot's discussion in the opening pages of this chapter outlines the scientific view of thermal processes, and indicates just how subtle and difficult some of the ideas are. Bearing in mind that most of the children in classes learning the basic ideas about temperature and heat will not go on to become physicists, but require instead an understanding of scientific principles which will be of use to them in tackling situations in their everyday lives as citizens, I wonder if an understanding rather closer to the 18th century 'caloric' model of heat might not be a more realistic teaching aim? Appreciating the difference between the intensive quantity, temperature, and the extensive one, heat (or energy), recognising that heat is transferred spontaneously from objects at higher temperature to those at lower temperature, and grasping the role of insulating materials in slowing the rate of this transfer - this is clearly a significant cognitive challenge for many learners. These ideas, however, simplification of the full scientific picture, are useful in understanding many everyday phenomena. Indeed much work by engineers and biologists is based upon them. It is interesting to note that some recent work by science educators takes as its aim the teaching of just this sort of 'pragmatic model' of thermal phenomena (Linn and Songer, 1991).

The second strand of Viennot's chapter deals with an issue which is clearly broader than basic thermodynamics: the forms of reasoning used by students when trying to explain phenomena. The tendency to use 'linear causal reasoning' is likely to be found in many areas of science. It is less easy to see how we might help students to overcome it. One starting point might be to recognise that all of us reason in more sophisticated ways when we are discussing familiar subject matter. When we move to domains where we are less sure of our knowledge, our style of reasoning also becomes more basic. I am inclined to think that the issue here is not students' ability (in a developmental sense) to use more sophisticated patterns reasoning about multivariate systems, but rather their ability (and confidence) to do so when the context is an abstract and unfamiliar one. Helping students develop scientific forms of reasoning may then involve practice in reasoning about more familiar multivariate systems and models drawn from everyday contexts, perhaps reflecting on the forms of reasoning used to draw these out and make them explicit.

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STUDENTS' UNDERSTANDING OF THE PROCEDURES OF SCIENTIFIC ENQUIRY

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Introduction: teaching science content and science method

The main aim of the science curriculum is to help students understand, and become able to use, the accepted scientific explanations of the behaviour of the natural world. In addition, most curricula also aim to develop students' understanding of the scientific approach to enquiry. Indeed, the very word 'understanding' implies that the student has not merely accepted a particular scientific explanation as valid but can explain their grounds for doing so. This requires some understanding of the methods used by scientists to establish the scientific view of phenomena. Implicit in many science curricula and much science education practice is the view that such understanding does not have to be made explicit: students will pick it up from their experience of seeing practical demonstrations and carrying out experiments by following instructions. Some science educators, however, have argued that explicit teaching about the methods of science is necessary, even (in some cases) that an understanding of science method (or science 'processes') is more important than a knowledge of science content.

Lack of consensus about scientific method: a problem for researchers in science education

Whilst a great deal of research has been carried out on students' understanding in many science content domains, much less work has been done on understandings of scientific enquiry. One reason for this difference is not difficult to discern: whereas there is general agreement within the scientific comunity about the scientific understanding of forces and motion, or electric circuits, or thermodynamics, there is little agreement amongst philosophers of science about whether a 'scientific method' exists and how, if at all, the scientific approach to enquiry can be characterised. This lack of consensus matters because research into students' ideas in science is essentially normative, that is, it uses the accepted scientific view as a 'template' and seeks to describe students' ideas in relation to it. Even in studies which do not set out specifically to compare students' understandings with the accepted scientific view, this view informs the initial analysis of the content of the domain and enables the researcher(s) to decide which ideas to probe. When we consider understandings of scientific enquiry, on the other hand, there is no agreed understanding to tell us which questions we should ask or which student behaviours we should observe. We lack an agreed 'map' of the domain of interest.

This, of course, may also explain why an understanding of the methods of scientific enquiry is often treated as a tacit aspect of science learning. By assuming that students will pick up the necessary understanding from their experiences in the science classroom and laboratory, we avoid the need to specify exactly what this learning entails. To appreciate the problem more clearly, let us consider for a moment what it would mean to develop students' understanding of scientific methods of enquiry and their ability to use these methods in their own investigations. We would be aiming, through our teaching, to help students become more 'expert' in selecting productive questions to investigate, designing suitable experiments to collect data which bear on these questions, making a planned series of observations or measurements with due attention to accuracy, validity and reliability, analysing and interpreting these data to reach a conclusion which is supported by the data, and being able to evaluate the quality of the support which their evidence gives to their conclusion. (The terms 'productive' and 'suitable' in the account above mean, of course, as seen from the perspective of science.) All the decisions involved clearly depend, to a very appreciable extent, on the students' science content knowledge in the domain concerned. So too do many of the specific 'tactics' or design features which are the marks of 'quality' in practical investigations in particular science domains: taking steps to reduce heat losses in thermodynamics investigations, deciding where to place the ammeter and voltmeter in a measurement of electrical resistance, and so on. As a result, some would question whether it makes much sense to talk of a *general* 'scientific approach to enquiry' or 'scientific method'.

On the other hand, it seems clear that students, especially those who continue the study of science to more advanced levels, do become better at designing suitable investigations and at carrying them out. They appear to have acquired some understanding of general characteristics of the scientific approach to enquiry, which they can then apply to new investigations they are asked to carry out. Much of this may, of course, derive from their growing science content knowledge. But some part of it may reflect a growing understanding of the procedures of scientific enquiry - an understanding of key ideas about systematic enquiry in the scientific mode which can be applied to many investigations in different areas of science.

The challenge, then, for science educators interested in this aspect of science education is greater than for those who set out to teach science content or to research students' understandings of science content domains. They must first produce a framework, or model, of the scientific approach to enquiry, on which to base their teaching approach or their empirical research on what students understand and how this affects the things they actually do, or can do. In the remainder of this chapter, I want to consider some of the ways in which researchers have tried to represent the methods of scientific enquiry, briefly discussing some of their main findings. In many cases, however, the value of these findings in helping us to understand students' learning or to take decisions about curriculum depends on the validity of the conceptual framework within which the work was planned and carried out. So my overarching aim is to draw some conclusions about the sorts of models which may be able to sustain a progressive research programme, and hence inform teaching, in this area.

The scientific approach to enquiry: educational models

1 The scientific approach as integration of 'process skills'

Some science educators and science courses, from a range of countries, have argued that the scientific approach to enquiry can be thought of as a set of 'processes': observing, classifying, hypothesising, inferring, predicting and so on. One well-known example, the course *Science - A Process Approach (SAPA)* (AAAS, 1967), was based on Gagné's analysis of the processes of science and of learning. Several science courses in the UK in the 1980's also followed this line, some using the processes (rather than science content) to structure the programme, and seeing learning primarily in terms of the development of pupils' 'process skills', that is their ability to carry out these processes in a range of contexts. Materials to assess 'process skills' were also developed. The characteristic of all these approaches is that they portray science method as a set of discrete 'thinking skills', which can be practised and developed separately before being combined to tackle more demanding problems.

Many small-scale evaluation projects were carried out on SAPA and other similar programmes. Bredderman (1983) and Shymansky, Kyle and Alport (1983) attempt to synthesize the findings of many such studies on several activity-based elementary science programmes of this period in the USA; they conclude that research shows some gains in various aspects of student learning. The individual studies, however, vary enormously in scale and approach, and in many cases the validity of both data and conclusions is questionable. Tests of students' learning can be criticised as too similar in structure or content to those used in teaching, so that successful performance reflects drilled responses or rote recall, rather than understanding - a perennial problem for any studies of transfer of learning from one context to another.

Problems with the 'process approach', however, run deeper than the issue of empirical support for its claims of effectiveness. The 'process' view of science method has been strongly criticised on epistemological grounds (for example, by Finlay, 1983; Millar and Driver, 1987; Hodson, 1990). Its view of scientific enquiry as beginning with unbiased observation, followed by classification of observations, leading to the emergence of hypotheses (in the form of generalisations or explanatory models) is a strongly (one might even say, naively) empirical, and inductive one, which receives little support from contemporary philosophy of science. Classroom studies demonstrate clearly the influence of prior ideas on observation (Hainsworth, 1956; Gott and Welford, 1987). The problems of discovery learning, in which the inductive approach is taken to its logical conclusion, are well documented (Atkinson and Delamont, 1977; Wellington, 1981; Harris and Taylor, 1983). Nor is the hypothetico-deductive element of the process approach without its problems. School laboratory experiments are not severe tests, in the Popperian sense, of the accepted scientific view (or even of children's own explanations).

The process approach has also been criticised on pedagogic grounds - that the ability to observe, classify, hypothesise and so on is something which every child possesses from infancy (Millar and Driver, 1987). If so, it is a mistake to believe that these 'process skills' need to be taught. Children's ability to use them, however, depends on the extent and confidence of their knowledge of the contexts they are asked to work on. This would explain, for instance, the finding that performance of tasks requiring these 'process skills' is strongly context-dependent (Song and Black, 1991; Lock, 1993).

The process approach is not, therefore, a sound basis for curriculum planning, nor does the analysis on which it is based provide a productive framework for research.

2 The scientific approach as logical strategy

One of the characteristics of scientific thinking is the commitment to logical reasoning in relating evidence and explanation. This, together with the use by Piaget of scientific contexts for his studies of young people's reasoning, have led some to identify 'scientific thinking' with the kinds of 'logical thinking' which Piaget came to see as characteristic of formal operational thought (Inhelder and Piaget, 1958). One indication of formal operations in Piaget's view was an understanding of the need to control variables in experiments with several independent variables, if valid conclusions are to be drawn. Many studies have been carried out by science educators to explore students' ability to control variables in multivariate tasks, and to evaluate the success of various approaches for teaching this. Lawson (1985) provides a comprehensive and detailed review. In general terms, research shows that many school students have difficulty in planning multivariate experiments and in interpreting results from such experiments, and that performance improves with age (Wollman, 1977; Karplus et al., 1979). As in other science domains, children's prior ideas and intuitions are important: the idea of 'fairness' in making comparisons is readily grasped by many children from age 7-8 onwards. Wollman and Lawson (1977), however, note that this basic idea 'does not usually develop spontaneously into a clear, generally applicable procedure [for planning experiments] as witnessed by the numerous studies of adolescents and adults' (p. 57). Levels of performance are also significantly influenced by the content and context of the task (Linn, 1980; Linn et al., 1983; Song and Black, 1992), and students' perform differently on tasks concerning 'natural experiments' (accounts of observed events occurring in an everyday setting) as compared to laboratory experiments (Kuhn and Brannock, 1977).

Many studies have also been carried out to evaluate teaching interventions intended to improve students' performance. Kuhn and Angelev (1976) found that practice in solving problems about control of variables led to improvement, but that explicit discussion of the solutions added little extra. Rowell and Dawson (1984) reported significant achievement gains using a teaching approach based on a general solution procedure, but again noted a strong influence of context on performance.

As with research on science 'processes', a central problem for work on teaching control of variables is to devise post-instruction test items which are sufficiently different from those used in teaching to convince us that some transfer of understanding has occurred, whilst not making the difference so great that a null result is inevitable. The extent to which individual studies achieve this is, inevitably, a matter of judgement. Taken as a whole, the literature suggests that students' performance is likely to improve with age and with exposure to tasks requiring this form of reasoning, and may be further enhanced by specific interventions if these are carefully planned. Both before and after any targeted teaching there is likely to be considerable variation in performance across contexts and between 'natural' and planned experiments.

The large surveys of student performance carried out in the UK by the Assessment of Performance Unit (APU) in the late 1970s and early 1980s were based on an analysis of science performance which emphasised the ability to carry out a scientific investigation, seeing this as requiring a synthesis of all the sub-components of performance. The investigation tasks which the APU used were of the control of variables type and this, in turn, strongly influenced the way in which an investigative component was incorporated into national examinations at age 16 and thence into the English National Curriculum (DES/WO, 1989). The APU research (APU, 1987), and later work specifically related to the National Curriculum (Gott and Duggan, 1995), corroborates the principal findings of the earlier work reported above, showing that students find tasks involving continuous variables appreciably more demanding than those involving categoric variables (comparisons), and that performance is strongly influenced by the science content of the investigation task and the context in which it is set (everyday or laboratory). Students' *procedural knowledge* - the APU's term for the understandings related to investigation performance - appears to account for only a small part of the observed variation in performance across tasks, with science content knowledge and informal knowledge of the context being much more significant. A similar result is reported by Erickson et al. (1991) from a major survey of students' performance in British Columbia.

A more general criticism, however, of the APU's, and later the English National Curriculum's, approach is that it limits 'scientific investigations' to tasks about the inter-relationships of a number of variables. Whilst the procedure of conducting and interpreting a controlled experiment is important in all the scientific and technological disciplines, there is surely more to scientific investigation than this.

A rather different kind of outcome is reported by Schauble and her co-workers (Schauble et al., 1991) from a study of students carrying out control of variables tasks. They see students as moving from an 'engineering approach', in which variables are altered to optimise an effect, towards a 'scientific approach', in which the inter-relationship of variables is explored. This places the emphasis not on the students' technical competence in manipulating variables, but on their understanding of the purpose of doing so. The findings suggest that students may need to be helped to understand the goals of investigative work in science if they are to perform as we would wish.

3 The scientific approach as problem-solving

One problem with both the 'process' and 'control of variables' approaches is that they are fundamentally 'algorithmic' in orientation: they portray science investigations as following an invariant template. They imply that there is a 'scientific method', rather than something rather looser and more flexible which we might term a 'scientific approach' to enquiry. The 'control of variables' approach achieves this by reducing the scope of what counts as a 'scientific investigation', and implicitly (perhaps unintentionally) adopting a strongly empiricist view of scientific knowledge, in which theoretical constructs (the variables deemed to be relevant) 'emerge' from the situation rather than being imposed on it by the investigator's prior understandings.

Some researchers, working from a cognitive science perspective, have treated the scientific approach as a form of problem-solving. Klahr and Dunbar (1988), for example, asked university students to investigate the function of one of the control buttons on the programmable robotic toy 'Bigtrak'. They analysed detailed records of the sequence of investigations carried out by each student to solve this problem, and argued that this can best be understood as a search through two memory domains: the domain of possible experiments, and the domain of possible hypotheses. Klahr and Dunbar criticise previous work by cognitive scientists on scientific reasoning, on the grounds that the tasks set are poor analogies for real situations where scientific thinking is required. Their own study can, however, be criticised on similar grounds: the task carries little conceptual load; the range of possible experiments is quite narrowly bounded; the outcome of each experiment is fairly clear cut; and the students know that the button they are investigating does have a unique and fairly simple function, which is known to someone. None of these is likely to be the case for a genuine science 'problem'.

Nonetheless, it is useful, I think, to see the task of tackling a science investigation as involving some kind of search through a 'problem space'. Ideas are drawn from long term memory, triggered by aspects of the problem being tackled. In designing an investigation, the investigator chooses 'tools' from his or her 'toolkit'. Not all are needed for any given investigation; skill resides in making the right choices and knowing how to use the tools required. Millar (1990) proposes a model of this sort, in which procedural understanding is divided into three categories: general cognitive skills (such as observing, classifying, and so on), practical techniques (such as knowing how to use various measuring instruments) and enquiry tactics (such as knowing to repeat measurements to improve their reliability). He argues that the first category cannot be taught, but are general features of cognition which all children possess. The other categories *can* be taught, but their selection and linkage into a strategy for tackling any given investigation is not simply a matter of following a 'set of rules'. Erickson (1994) has used this framework to analyse the performance of students on an investigative task involving magnets. Amongst other findings, he shows the influence of students conceptual knowledge of magnetism on their choices of investigation procedure.

A similar model (Figure 1), emphasising the selection of relevant ideas from memory, is proposed by the PACKS project (Millar et al., 1994) for interpreting data on students' performance of seven science investigation tasks.

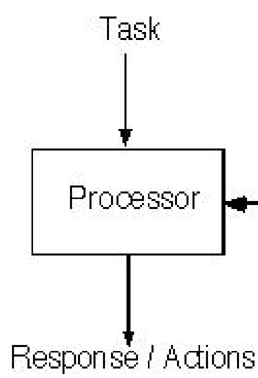

Figure 1 Designing a science investigation: a simple model

Their analysis of students' responses led to an elaboration of this basic model, identifying four specific aspects of understanding linked to different stages in the progress of an investigation (Figure 2).

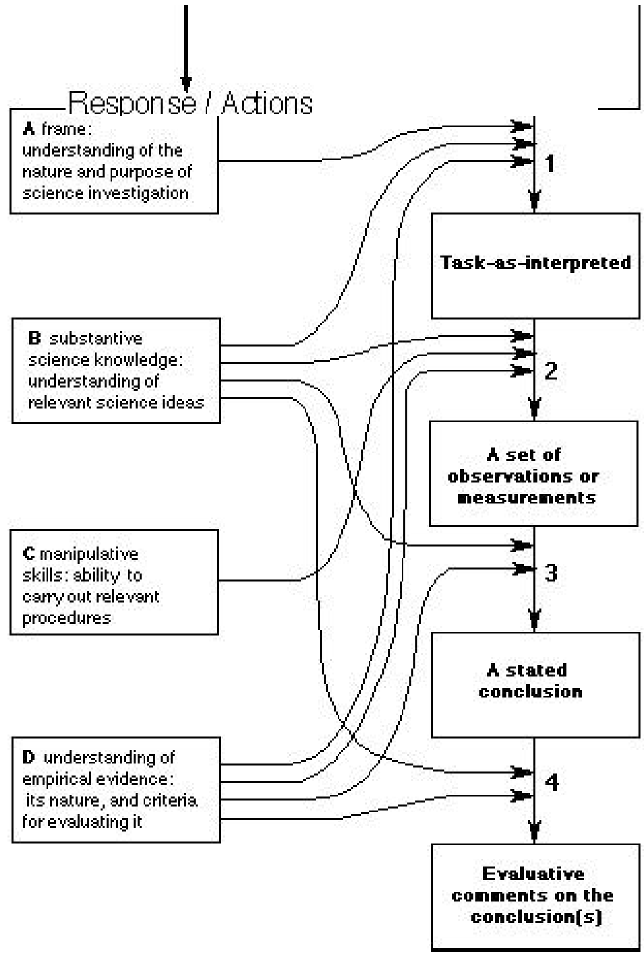

Figure 2 Relating understandings to actions in carrying out a science investigation: the PACKS model

One of these, understanding of the relevant science content, has been shown by many studies to influence performance significantly. It is also easy to accept that ability (and skill) in using measuring equipment and other apparatus influences performance. A third category, labelled 'frame', develops Schauble's idea of 'approach', drawing attention to the influence of an understanding of the purpose of an investigation task on its interpretation by students, and hence on their actions. The fourth aspect, an understanding of the nature of empirical evidence (that is, an understanding that measurements are subject to error, of how to reduce this, and of how to assess the reliability of the data collected), had a particularly strong influence on the overall quality of students' performance on the PACKS investigation tasks. (This aspect of procedural understanding is discussed further in section 4 below.)

4 The scientific approach as the collection of empirical evidence

The three perspectives discussed above emphasise the ability to design and execute a strategy for tackling a given investigation. It may, however, be more productive to shift the emphasis from this essentially creative aspect of investigating and on to the stage of using data as evidence to justify conclusions. The distinction is similar to that made by philosophers between the context of discovery and the context of justification of scientific knowledge. The former is much more difficult to describe and explain - indeed there may be little we can say about it at all. The same may apply to teaching students how to carry out science investigations: it may be more feasible to teach them how to evaluate their data and present justifications to support conclusions, than to teach them how to tackle new tasks. From this sort of perspective, some researchers have explored students' understanding of measurement, data collection, and the interpretation and use of data as evidence. The PACKS project, discussed above, found a lack of understanding of ideas about the collection and evaluation of empirical data to be a major weakness in many students' work. Using a survey instrument to collect students' responses to diagnostic questions involving the interpretation and evaluation of data, Lubben and Millar (forthcoming) propose a sequence of levels of understanding of measurement in science. At the lowest level, students see measurement as unproblematic: a careful measurement yields the 'true' value. At an intermediate level, students appreciate the possibility of error, and may know that repeating measurements is a way to improve their results, but still consider that a value can only be assessed by using an external authority (a teacher, or a data book). The highest level involves understanding how the variation in repeat readings can be used to assess the 'trustworthiness' of a measurement. Séré and her colleagues (1993) report on understandings of similar ideas at a more advanced level amongst university students.

The significance of this sort of understanding is very clearly shown by a recent study (Bailey and Millar, 1996) in which students (aged 11-16) were asked to draw conclusions from tables of data from multivariate experiments. In some questions, 'ideal' results were presented, with only one measurement of the dependent variable for each combination of values of the independent variables, and showing no change in the dependent variable when an independent variable which has … giving three repeat readings for the dependent variable each time, and showir… ithin the range of repeat readings) when an independent variable which has no effect is altered. Students' ability to draw the intended conclusion and to explain their reasoning was markedly lower on the second type of question, and correct answers all came from students who had got the corresponding question on 'ideal' data right. This suggests that understanding how to assess whether small differences are evidence of a real effect or are simply due to experimental uncertainty poses an additional, and quite significant, problem for students on top of the requirement to reason logically about variables.

comments on the conclusion(s)

Teaching (and researching into) students understandings of scientific enquiry: a way forward

As I pointed out earlier, in most science content domains, there is broad agreement about the kinds of understandings we are aiming to develop in school science, and the kinds of tasks we want students to be able to carry out successfully. As regards science enquiry procedures, there is less agreement about both of these. A first requirement, therefore, is greater clarity about what we want our students to be able to do: if we want them to become better at carrying out a scientific investigation for themselves, then we need to agree about the kinds of task which will count as 'scientific investigations'. Then we may be able to analyse the types of understanding required to carry out such tasks, and develop models to link aspects of understanding to aspects of performance. At present, the model developed by the PACKS project (Figure 2) is the most detailed available. An important feature of this model is that it does not portray scientific enquiry as 'rule governed'. Instead it sees it as involving a search of available knowledge in four sub-categories. More work, however, is needed to test and improve this model. We need to know more, for example, about the kind of memory elements recalled: are they isolated facts, or principles, or are they, as may be more likely, larger 'scripts' drawn from everyday or previous school experience? And how can we help students access those elements of their knowledge which are salient and useful in responding to a given task?

From a teaching point of view, I think it is helpful to see performance in practical investigation tasks as substantially knowledge-based (rather than, for instance, to think of it as showing 'skill', which is a very loosely defined term). Many studies have shown that science content knowledge is very important: the more you know about the science ideas which relate to an investigation, the better (from a scientific perspective) your investigation is likely to be. But other areas of understanding are also important. Amongst these are:

a clear understanding of the purpose of the investigation (in science, directed towards explanation rather than optimisation of an object or an effect)

an understanding of the idea of a variable, and of control of variables in multivariate experiments

an understanding of the problem of collecting valid and reliable data, and of how to assess the validity and reliability of the data one has collected.

This teaching agenda also generates its own research agenda, into students' understandings and how these develop, and into the effectiveness of specific kinds of teaching intervention.

Finally, it is worth noting that these understandings are not only important in the context of student investigations. They are also essential in teaching programmes which do not involve students in designing and carrying out science investigations. Unless students understand these key ideas about scientific enquiry, they have a rather weak basis for engaging in class discussions about the interpretation of data from practical exercises and teacher demonstrations intended to illustrate, and provide warrants for accepting, established science ideas. Procedural understanding is not an optional extra; rather it underpins the teaching and learning of science content.

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SectionC4, *Student's Understanding of the Procedures of Scioentific Enquiry* from: Connecting Research in Physics Education with Teacher Education

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TEACHING FOR CONCEPTUAL CHANGE: A REVIEW OF STRATEGIES

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Introduction

Over the last twenty years an active research programme has been established in the area of children's conceptual understanding in science. Outcomes of this research include detailed information about children's conceptions, at various ages, in a wide range of science domains. Review articles and edited collections of papers are available which provide an overview of this field (Gilbert and Watts, 1983; Carey, 1985; Driver, Guesne and Tiberghien, 1985; West and Pines, 1985). The importance which is accorded to children's existing conceptions about natural phenomena is a common theme running through the research programme. Learning is seen in terms of conceptual development or change rather than the piecemeal accretion of new information. Various models of learning, based upon this viewpoint, have been proposed, some deriving from epistemological literatures (Posner, Strike, Hewson and Gertzog, 1982), others from cognitive psychology (Osborne and Wittrock, 1983). All of this work has strong implications for classroom practice, and approaches to teaching which acknowledge children's alternative conceptions have been researched, developed and tested. These teaching approaches involve a range of different pedagogical strategies, they draw upon various aspects of underlying theory and have tended to be tested and reported for a limited age-range of pupils.

This paper provides a review of those pedagogical strategies reported in the literature which are broadly based on a view of learning as conceptual change. As yet the alternative conceptions research programme has had limited impact on classroom practice. At Leeds we are currently examining ways in which its findings can be used to inform science teaching more generally and this review has been prepared in order to identify the range of strategies being proposed and to analyse the different assumptions on which they are based.

Shuell (1987) has suggested that 'the teacher's task is the non-trivial one of determining which learning tasks are the most appropriate for students to work on' (p. 245*).* This poses the central question for science educators and teachers - on what basis does the teacher make decisions regarding the selection of learning tasks and strategies? Furthermore, what guidance can the research programme on children's conceptions and conceptual change offer in response to this real and practical problem?

We suggest that there are pedagogical decisions to be made at three levels. Firstly, the teacher needs to foster a *learning environment* which will be supportive of conceptual change learning. Such an environment would, for example, provide opportunities for discussion and consideration of alternative viewpoints and arguments. A second level of decision-making involves the selection of *teaching strategies.* We see strategies in terms of overall plans which guide the sequencing of teaching within a particular topic. Finally, consideration must be given to the choice of specific learning tasks. The *learning tasks* fit into the framework provided by the selected strategy and must address the demands of the particular science domain under consideration.

In making decisions about appropriate teaching strategies, four factors may need to be taken into consideration:

1. Students' prior conceptions and attitudes: students' prior conceptions across a broad range of science domains are extensively documented in the literature, but consideration now needs to be given as to how this literature is to inform teaching.

2. The nature of the intended learning outcomes: learning outcomes and the logical analysis of those outcomes in science terms have traditionally provided a principal focus for planning teaching.

3. An analysis of the intellectual demands involved for learners in developing or changing their conceptions: this analysis focusses upon the nature of the intellectual journey required of the learner in moving from existing conceptions to the intended learning outcome.

4. A consideration of the possible teaching strategies which might be used in helping pupils from their existing viewpoints towards the science view.

This paper addresses the fourth of these factors in reviewing the literature on conceptual change teaching strategies. After presenting an account of various documented strategies we identify and analyse a number of theoretical questions emerging from the review. This is followed by a consideration of practical concerns in teaching for conceptual change.

Review of Strategies to Promote Conceptual Change

We have identified two main groupings of strategies to promote conceptual change. The first grouping is of strategies which are based upon cognitive conflict and the resolution of conflicting perspectives. The second grouping is of strategies which build on learners' existing ideas and extend them, through, for example, metaphor or analogy, to a new domain. Underlying these two groupings are different emphases on where the balance of responsibility for promoting conceptual change in learners may lie. Strategies which emphasise conceptual conflict and the resolution of that conflict by the learner may be seen to derive from a Piagetian view of learning in which the learner's active part in reorganising their knowledge is central. The strategies which build on learners' existing knowledge schemes, extending them to new domains, may be seen to place less emphasis on the role of accommodation by the learner and instead focus on the design of appropriate interventions by the teachers to provide "scaffolding" for new ways of thinking.

Teaching strategies based upon cognitive conflict and its resolution

Cognitive conflict has been used as the basis for developing a number of approaches to teaching for conceptual change. These approaches involve promoting situations where the student's existing ideas about some phenomenon are made explicit and are then directly challenged in order to create a state of cognitive conflict. Attempts to resolve this conflict provide the first steps to any subsequent learning. Various approaches to conflict based teaching are reviewed in the following paragraphs.

a) Discrepant events:

Nussbaum and Novick (1982 a,b) suggest a teaching sequence which draws upon the Piagetian notion of accommodation (Piaget 1964) and includes four main elements:

- initial exposure of students' preconceptions through their responses to an exposing event.

- sharpening student awareness of their own and other students' frameworks.

- creating conceptual conflict by attempting to explain a discrepant event.

- encouraging and guiding cognitive accommodation and the invention of a new conceptual model consistent with the accepted science view.

This sequence was used as a basis for teaching aspects of the structure of gases (including the notions of vacuum between particles and of particle motion) to students of age 11 to 13. In evaluating the teaching approach, the authors comment upon its success 'in creating cognitive challenge and motivation for learning' but acknowledge that the instruction, 'did not lead to the desired total conceptual change in all students.' In conclusion, they make comparisons with the history of science in suggesting that 'a major conceptual change does not occur .... through revolution, but is by nature an evolutionary process'.

b) Conflict between ideas:

Stavy and Berkovitz (1980, p.679) draw attention to two types of training by conflict. They make a distinction between where "a conflict is produced between a child's cognitive structure related to a certain physical reality and the actual physical reality" and where "a conflict is produced between two different cognitive structures related to the same reality".

They made use of the second type of conflict in developing a teaching strategy which is aimed at advancing children's understanding of the concept of temperature. In particular they explored the conflict between two different representational systems that the child uses to describe temperature: the qualitative-intuitive system and the quantitative-numerical system. The conflict training took advantage of the fact that children's qualitative knowledge regarding certain aspects of the concept of temperature is correct at a certain age and can be used to encourage them to apply their knowledge to solve a problem in numerical form. For example, at the age of 9/10 years a significant proportion of children will assert that warm water added to warm water will still produce warm water and yet they will maintain that water at 30^0C plus more water at 30^0C will produce water at 60^0C.

The teaching strategy used a combination of worksheets and practical work designed to make children become aware of the conflict existing within their thinking. It was tested with pupils with an average age of 10 years, who worked individually and in class groups. In conclusion the authors write, 'our findings indicate that training by conflict did improve children's understanding of the concept of temperature both in individual and in classroom training situations' (p.689). They note the particular success of the strategy in helping to develop children's understanding of the 'intensivity' of temperature.

Cosgrove and Osborne (1985), Champagne, Gunstone and Klopfer (1985) and Rowell and Dawson (1985) have developed teaching approaches which require students explicitly to resolve differences between ideas from a range of different sources (e.g., other students, the teacher, the science text). Cosgrove and Osborne (1985) have proposed a 'Generative Learning Model of Teaching' which is organised into four phases:

Preliminary Phase: teacher needs to understand the scientist's view, the children's view, his/her own view.

Focus Phase: Opportunity for pupils to explore the context of the concept, preferably within a 'real' everyday situation. Learners to engage in clarification of own views.

Challenge Phase: learners debate the pros and cons of their current views with each other and the teacher introduces the science view (where necessary).

Application Phase: opportunities for application of new ideas across a range of contexts.

The authors emphasise the point that an alternative science view may not be 'received with much enthusiasm until it can be rendered intelligible and plausible by experimentation, demonstration or reference to analogy' (p.107). They also stress the importance of the preliminary phase in preparing for teaching.

The model has been applied to teaching about current flow in electric circuits and includes, within the Challenge Phase, a 'critical test' which involves measuring the electric current on either side of a bulb. The electric current unit has been used on many occasions (11 to 14 age range) and the authors report its success in helping pupils move from a view of electricity "being used up" to adopting a view of current being conserved around the electric circuit.

They draw attention to problems of stability of new ideas with regard to both context and time and suggest that, 'where ideas are counter-intuitive and not reinforced by other learning situations, then it would appear highly desirable for further experiences with the topic to occur at some later date' (p. 122).

Champagne, Gunstone and Klopfer *(1985)* have proposed a dialogue-based strategy which they call Ideational Confrontation and which is specifically designed to alter students' declarative Imowledge within a particular domain (e.g., the motion of objects). It involves the following steps:

-students make explicit the' notions they use to explain, or make predictions about, a common physical situation, (e.g., the motion of a deflating balloon).

-each student develops an analysis that supports his/her predictions and presents it to the class.

-students attempt to convince each other of the validity of their ideas; discussion and argument results in each student becoming explicitly aware of his/her ideas about motion in that context.

-the instructor demonstrates the physical situation (e.g., releases the balloon) and presents a theoretical explanation using science concepts.

-further discussions allow students to compare their analyses with the scientific one.

Use of the strategy is reported with two age-groups of students: middle school and graduate teacher trainees. The authors suggest that discussion, considering the views of others, and relating a situation under consideration to other real-world phenomena are significant in promoting change of views. They also make the point that students must be motivated and that the quality of arguments improved over the course of instruction.

Rather than attempting to promote conceptual change by inducing conflict with students' prior conceptions at the beginning of a teaching sequence, Rowell and Dawson (1985) propose a strategy in which resolution between students' prior ideas and new conceptions occurs after new conceptions have been introduced. Their approach, which draws upon a perspective from the history and philosophy of science and equilibration theory (Piaget 1977), is based upon the following premises:

-a theory is only replaced by a better theory and not discarded on the basis of contradictory evidence alone.

-the construction of a better theory need not involve an immediate confrontation with the knowledge that an individual spontaneously considers relevant.

-although cognitive change involves both strategic and metastrategic knowledge (Kuhn 1983), they need not be constructed together.

The teaching approach involves six steps:

-the ideas which students consider relevant to the problem situation are established.

discussion and are retained in a 'paper memory' for subsequent consideration.

-students are told that a theory is going to be taught to them which may solve the problem and that their help will be required both in its construction and later, its evaluation against the alternatives they have proposed.

-the new theory is presented by linking it to basic knowledge already available to the class.

-students are asked to apply the new theory to problem solution, in order to indicate its construction by individuals. Written work must form a part of this procedure to provide a second paper memory for each student.

-each student compares paper memories from steps 1 and 5 and the quality of the ideas is examined. Initial examination is directed to the stimulus problems used in the tests, to which the paper memories relate. Subsequent examination is broadened to cover as many relevant situations as possible. That is, the student is involved in gaining metastrategic knowledge.

Dawson (1990) reviews the use of this approach in the context of introducing chemical change to novices.

Teaching strategies based upon the development of ideas consistent with the science point of view

In contrast to the strategies which promote conflicts and require students to resolve them, a second group of teaching strategies can be identified which builds on pupils' existing ideas. Subsequent teaching and learning involves the pupil in developing and extending these existing ideas towards the science viewpoint.

Clement et al. (1987) have developed and tested an analogical teaching strategy, within the field of mechanics, which aims to 'increase the range of application of the useful intuitions and decrease the range of application of the detrimental intuitions' (Brown and Clement, 1989, p.239). The strategy assumes that conceptual change can be encouraged by providing opportunities for students to build up qualitative-intuitive understandings of phenomena before mastering quantitative principles. Such understandings are developed by forming analogy relations between a misunderstood target case and an 'anchoring example', which draws upon intuitive knowledge held by the student The use of a bridging strategy' has been found to be useful in developing this relationship.

As described by Brown and Clement (1989) the bridging strategy consists of four steps:

- the students' misconceptions relating to the topic under consideration are made explicit by using a target question. For example, a question which draws out a misconception for a majority of introductory physics students concerns the existence of an upward force on a book resting on a table. Students typically view the table as passive and unable to exert an upward force.

- the instructor suggests a case which she/he views as analogous (such as a hand holding up a book) and which will appeal to the students' intuitions. This case is termed an 'anchoring example' or simply an 'anchor'. (M anchoring intuition is defined as being a belief held by a naive student which is roughly compatible with accepted physical theory. This belief may be articulated or tacit, Clement et al., 1987).

- the instructor asks the student to make an explicit comparison between the anchor and target cases in an attempt to establish the analogy relation.

- if the student does not accept the analogy, the instructor then attempts to find a bridging analogy' (or series of bridging analogies), conceptually intermediate between the target and anchor. In the book on table' example, such a bridging analogy might be a book resting on a spring.

Experimental use of such strategies to overcome misconceptions about static forces, frictional forces and Newton's Third Law for moving objects have been reported as producing significantly greater pre-post test gains than for control groups. Recent work (Clement, Brown and Zietsman, 1989) has involved further research on anchoring conceptions.

Stavy (1991) also reports work which aims to use students' intuitive perceptual knowledge, in this case to understand that matter is conserved on evaporation. Stavy suggests that the use of an analogical relation between the known and the unknown can help students learn new information and discard or modify misconceptions. In the study reported, students from grades 5 and 6 were divided into two groups. One group completed a task involving iodine evaporation where the gaseous iodine is visible as a coloured gas before attempting a similar task using acetone, an invisible gas. The second group used acetone first, followed by iodine. It was found that performance in the acetone task was significantly higher when it followed the iodine task. The intuitively under-stood, perceptually supported iodine task apparently served as an analogical example for the misunderstood acetone case ('the acetone .... it's no longer there').

A rather different approach to the problem of producing conceptual change has been reported by Niedderer (1987), working with 16 to 19 year-olds. This approach is acknowledged by the author as being based in the 'New Philosophy of Science' as outlined by Brown (1977) and aims not to replace students' theories (related to everyday-life thinking) by the scientific theory but to allow them to arrive at a conscious knowledge of both and to learn scientific concepts by learning the differences between everyday-life thinking and scientific thinking, a position which has also been argued by Solomon (1983). In outline form, the strategy consists of six stages:

- *Preparation:* the teaching process which precedes the intervention, and which may contain tools and concepts that may be drawn on.

- *Initiation:* an open-ended problem is posed.

- *Performance:* this comprises parts of the following sequence: formulating questions or hypotheses, planning and performing experiments, making observations, theoretical discussions, formulation of findings.

- *Discussion of findings:* in a class forum.

- *Comparison with science:* class findings are compared with similar historical theories or modern ideas. Differences are stated and possible reasons for those differences are discussed.

- *Reflection:* students are encouraged to look back on the process of performance and to consider particular questions or difficulties which have arisen.

An illustration of this sequence is given for a teaching unit on 'force', whereby, following a preparation phase in which students learn concepts such as distance, time, velocity, acceleration, they are given the general question, 'what does acceleration depend upon?' Working in small groups, students formulate questions or hypotheses, carry out experiments and report back. The teacher then explains the power of general theories relevant to a range of circumstances and considers the formula F=ma in relation to the specific instances investigated by the groups.

The author notes that in their investigations students generally arrived at solutions to their particular problems but not at general relationships. There appeared to be some success in introducing students to fundamental ideas about the nature of scientific enquiry. The author also claims that, 'It seems plausible that this teaching strategy has started a far reaching learning process by letting students come to own results and by comparing those results systematically with the results of scientific research' (p. 365*)*.

Theoretical Issues in Conceptual Change Teaching

Two broad approaches to teaching for conceptual change ('cognitive conflict and its resolution' and 'development of ideas') have been identified in the literature. We now consider a number of theoretical issues, some of which arise directly from the review and others which are of more general concern.

Acknowledging Students' Ideas

The fundamental principle underlying all of the approaches reported is one which stresses the importance of acknowledging the learner's existing ideas and understandings in any teaching/learning event. This process has been put into operation in various ways:

- through explicit elicitation of students' ideas in class.

- in informing selection of starting points to teaching.

- in informing curriculum design.

All of the conflict strategies (and Niedderers work in addition) involve phases where pupils have the opportunity to make explicit, and to clarify, their own views. Differences, both between the pupil ideas and with the science view-point, are then identified. Niedderer works from the students' ideas in an alter-native way in using them as a basis for developing generalizations within the science perspective. In all of these instances, pupils' ideas are explicitly brought out into the open and used as a basis for subsequent teaching.

Clement et al. (1987) take as their starting point a target question designed to reveal pupil 'misconceptions' about some phenomenon but then shift the focus to consideration of an 'anchoring case' which the teacher views as being analogous to that phenomenon. Here we have a situation where knowledge of children's ideas and understandings is used to inform the choice of starting points to teaching; the initial teaching is not designed to respond to pupil ideas explicitly raised in class. In a similar way, Stavy (1991) uses awareness of children's understandings (their intuitive perceptual knowledge) to provide a starting point for teaching on conservation of matter.

Other researchers have used knowledge of children's conceptions to inform the design and sequencing of parts of the science curriculum. Thus Schollum, Hill and Osborne (1982), in teaching mechanics to 11 to 13 year old children, base their instruction on the conception held by many children that objects move forward because, 'there is something in them that keeps them moving.' They start by introducing the idea of momentum for this "something". Teachers using the approach report that the children, 'seem to have the ideas already.' In a similar way, Eisen and Stavy (1987) have developed a unit for teaching photosynthesis which works from material cycles in nature which they consider to represent a form of natural order for pupils.

The Nature and Role of Conflict

It could be argued, from the point of view of the teacher, that all the teaching approaches reviewed above, including those which are not considered to be based in cognitive conflict, have an element of actual or potential conflict in them. This conflict is between accepted scientific theory and those ideas which students either bring to the learning situation or might construct as a result of it. In Stavy's work, for example, knowledge of students' ideas about conservation of mass on evaporation leads the teacher to expect that the likely response to the question involving acetone evaporation will be in conflict with the science view. Such a situation, in this case, is avoided by using the iodine evaporation task first. However, while the teacher may be aware of conflict situa tions, the student may be entirely unaware. Indeed, even if the conflict is highlighted by some means, there is no guarantee that the student will recognise either its existence or its significance.

Teaching strategies which deliberately aim to use a conflict-based approach are likely, at some point, to make such conflicts between the students' ideas and the science perspective explicit (e.g., Rowell and Dawson, *1985)* but may also utilise discrepancies between:

- two sets of ideas already available to the learner, e.g., Stavy and Berkovitz (1980) qualitative-intuitive and quantitative-numerical representations of temperature.

- an explanatory model held by the learner and an event which cannot be explained by this model, e.g., Nussbaum and Novick (1982a) continuous model for the structure of a gas versus evidence that a gas can be compressed.

- ideas which a student holds and the ideas of his/her classmates, e.g., Champagne et al. (1985) various student ideas about the motion of objects.

The success of any conflict-based strategy depends upon the willingness and ability of the learner to recognise and resolve the conflict. For example, different student ideas within a class, or a student expectation and a physical event, cannot be brought into conflict unless the learner is prepared to construct an understanding of such ideas and events and then attempt to relate them to each other. In addition, Dreyfus et al. (1990, p.567) make the point that, 'even meaningful conflicts are not always successful, in the sense that they do not always ensure the construction of the required knowledge and/or only of the desired knowledge.'

In the teaching strategies reviewed in this paper, four positions about the role of conflict and its resolution can be identified:

i) Strategies where the conflict must be recognised by the student in the early stages of teaching if learning is to occur.

Nussbaum and Novick (1982a) describe their rationale for introducing conflict at the beginning of the teaching Sequence in terms of the need for, 'recognition by the learner of a problem and his inability to solve it with his existing conceptions' and assume that human beings have, 'an innate need to reduce dissonance, incongruity and conflict between two cognitions' (p.186). The presence of conflict is thus seen as a motivating factor in the search for a better explanation. This is also true for Stavy and Berkovitz's (1980) work on representations of temperature.

ii) Strategies where an alternative 'way of looking' is introduced and the conflict highlighted later.

Rowell and Dawson (1983) suggest that conflict should only be invoked after pupils have had the opportunity to clarify their own ideas and the science viewpoint has been introduced. They consider that this approach is more effective and reduces threat to the learner in that, 'no challenge is raised to the child's old way of thinking until a new way is already available to him/her which can take its place' (p.124).

iii) Strategies where conflicts 'nay occur but are not seen as being essential for promoting learning.

Clement (1987) sees conflict as a potentially useful motivator for learning. He suggests that, in the case of tensions between a misconception and a correct conception in the same student, an appropriate approach is to 'draw out both .... and play them off against one another' (p.94). Although Clement's basic strategy is one of using analogy to develop 'useful' conceptions, rather than challenging misconceptions, he notes the potential for utilising conflicts between students who hold different points of view. He suggests that, 'skillfully led classroom discussions appear to be one effective vehicle for fostering dissonance, internal motivation and conceptual restructuring' (p.94).

iv) Strategies which aim to avoid conflict for the student.

Stavy (1991), expresses the opinion that conflict strategies may cause a loss of self confidence in students and, on occasions, regression from correct to incorrect judgements. In her approach to teaching by analogy (1991) she claims that students, 'are not made aware of the conflict or of the learning process the learning takes place without the student's awareness. From the student's point of view, there were no misconceptions and no learning took place.'

The Construction of scientific conceptions

Students are not going to adopt a new conception unless they can first represent it to themselves. In other words, they must find it intelligible. Where such new conceptions originate from and how they are made intelligible to students varies across different strategies. In some strategies, for example those emphasising conflict, there tends to be an assumption that alternative conceptions will be generated from among the students; that if some students suggest viable alternatives, these are then available in a 'pool' of ideas to be consider ed, both through discussion and experiment, by all students. Such a strategy may be effective in some cases where viable alternatives are readily put for-ward by students.

This is not always the case. Some researchers in the field acknowledge that the teacher may need to intervene to suggest the 'accepted view' alongside other students' suggestions. This draws attention to a fundamental theoretical point about the process of construction of scientific conceptions. We would argue that scientific conceptions are not simply individual constructions which are developed to make sense of experience. They are 'ways of seeing' which have been developed within the social community of science. In this sense they may need to be transmitted through the culture of science rather than be 'discovered' from personal experience. Helping students in constructing scientific conceptions thus involves a process of induction into a scientist's culture and the teacher has an important role to play in guiding that induction.

In reviewing the different strategies for conceptual change we identify different ways in which this process of construction of science conceptions is facilitated. At one extreme there are the strategies where students, through brainstorming and reflection, are encouraged to generate more viable conceptions themselves. The way the teacher then encourages some ideas and discourages others may give differential status to certain ideas (see Edwards and Mercer, 1987) and in this indirect way induct students into a scientific perspective.

Other strategies are much more direct in supporting the knowledge construction process. The careful and disciplined choice of analogies to support the construction of new conceptions (as in the work of Clement et al., 1987) is a case in point. The strategy proposed by Rowell and Dawson explicitly gives time for the construction of a new model but without saying how. In other strategies, (for example, that described by Niedderer) the teacher, drawing on the range of experiences provided for by students, offers an integrative 'way of seeing' and negotiates its use with students. We see this process as one in which the concepts and theories of the scientific community are being made available to students and their meanings are being negotiated with them. Work undertaken in the tradition of Vygotsky emphasises this process whereby learners are supported in their development of new capabilities through an explicit phase of 'scaffolding'.

In our own work in mechanics at needs (Twigger et al., 1991) we are explicitly introducing representational devices (such as arrows for force vectors) at appropriate points in the students' work with computer microworlds. We do not expect students to 'discover' such devices for themselves, although they do need opportunities to use such notation in thinking about and interpreting a range of situations so that it becomes appropriated by them.

A problematic feature of the knowledge construction process is that in some domains the construction of a scientific model requires the establishment of a quite extensive series of concepts and inter-relationships. This is the case in students' construction of Newtonian mechanics (with the links between concepts such as force, velocity, acceleration, momentum), and current electricity (where concepts of current, voltage resistance, power need to be established and related). In these cases it takes time to establish a new theoretical model and during this time students may, even without being aware of it, be trying to interpret experiences they are given in terms of their prior ideas in that domain. Although they can only be constructed in bits, such complex ways of seeing may only make sense as a whole - thus presenting a complex problem for pedagogy.

The Evaluation of Scientific Conceptions

Students may be able to construct a representation of a scientific idea. It may be intelligible to them. However, there is still a further aspect of the process of conceptual change and that is what status the learner gives the scientific conception. There are various possibilities here. The conception may be under-stood (i.e. the student can create an internal representation of it) but the student does not believe that it represents the way the world is. We have experience of secondary students responding to the particle theory in this way.

Rather than evaluating a new conception ontologically, i.e. as representing how things are in the world, students may evaluate them in a utilitarian way. In this case the conception is evaluated in terms of its usefulness in particular contexts (both social and phenomenological). What may be important here is the point that Solomon (1983) made that, rather than instruction being orientated to changing students' conceptions, what is necessary is helping them to appreciate the appropriateness of particular 'ways of seeing' to particular contexts.

A further way in which a new conception may be evaluated is in terms of its generality. Here the feature is not whether a new conception better 'fits' experience nor whether in particular instances it is judged to be more useful or appropriate. This way of evaluating introduces an epistemological criterion - that of consistency. Although there is probably some internal cognitive pressure towards consistent as opposed to inconsistent mental representations, studies of children's and adults' reasoning indicates that this is far from a powerful influence. Inducting students Into science however involves adopting this criterion as a major one. Just as we argued earlier that teaching in science needs to involve the explicit "scaffolding" of scientific conceptions so we would argue that it also needs to introduce explicitly the epistemological assumptions underlying the 'language game' of science. It is a criterion such as parsimony that also introduces a discontinuity between students' everyday conceptions and scientific conceptions. It is not only that their everyday conceptions are in-commensurable with those of science but also that the criteria for evaluation differs significantly in emphasis. Whereas for everyday conceptions ontological and perhaps utilitarian criteria probably dominate, in evaluating scientific conceptions parsimony has much greater status.

There are a number of comments to be made in the light of this about specific conceptual change strategies. Many include opportunities for students to evaluate competing conceptions, either explicitly as in the strategy proposed by Rowell and Dawson (1985*)* or by discussion and the general interplay of ideas as in the strategies suggested by Champagne et al. (1985), Cosgrove and Osborne (1985) and Niedderer (1987).

Such an evaluation process involves a comparison of two or more competing conceptions on the basis of Various criteria including internal consistency and their extension. In practical terms what this means is that in order to evaluate a scientific conception, students need to have opportunities to consider not just single well chosen phenomena but a wide range of instances. An important part of adopting a scientific conception is appreciating the range of situations to which it relates.

Practical Concerns in Conceptual Change Teaching

Students and their teachers are clearly the central players in all of the class-room activity which has been described in this paper. What then are the special demands which 'conceptual change teaching' might place upon them?

Demands Upon Students

One feature common to many of the teaching approaches reviewed is the extent to which students are involved in discussion, both in small groups and in whole class situations. Discussion provides the means by which students become more aware of their own, and other students', ideas and understandings. It makes various demands upon students including the need to listen to, construct meaning for and evaluate, the points of view of others. Having considered these different points of view, the student (especially in the conflict based approaches) is then often confronted with a further perspective which may carry the additional authority of being introduced by the teacher. A range of perspectives is thus placed on offer and the student is expected to consider the relative merits of them all.

A fundamental point which might be made about such a learning environment, in which a plurality of viewpoints is encouraged, is that it follows from particular views of science and of learning and these views may or may not be shared by the students. This can lead to problems. If, for example, students have views of learning which are essentially transmissive in nature and they adhere to positivist views of science then asking them to consider their own, and other, perspectives about a phenomenon may not appear sensible to them. This dilemma is encapsulated in a comment made during a practical science lesson; a fourteen year-old girl, on being asked for her ideas about a phenomenon, replied, 'why ask me? Just tell us the right answer.' The girl's response is perfectly valid in the context of her own thinking about science and learning. If students are to engage usefully in the kinds of approaches to teaching and learning which are described in this paper then they must be introduced to, and encouraged to reflect upon, the underlying assumptions.

Through these teaching approaches the student is clearly placed in an intellectually challenging position and that, of course, is the point of the exercise. Dreyfus, Jungwirth and Eliovitch (1990), however, remind us that students bring more than alternative conceptions with them to science lessons, they also import attitudes which will influence subsequent learning. In particular, they found that 'bright successful students reacted enthusiastically to cognitive conflicts.' They liked the 'flabbergasting effect' of the method and the confrontation with new problems.' In contrast, 'unsuccessful students .... have been shown to develop negative self-images, negative attitudes towards school and school tasks and high levels of anxiety.' As a result, 'they tried to avoid the conflicts. They were most characteristically apologetical when confronted with a conflict which, to them, seemed to represent just another failure' (pp. 565-566). Stavy (1991) makes a similar point when she argues that conflict training can, result in students' loss of self-confidence and can sometimes cause regression.'

Whatever the strategy that is adopted, however, a central feature from the student's point of view is that knowledge is not provided for them 'ready made'. They need to take ultimate responsibility for making sense of learning activities.

Demands upon Teachers

All of the approaches reported require the teacher to be responsive to the ideas and understandings of pupils. This responsivity is achieved in different ways with different approaches and the associated demands upon teachers vary accordingly.

In some situations the teacher is required to take on a neutral 'consultative role.' Aspects of this role may be unfamiliar to the teacher in, for example, acting as a sounding heard for ideas and declining to express opinions, or sup-porting students as they develop their own programmes of questions for future investigation.

At other times the teacher will need to respond directly to student ideas in helping them towards the science viewpoint. In such situations, knowledge of the science domain in which the teaching is located, of the conceptions that students tend to use in that domain and of the conceptual pathways they tend to follow once teaching is under way are all essential. Knowledge of conceptual pathways provides insights into the dynamic processes and routes of class-room learning within any particular domain. By their very nature conceptual pathways can not be defined, for individual learners, in advance of teaching (through, for example, a theoretical comparison of a student's conceptual starting points and the intended learning outcomes). Knowledge of common conceptual pathways can only be gained through practice and the development of such knowledge is likely to contribute greatly to the expertise and confidence of the teacher.

A further and fundamental demand upon the teacher lies in creating a classroom environment within which students feel confident and able to express and discuss their views openly. Such an environment can only be created through the teacher both being sensitive to students' needs, feelings and ideas and being an effective manager of class groups.

We would contend that, for many teachers, demands such as these are likely to represent a significant change from existing practice. The teacher is required to:

- be aware of students' ideas and understandings relating to the topic under consideration.

- be aware of likely conceptual pathways for that topic.

- be sensitive to students' progress in learning.

- be able to generate learning tasks to support and encourage that progress in learning.

- be sufficiently confident in his/her own understanding of the subject topic to be able to appreciate, and respond to, differing points of view.

- be able to organise and manage a classroom which will allow for all of this to happen.

Final Comments

This paper has reviewed a range of teaching strategies designed to promote conceptual change in students. The principal aim of all the approaches is to help students towards a more scientific view of the world. There are differences, however, in how this general aim is realised. Students have variously been encouraged: to exchange their existing ideas for entirely new conceptions (Nussbaum and Novick, 1982); extend or develop existing views and apply them in new situations (Brown and Clement, 1989); develop a scientific understanding which may be held in parallel with existing notions (Niedderer, 1987); recognise the appropriateness and/or applicability of models in different situations (Stavy and Berkovitz, 1980).

It is clear that different strategies make differing cognitive demands upon students. This point brings us back to the fundamental issue raised in the introduction to this article, that of selection of teaching strategies. A comparison of a student's existing conceptions with intended learning outcomes provides an overview of the desired conceptual change and gives some indication of the extent and nature of the intellectual journey which the learner must make. Additionally, any strategy which is selected to promote that change will introduce, for the learner, its own cognitive demands and these need to be taken into account during planning along with other relevant factors.

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Reprinted by permission from: *Research in Physics Learning: Theoretical Issues and Empirical Studies. Proceedings of an International Workshop.* R. Duit, F. Goldberg, H. Niederer (Editors) March 1991
IPN 131, ISBN 3-89088-062-2

Section C5, *Teaching for conceptual change: a review of strategies* from: Connecting Research in Physics Education with Teacher Education
An I.C.P.E. Book

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INTRODUCTION

Anna-Maria Pessoa de Carvalho *and* ***Richard White***
Section editors

As do other sections of this book, the chapters in Section D express concern about the general quality of teaching and learning of physics.

The authors fear that physics teaching concentrates on transmission of established facts and principles, and routine mathematical exercises, at the expense of portraying physics as a dynamic, human construction of a way of perceiving the natural world. As well, the relations of physics to other knowledge, such as history, and its importance for current issues of society and technology, are too often ignored. This limited teaching is a consequence of attitudes.

The chapters point out that beliefs are a crucial element of attitudes. If we are to improve the teaching of physics, we must attend to beliefs about the nature of scientific knowledge, about the purpose of schooling, and about teaching and learning.
Attitudes form slowly, and are a result of experience. There is then a cycle, in which teachers experience transmission of knowledge when they are shoolchildren, and go on to teach in the same manner to their own pupils, some of whom will become teachers in turn and so continue the cycle. The challenge that the chapters address is how to break this cycle of mediocrity, through training of teachers and their involvement in research on learning.

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SectionD, *Introduction* from: Connecting Research in Physics Education with Teacher Education

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TEACHERS' ATTITUDES ABOUT PHYSICS CLASSROOM PRACTICE

Richard F. Gunstone *and* ***Richard T. White***
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A teacher of final year high school physics is talking about her views of teaching and learning physics, in particular on her use of examples in her teaching of mechanics.

...I mean, physics is fairly remote for most [students] and I think ... you can link it to things that are happening to them .... There are things you can talk about in life all the time ... I do think that is important. Why do I think it is important? I just think in any teaching unless you can relate to it you've got a problem .... I suppose when I go to mathematics [teaching] it's different, but I think in physics, which I believe is very much based on practical kinds of things that can be quantified and can hopefully end up being systematised in some fashion, that's a fairly abstract process with a lot of students. Getting through to that point [is difficult], but if it relates to something I think they'll remember it better.

What this teacher says illustrates factors that influence teacher attitudes to classroom practice. Her teaching is shaped by what she believes about student learning ("*if it relates to something I think they will remember it better* "), about the nature of physics ("*physics ... is very much based on practical kinds of things that can be quantified* "), and how she sees these influencing what she should do in her classroom *("I think you can link it to things that are happening to them* "). More significantly, it illustrates the way in which these influences on teachers' attitudes to classroom practice are often intertwined.

The teacher's statement comes from a lengthy interview conducted during a study of the views that senior high school physics teachers and first year university physics teachers in one state in Australia hold about quality learning of physics (Gunstone, Brass and Fensham, 1994). At other points, the interview showed how her views of the purpose of education influenced her attitudes to classroom practice. The high school and the university physics teachers in this study differed in their attitudes to classroom practice; their distinctive characteristics provide contrasting illustrations of the links between views of learning and teaching, nature of physics, and purpose of education. Hence each group also has distinctive attitudes to the practice of physics teaching.

The high school teachers placed high value on students designing and undertaking experiments, and on students linking the ideas of physics with personal experiences from outside the classroom. They valued pedagogies that would foster these student behaviours. At the heart of this valuing was belief in a particular view of learning - that the individual learners each construct their own understandings, and are therefore responsible for their learning. The pedagogies that these teachers claimed to see as more appropriate were derived from this view of learning. Also contributing to the valuing of laboratory and linking approaches were beliefs about the nature of physics and the purposes of education that were consistent with the approaches. These teachers expressed the purpose of their students studying physics more in terms of general education, of seeing the significance of physics for understanding the world around them, than in terms of preparation for further study of physics at university. The beliefs of these teachers about the nature of science can only be inferred, but the data from this research suggest that they saw physics as both empirical and a construction by scientists.

No inference at all was needed to determine substantial aspects of the views of the nature of physics held by the majority of the university physics teachers. Their statements showed that they saw physics as a highly logical structure, based on a set of uniformly applicable generalisations. This structure represented, for them, an obvious and powerful way of understanding natural phenomena. The purpose of teaching physics was to lay out this structure and, in the process, prepare first year university students for research in physics. The structure of physics was so important for most of the university teachers, it was the overwhelmingly dominant criterion for deciding curriculum and pedagogy. For example, for these teachers, laboratory work was of relatively low value. Any value it did have was in the extent to which students might learn skills of experimental design, not in the learning of physics concepts. Linking physics with the "real" world had no cognitive value (only some affective value). A small number of this group even argued that teachers should not begin with the real world in teaching physics as this would diminish student learning.

These two groups of physics teachers provide contrasting examples of the links between views of the nature of science, teaching and learning, and the purposes of education. For the high school teachers it appears that a view of learning was central, and that views of purposes and the nature of science were then consistent. With the majority of the university teachers it was the view of the nature of science that was central, so much so that this overrode any consideration of learning and pedagogy.

These two different examples also illustrate important issues in considering links between the beliefs considered in this chapter : the links are variable, one belief may dominate all others, and there may not always be consistency between the beliefs (see, for example, Koulaidis & Ogborn, 1995).

Just as one belief can dominate all others in shaping attitudes to classroom practice, so can the teachers' understanding of physics. In particular, if the teacher's knowledge is poor then his or her classroom practice is necessarily very limited. For example, Tabanera (1995) shows that where teachers' understanding of electricity is very poor, they do not use analogies (for they do not understand their significance themselves); they avoid laboratory work; they reject any form of student discussion; they use no examples. Their classroom practice is limited to lectures taken from texts and demonstration of solutions of standard quantitative problems. Although we do not discuss teacher understanding of physics in this chapter, it is clearly of great significance.

Other than teacher knowledge, it is teachers' views of teaching and learning, the nature of science and the purposes of education that are of prime influence in shaping their attitudes to classroom practice. Again these are intertwined and one can dominate all others. However, for convenience, we consider each of the three influences separately in the remainder of this chapter, with greatest attention being paid to views of teaching and learning. We conclude the chapter by briefly discussing some implications for teacher education.

As research in these areas often addresses science teaching generally, rather than physics specifically, we will use both "physics" and "science" as contextual descriptors as appropriate.

TEACHERS' VIEWS OF TEACHING AND LEARNING

Formal studies of physics/science teachers' ideas and beliefs about teaching and learning have used a variety of methods, and have investigated practising teachers (at school and university) and pre-service teacher education students. These methods include interviews directly focussing on views of physics learning (e.g. the study by Gunstone, Brass and Fensham discussed above) or views of physics learning and teaching (e.g. Donald, 1993), interviews using specific instances that may or may not be seen as science teaching (e.g. Hewson, Kerby & Cook, 1995), interviews exploring the metaphors used by teachers to describe their practice (e.g. Tobin & LaMaster, 1995), detailed and long term case studies of science teachers (e.g. Brickhouse & Bodner, 1992), and questionnaires administered to larger groups (e.g. Aguirre, Haggerty & Lindner, 1990). Substantial data about teachers' views of learning and teaching have also emerged in collaborative research and development work involving teachers and researchers (e.g. Baird, Fensham, Gunstone & White, 1991; Baird & Northfield, 1992). These various approaches reveal a wide range of ideas and beliefs about teaching and learning. We illustrate this diversity of views and the ways the views affect the attitudes of teachers to classroom practice by considering two fictitious extremes, which we have created by combining features from a number of different studies.

Imagine teachers who believe that what they say in a classroom is then known, in the form it was uttered by the teacher, by every student in the classroom. That is, imagine teachers whose ideas and beliefs about learning and teaching are solely that the teacher gives and the learner receives - and that the learner receives only that which the teacher gives. Such teachers would have attitudes to and behaviours in classrooms that are extraordinarily limited: they would see the teacher's role solely in terms of organising a clear and logical exposition and ensuring that students listen. While concern with having students listen may well lead these teachers to use some demonstrations, their general approaches would be limited and didactic. And the teachers would see these limited approaches as appropriate. The approaches would be consistent with the beliefs they hold.

At the other extreme, consider teachers whose beliefs about teaching and learning are that all student learning must come from students themselves, that the teacher cannot directly tell students anything. In the language used for the first fictitious example, the teacher cannot give and the learner cannot receive. In such cases the teachers would again have attitudes to and behaviours in the classrooms that were extraordinarily limited: they would see the teacher's role solely in terms of organising resources that students have decided they need; they would not give answers to any student questions; etc. Again, such teachers would justify their classroom approaches by reference to their underlying beliefs about teaching and learning.

An obvious point from these two fictitious examples is that for both extremes the underlying beliefs about teaching and learning are indefensible. Justifiable views of teaching and learning and consequently more appropriate classroom approaches will lie between these extremes. As one of us has written elsewhere (White, 1992), the question of balance between alternatives is frequently of great importance in considering educational issues.

We began this section by listing some of the wide variety of approaches that have been used to explore teachers' ideas and beliefs about teaching and learning. One fundamental issue to emerge from all these various approaches is that teachers' actions in classrooms <u>are</u> based on ideas and beliefs about teaching and learning. It is true that these ideas and beliefs may be hard to justify, as in our two fictitious examples above, and that the ideas and beliefs may be implicit and not easily seen (a point to which we return in the final section of this chapter). But these ideas and beliefs do exist. In the explorations of teachers' ideas about teaching and learning it is hard to find any example of a teacher with no such views. The notion of any teachers planning and implementing approaches in their classrooms without underlying beliefs is a highly unlikely one. These beliefs may be profound, they may be sadly limited, but they are held. It is the nature of the beliefs that is of interest; their existence can be assumed.

Our description above of teachers' beliefs about teaching and learning being sometimes implicit and sometimes hard to justify clearly implies a concern with teachers recognising and evaluating their beliefs. Doing this with the intent of teachers understanding and evaluating their attitudes to and practice in classrooms raises a related issue - the beliefs of the students about learning and teaching and what are appropriate roles for learners and teachers. Students' beliefs about these are significant factors for teachers, and will strongly influence what teachers can do. As an example, we give the case of a senior high school physics teacher who, as a result of developing broader and more profound views of teaching and learning, spent considerable time in her physics class attempting to develop students' abilities and motivations to ask questions (Bakopanos, 1989). Many students were unhappy about this because the approach was at odds with their beliefs. For example, after the teacher had spent some time on this approach, one student objected, expressing a different view of appropriate behaviour: "You don't ask questions. You listen to what the teacher says and you take down notes. The teacher tells you what to do and learn. That's the way it is done". The fact that some students had beliefs of learning, teaching and appropriate roles that were at odds with the beliefs of the teacher limited what the teacher could easily achieve, even though the teacher's beliefs were informed and profound and the students' beliefs were narrow and inadequate. A number of similar cases emerged in research by Gunstone, Gray and Searle (1992). In that study, students in the final year (Grade 10) of junior high school experienced teaching approaches that led to substantial understanding of aspects of Newton's laws. This understanding was a significant advantage for those who studied physics at senior high school in the following year: the achievement in mechanics of the students involved in the research was significantly higher than their peers in the senior high school classes. However, when interviewed during their senior high school year about the mechanics teaching they had experienced in junior high school, about one quarter of the students were quite negative about the junior high school experience (e.g. *"It [the teaching approach used by the researchers in junior high school] takes too much time to work. We have been brought up to sort of working quite quickly, and although we don't know what we are learning we still get through [pass exams] alright* "). These negative students gradually lost the cognitive advantage that they had gained. Because their ideas and beliefs about teaching and learning were at odds with the ideas and beliefs underlying the junior high school teaching, they rejected the classroom approaches. As a consequence they did not value the understanding they had gained and did not again use the approaches that had been central to the junior high approach.

The same general problem arises when it is the students who have the informed beliefs and the teacher who has the inadequate beliefs. One instance of this is some students who had had extensive experience in science classes conducted by teachers with the perspectives of the physics teacher above, and who then found themselves with a highly didactic teacher, rather like our first fictitious example. Their reactions included comments *like "Mr ... won't let us talk. If we can't talk how can we learn? All he does is give us notes and expect us to understand it* ". (Baird & Northfield, 1992, p85).

So, teachers' ideas and beliefs about teaching and learning are powerful influences on their attitudes to classroom practice and thus on their actual approaches to physics teaching. Students' ideas and beliefs about teaching and learning are powerful influences on their attitudes to classroom practice, and thus are a fundamental factor in shaping what it is possible for teachers to do. These two assertions about teachers and students imply the need to consider approaches to changing ideas and beliefs about teaching and learning.

Changing views of teaching and learning

In the final section of this chapter we consider approaches to changing views of trainee physics teachers. Here we give a more general comment about changing views, comments we see as applicable to both students and teachers. Greater detail about approaches can be found in accounts of our collaborative work with teachers (e.g. Baird, Fensham, Gunstone & White, 1991; Baird & Northfield, 1992).

We find particular value in the Conceptual Change Model of Posner, Strike, Hewson and Gertzog (1982) for considering possibilities for change of views of teaching and learning. The model was devised as a way of thinking about conceptual change in cognitive terms. This model argues that, for conceptual change, the individual must initially feel <u>dissatisfied</u> with the existing conception; then, for this existing conception to be replaced by a new conception, that new conception must be <u>intelligible</u>, <u>plausible</u> and <u>fruitful</u>.

Applying the same set of criteria to considerations of the views of teachers and students is helpful. If it is seen as appropriate to try to change such views, then the initial step is often to attempt to generate dissatisfaction with them. This is not easy. Teachers (and students) have views about teaching and learning that have evolved in response to their experiences. From the perspective of the teachers (or the students), the existing views are most likely to be seen as appropriate to the context in which they are functioning. While there are many aspects to "appropriate" here, assessment is usually a significant one.

Many teachers (and students) hold views of teaching and learning which they see as consistent with the way learning is assessed in their context. A case study by Wildy and Wallace (1995) illustrates this with particular clarity. If, in the extreme, the assessment of learning is the assessment of students' ability to reproduce single elements of propositional knowledge, then one can expect views that see appropriate teaching to involve no more than students having in their notebooks correct elements of propositional knowledge. Having assessment that rewards particular teaching and learning approaches is a necessary step towards fostering views that value these approaches.

Making new views of teaching and learning intelligible is relatively easy. Having the views seen as plausible is more difficult, and as fruitful even more so. Again, assessment is central - both teachers and students are right to expect that grades from physics courses will reward the ability and motivation to master the tasks undertaken in classrooms.

When considering how to change views of teaching and learning, a fifth criterion can usefully be added to the conceptual change model, that the new views of teaching and learning should be seen by the teacher as feasible (Gunstone & Northfield, 1986). The teacher has to be able to see how to cope with the demands that follow from attempting to implement the classroom consequences of the new views.

TEACHERS' VIEWS OF SCIENCE

Attitudes of teachers to science and technology are the subject of another chapter in this book. Even so we consider views of science briefly here because of their links with views of classroom practice, as already outlined. We do not discuss how the view of science contained in the curriculum affects teaching, although this is clearly of major significance. (As an obvious example, consider the process - product curriculum debate in science education, the stance taken by each side of this debate about the nature of science, and the consequent impact on teachers' attitudes and approaches to classroom practice.)

In the context of a detailed discussion of links between a constructivist view of the nature of science and how and what science to teach, Carr et al. (1994) argue that

Many teachers hold the view that:

- science knowledge is unproblematic
- science provides right answers
- truths in science are discovered by observing and experimenting
- choices between correct and incorrect interpretations of the world are based on commonsense responses to objective data.

(p147)

While the assertion that these are the views of "many" teachers may or may not be justified, this quote does illustrate links of views of science with attitudes to classroom practice. A teacher with this set of views will approach classroom teaching with the intended endpoint of students having clear statements of the relevant knowledge, and will approach laboratory work with the intent of students discovering relevant knowledge through observation. Equally important is that these views are quite common among students. Hence students often expect the same approaches, a point well made by Hirschbach, a Nobel Laureate in chemistry:

In our science courses, the students typically have the impression - certainly in the elementary or beginning courses - that it's a question of mastering a body of knowledge that's all been developed by their ancestors.... Particularly ... they get the impression that what matters is being right or wrong - in science above all .... I like to stress to my students that they're very much like the research scientists: that we don't know how to get the right answer; we're working in areas where we don't know what we're doing ... I think any way we can encourage our students to see that, in science, it's not so important whether you are right or wrong ... Because the truth is going to wait for you.

(Hirschbach, as quoted in Marton, Fensham & Chaiklin, 1994 (p 472)

As with views of teaching and learning, students' views of the nature of science impose a constraint on what teachers can do in classrooms.

It should not be surprising if Carr et al. (1994) are correct in the above quote in their view that "many" teachers hold the described view of science. Almost all physics (and science) teachers acquire views of the nature of science implicitly through their experiences of learning science content. The further they progress through their science learning the more likely it is that the learning expected of them will be consistent with the view described by Carr et al. Serious consideration of the nature of the discipline they are learning, of the origin and status of knowledge claims, is quite rare for university physics students.

Explicit study of the nature of science is not an automatic remedy. Gallagher (1991) describes two teachers with strong formal backgrounds in the history and philosophy of science whose general views of the nature of science and its links with the practice of school science were broadly similar with the views of other science teachers in his study, who had not had that study of the history and philosophy of science. It appears that, as with the content of physics per se, knowing the content of history and philosophy of science by itself is not enough. One also needs to understand how and why and for what purpose that knowledge interacts with pedagogy.

TEACHERS' VIEWS OF THE PURPOSE OF EDUCATION

The last twenty or so years have seen dramatic changes in the ways one might see the purpose of education in general and the purpose of physics teaching in particular. The growth of the Science for All and Science-Technology-Society movements (e.g. Fensham, 1992), and the changing nature of students in those countries with increased school retention rates, make considerations of the purpose of physics teaching much more complex. When school physics was seen solely as the beginning of a sequence with the end point of post-graduate university research students, things were simple. Both the content of school physics courses and the pedagogy used in classrooms could be seen solely in terms of the requirements of university physics departments, and the purpose of physics teaching to be as selection into those departments. While these requirements remain, the physics teachers of many countries today also are faced with competing purposes such as scientific literacy in which physics is a component of general education. These new purposes are usually in direct conflict with the university preparation and selection purposes. This conflict has no ready resolution. An extremely helpful beginning point, however, is to be clear about the purposes implied by the physics course one is teaching and the educational context in which the course is placed. For this purpose, we find the science curriculum emphases described by Roberts (1982, 1988) to be helpful. Roberts derived these emphases from inspection of curricula and text books from the first three-quarters of this century. The emphases are messages about science that Roberts found in the documents he examined. They provide a means of considering the possible emphases that teachers can give to their physics teaching, and hence possible purposes that can underlie the approaches teachers adopt.

Although it is strongly focussed on curriculum in the U.S., the review by Bybee and DeBoar (1994) of the goals of science education and the changes in these goals over time is also helpful in considering purposes.

IMPLICATIONS FOR TEACHER EDUCATION

In this final section we consider briefly what the issues discussed in this chapter might mean for teacher education. We do this by considering together all three of the broad areas we have discussed. As we argued at the beginning of this chapter, teachers' views of teaching and learning, of the nature of science, and of the purposes of education (and, specifically, physics teaching) are intertwined.

Central to our considerations here is the notion of reflection. Prospective physics teachers need to reflect on the views they hold, and the appropriateness of these views (Baird, Fensham, Gunstone & White, 1991). These are not issues that can be addressed with lectures that lay out some form of "acceptable" position. Beliefs are rarely changed by contrary assertion.

The beginning point for most pre-service physics teachers, and for views in all three of the broad areas we have discussed, is to help them recognise and articulate the views they currently hold. Because their existing views are often implicit rather than explicit, direct approaches such as asking "How do you learn?" are rarely helpful. These direct questions usually result in general and uninformative responses. We find that helping the articulation of these views is best approached by placing the student teachers in a genuine learning context, and then having them reflect on this specific experience in terms of their own learning and the learning of others. The value of this approach is that there is a common learning experience for the student teachers to discuss. In discussing the learning that they perceive to have occurred during this experience, the student teachers often also consider the nature of science. This is because, as they reflect on and debate learning, perceptions of the nature of the significant content to be learned in the experience are also addressed. For example, if the learning experience is based on a qualitative teaching approach, debate about the merit of qualitative approaches to physics is common. The essence of this debate is invariably whether the ability to apply the appropriate formula is a sufficient understanding of the concept to be learned. (Details of one such approach involving the concept of normal reaction are given in Gunstone, 1994; a similar approach with appropriate content is also a most helpful beginning point with practising physics teachers.) Consideration of the purposes of physics teaching arise more rarely. We find these views more helpfully addressed after considerations of teaching and learning and the nature of science. In this process, many individuals begin to recognise and articulate their views. For some, the challenges to these views that come from the responses of others start the process of reflection on and reconsideration of the views.

Others have used approaches such as personal metaphors to assist pre-service and practising science teachers to recognise and evaluate their views. Tobin, Tippins, and Gallard (1994) provide a helpful review of this work.

Once existing views have been articulated, and reflection on them begun, it is appropriate to elaborate alternative ways of conceptualising teaching and learning, including some specifics of teaching and learning approaches consistent with these alternative ways. As far as possible, this giving of an alternative should be through direct experience. Learning assertions about alternative ways is not enough; it is also important to experience examples that illustrate what is being elaborated and examples of learning via teaching that is consistent with what is being elaborated.

While change in these areas is not easy, it is certainly possible. We conclude by pointing to examples of work showing that substantial change can be achieved with both pre-service teacher education students (e.g. Gunstone, Slattery, Baird & Northfield, 1993; Hollen, Roth & Anderson, 1991)(Anderson & Mitchener, 1994, review a number of such studies), and with practising teachers (e.g. Baird & Northfield, 1992).

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SectionD1, *Teacher's attitudes about physics classroom practice* from: Connecting Research in Physics Education with Teacher Education

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Comments on D1: "Teachers' Attitudes about Physics Classroom Practice"

(Richard White and Richard Gunstone)

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I found the article Teachers' Attitudes about Physics Classroom Practice very rewarding reading in that it leads us to reflect on a systematization of recent research results and on our own practice and experience as teachers in teacher education courses. The article points out research showing key influences of teachers' (and students') views about learning and teaching, intertwined with their views on the nature of science and the purposes of education as related to teachers' attitudes in classroom practice.

There are some aspects I would like to comment on, starting at the end of the article where the authors address the theme of changes in such views. It is always encouraging when examples show that it is possible to achieve substantial change, not only among pre-service teachers, but among practicing teachers as well. My comments will be aimed at this aspect, since such changes constitute one of the prime targets of teacher education research.

Gunstone and White present a topic on changing views about learning and teaching based on the 1982 article by Posner, Strike, Hewson and Gertzog. The authors argue that, to achieve conceptual change, the individual must initially feel dissatisfied with the existing concept, and that the new concept must be intelligible, plausible and fruitful. To a certain extent, this model seems to comply with what the authors present concerning university physics teachers' views on the nature of science, that is, physics as a highly logical structure.

Nevertheless, Gunstone and White introduce a fifth criterion to the conceptual change model: teachers must perceive new views on new teaching and learning as *something feasible* . In our opinion, this criterion may diminish claims that conflict is essential if teachers are to change their classroom attitudes. Although reassessment will be necessary at some point, it hardly seems plausible that teachers must necessarily feel dissatisfied with their current views before they can be persuaded to try out new classroom procedures.

On the other hand, we must insist that the contribution provided by groups of teachers when they collectively address the issue of what science teachers must "know" and "know how to do" to achieve quality teaching is extremely valuable. We would also point out the consistency of proposals set forth by groups of teachers with those obtained in Science Teaching research work. Even though the groups' contributions may be less clearly stated and less detailed than studies published by researchers, they do cover the main aspects so consistently featured by research, and allow teachers to find, in published works, support and more in-depth coverage of their own production.. These contributions are consistent in that if "to know how to do" is one of the prerequisites of quality teaching, examples of activities are important. According to Gunstone and White, "the teacher has to be able to see how to cope with the demands that follow from attempting to implement the classroom consequences of the new views".

We also find the feasibility criterion elsewhere showing the need for discussion and participation of teachers in well structured classroom activities. We can hardly agree with Gunstone and White when they state that "learning assertions about alternative ways is not enough". It is necessary to help the teachers recognize and articulate the views they currently hold, and the appropriateness of these views, but it may not be the proper "beginning point". This may be interpreted as the view held by the authors when they attest to the importance of reflection on "genuine learning contexts" in which teachers reflect on their own learning and the learning of others. But, in our opinion, this alone is not sufficient. Teachers must also reflect on their individual behavior as teachers, and therefore, it is also important that even pre-service teachers go to the classroom and test new teaching proposals in order to bring results and classroom processes for discussion. Such process do not simply sprout up by themselves. They must be encouraged in teacher education.

Teacher education must address both aspects - reflection (ideas and beliefs) and practice - according to the criterion of feasibility, the two are unalienable, inseparable : one cannot exist without the other.

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SectionD1C, *Comments on: Teacher's attitudes about physics classroom practice* from: Connecting Research in Physics Education with Teacher Education

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PHYSICS TEACHER'S ATTITUDES: HOW DO THEY AFFECT THE REALITY OF THE CLASSROOM AND MODELS FOR CHANGE?

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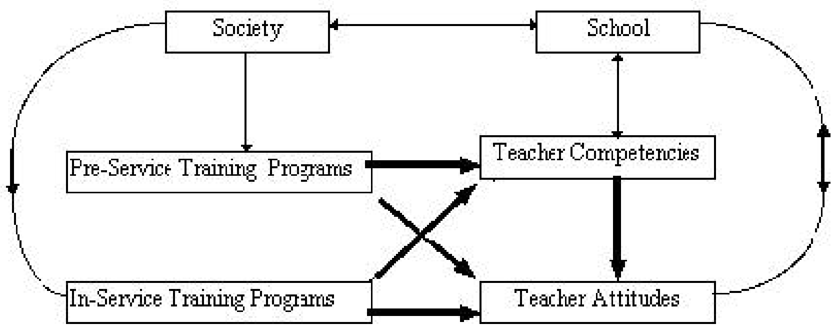
A theory in education acquires scientific character if it can establish self-correction processes and value itself at the light of its own practices. (H. Putnam, in 'The primacy of practice', 1974).

I. Introduction

While it is true that there are teachers whose attitudes are positive towards the promotion of good science teaching- learning situations, for most students, in many countries, the reality of the school classroom consists of lessons where science is *transmitted* by their teachers, *at best* , as a set of facts, laws and data. The results brought about by physics education researchers' pedagogical experiments have good consequences only when rooted within the school as an institution (teacher, curriculum and defined pedagogical practices) and within a particular context (culture, program, country). So, we conclude that there are no universal methods to modify this situation. That is, there are a variety of science teaching styles as a result of the strong interaction existing between teaching attitudes and competencies, school and society, as suggested by the model shown below.



MODEL

In what follows we first give a description and make some comments about current science teaching attitudes and competencies, trying to clarify some issues and bring forward some ideas being tested in different parts of the world. Next, we discuss ways that could lead to changes towards adequate teaching attitudes through both the training of future teachers and the in-service teacher education programs.

The present discussion is mostly limited to secondary school physics (science) teachers (15-18 years old pupils), but it applies to primary teachers, without loss of perspective. At the university level research in science education has been less extensive. Teachers have seldom been the object of studies in spite of wide recognition that there is room for improvement, as evidenced by the new proposals to improve teaching at the university introductory level (i.e.*Powerful ideas in physical science: a model course* , AAPT, 1995). Fensham (92) mentions that secondary school teachers are more aware of their difficulties, seeking answers to cope with their and their students' problems, while university and college teachers have a naive standing in relation to what goes wrong in the classroom. Bliss (93) says that children find *science learning difficult,* and we may add that teachers also find *science teaching difficult* .

II. The role of teachers' attitudes

The word attitude (from Latin aptus) is defined within the framework of social psychology as a subjective or mental preparation for action. It defines outward and visible postures and human beliefs. Attitudes determine what each individual will see, hear , think and do. They are rooted in experience and *do not become automatic routine conduct* .

Attitude means the individual's prevailing tendency to respond favorably or unfavorably to an *object* (person or group of people, institutions or events). Attitudes can be positive (values) or negative (prejudice). Social psychologists distinguish and study three components of the responses: a) *cognitive component,* which is the knowledge about an attitude object, whether accurate or not; b) *affective component:* feelings towards the object and c) *conative or behavioral component,* which is the action taken towards the object**.**

We understand that in most situations the three components appear concomitantly to shape teachers' classroom postures, through a direct and indirect interaction between society, school and teachers, following the model presented above. Leite (94) raises questions about how does society see the need for change, what are its demands, what is considered modern, and how do these beliefs influence teachers' views and behavior in school.

Table I-A lists seven types of teaching attitudes, grouped into three classes (a, b and c) which may characterize teacher's traits as will be discussed in the results. Table I-B represents teacher's competencies, which combined in different ways and weights, could give an understanding of teachers' behavior(s) in the classroom. Teachers have a decisive role (+/-) in any educational reform and their competencies do not automatically insure positive attitudes towards the teaching process.

TABLE I: Teaching Attitudes and Competencies

Classes	I -A Teaching Attitudes	I - B Teaching Competencies
	i. Lack of confidence about subject content .	**1.** The role of the physics laboratory
a	**ii.** Provider of established knowledge	**2.** The understanding of the nature of science
	iii. Prioritizing manipulation of mathematical symbols.	**3.** The role of history of physics.
	iv. Resistance to curricular and methodological innovations.	**4.** Psycho-pedagogical understanding of students' learning processes, cognition and mental models.
b	**v. L**ack of coherence between classroom practices and expressed educational beliefs.	**5.** Evaluation.
	vi. Lack of commitment towards good learning.	**6.** Actualization in Science, Technology and Society (STS) issues
c	**vii.** Make believe teaching: doing what *can* be done not what *should* be done.	**7.** Critical use of new and old technologies (printed, video, multimedia, software, WWW, etc.)
		8. Physics Academic New Curricula
		9. Knowledge of results obtained in the field of Research in Physics Education

III. Teaching attitudes affecting negatively the learning process

i. Teachers' lack of confidence due to poor conceptual and phenomenological physics foundations. In many countries around the world the number of lay science teachers is high, and many of those that have undergone formal education are not ready for the job.

ii. The fact that most teachers most of the time behave as information providers (Brown, 82). The basic model of teaching in this case is: a) spontaneous ; (b) belief that all students are identical and ready to follow same type of instruction; © acceptance of models the teachers were taught; and (d) lack of readiness about students' forms of learning and thought, (Hallbawchs,75).

iii. Physics teachers have a tacit understanding, strongly shared by the students, that the important aspects of physics have to do with manipulation of mathematical symbols. At primary and secondary levels this is done at the expense of a better treatment of phenomenology and intuition, seldom treated with (when adequate and possible) formal theory. There is an epistemological separation between theory and practice and the teachers' performance in the teaching of science and mathematics, as the result of their training at the university, as discussed by Ciscar (90) and Ryu (87).

iv. Teachers do not carry out innovations of new curricula and methodologies. Partly due to entrenched beliefs about teaching science as *telling science,* instead of teaching as a process, *science as a way of thinking.* Good practices in physics teaching are expected to promote critical thinking (Arons, 90), problem solving abilities and readiness for data interpretations as well as good communication skills. Via non-explicit forms of action, teachers' attitudes indicate the lack of confidence to implement new projects and passively reject new methods and technologies. Reay (75) says that one of the reasons for this attitude could be due to the little time allowed for preparation within the teacher's working day. Another explanation could be the teacher's *personal style* in the interpretation of curricula, content and pedagogy (Sacristan, 89, Gallard and Gallagher, 94). Studies carried out in Brazil (Garrido et al., 91) indicate that teachers show little interest and lack of compromise towards innovation in school.

v. The lack of coherence between the teachers' classroom attitudes and their expressed belief on active methods of interaction. Black (89) reported a study made in a physics classroom were the teacher strongly believed in his ability to conduct an interactive science class. When observed, he was talking to the class 90% of the time. Activity dominated learning situation studies show that students listen to the instructor more than 50% of the laboratory time.(Hegarthy-Hazel, 90). Bliss and Ogborn (77) did a naturalistic study and reported 43 stories about the science laboratory. More than half of the students had bad recalls from their laboratory work. Carvalho (92), mentions the dichotomy between the liberal discourse in opposition to repressing action that dominates the teacher training courses. A study of the beliefs and opinions of science teachers (physics, biology and chemistry and mathematics) about the nature of science and science education (Souza Barros et al., 87) indicated that though physics teachers were less dogmatic about the nature of science and approved curricular modifications and active methods in the classroom, their standing in the classroom indicated otherwise. Koulaidis (87) found that science teachers' pedagogical positions are quite traditional, giving great emphasis to presentation of knowledge and pupils' abilities to think in abstract terms.

vi. Teachers tend to see school failure as a result of the socio-psychological deprivation due to social conditions of child and family. Low expectations for these students generate poor teaching practices. Therefore, the tendency to put the responsibility of their (teachers) ineffectual performance on the students (Silva et al, 87; Carvalho and Gil- Pérez; Alves, 93; Mazotti, 94).

vii. Last, but not least, the conditions under which teachers work. Professional and social status; school infrastructure, poor libraries, laboratories, safety conditions, etc., create new variables that (re)define the attitudes of even the most devoted and well prepared teacher. The analysis made by a secondary teacher (Cedrez, 93) that comes from a country that enforces the implementation of official curricula via regular inspections of the classrooms) presents a good picture about what goes on in the classroom, - ... *the official physics curriculum cannot be accomplished with the basic mathematics foundations the students bring from early school years. So, I need to train the students to do problems, instead of helping them to understand phenomena and learn physics.*

IV. Teaching Competencies

Pointing out some of the negative aspects, allows defining actions to change the general picture. There is good agreement (Baird et al, 91) that teachers who are seldom asked to reflect upon their own teaching could be no more than mere repetitors of book material. Since teachers have a major role in any education reform they should be solicited to understand new proposals and to participate in their formulation, to analyze their performance and modify their behavior, their *personal conceptions* on how to teach and what to teach. Most teachers, influenced by how they were taught tend to replicate the model.

The set of competencies presented below, necessary but not sufficient to insure good teaching -learning procedures, is by no means complete, but there is high consensus about it within the community of scholars.

1. The role of the physics laboratory (objectives, processes, outcomes). In spite of much that has been said and the perception that practical work has a priority role for the teaching-learning process of sciences its effect is not well established, mainly because many teachers are technically incompetent and lack fundamental components related to points 2), 3) and 4) discussed below. Science objectives at the fundamental level cannot be separated from laboratory science objectives (Nedelsky, 65; Elia, 81).

2. The understanding of the nature of science (the construction of scientific knowledge) and the conceptual mastery of content in classical, modern physics and information about frontier physics.

These two aspects cannot be separated, as is done in most courses. Both require emphasis and should be integrated from the beginning. They are recognized by the teachers as major aspects in need of much improvement. One aspect that needs research is the role that teaching theory plays in learning (private discussions, J. Ogborn and I. Martins). Several studies point out that the *physics taught* and the *physicist 's physics* have little in common (i.e.Hallbwachs,75; Vianna, 93).

3. The role of history of physics. As Jenkins (94) puts it: a radical appraisal of science education is necessary. Nowadays it has become an international phenomena to introduce historical and philosophical insights into science education. This topic is discussed in the first part of this chapter.

4. Cognitive and social psychology, linguistics and anthropology . What is the effect on teaching strategies of theories learned in the education courses at the university ? The present domination and the acceptance of constructivism, as the only *correct teaching paradigm;* the scarce understanding of the true meaning of the word (Moreira, 91) as well as the framework of learning theories as applied to real classes, only adds to the confusion that has permeated the teaching process along the last 20 years. Zanarini (92) discusses what conceptions of knowledge are basic to the performance of scientific activities, exploring the complexity of the processes by which scientific knowledge is built and their relationships with the effective domain of common-sense knowledge. He examines the implications for totally constructivist perspectives of science learning, especially in the first years of schooling. Derek (90), in discussing the relations between language, knowledge and psychological development that deal with *shared* building knowledge, mentions three aspects: a) power and control of the teacher in the construction of knowledge by their students; b) contextualization of language in the school and c) relations between discourse in the classroom and knowledge.

5. Evaluation . There is a need to understand and apply both qualitative and quantitative evaluation modes. Since many teachers have not had formal studies on the subject they mainly evaluate their students for promotion. Little conceptual knowledge is verified. Poorly constructed and mainly not validated instruments, that mostly reflect the knowledge as *passed by the teacher in factual form,* are used. The consequence is that many students do poorly in external evaluation as evidenced by the results obtained in university entrance examinations, science literacy surveys, etc. Qualitative evaluation as presented by White and Gunstone (92) propose the use of instruments developed for researches in science education, as *probes* for the teacher to follow the learning that is taking place along instruction.

6. Actualization in Science, Technology and Society (STS) issues. New curricular approaches are needed to discuss the significance of science and technology for the citizen of our times (Souza Barros, 91, Dal Pian, 91, Krasilchick, 91). Excellent programs have been devised and applied, so far in small scale, like PLON (Holland), GREF (Brasil) , SISCON, SATIS (England). Most of the latest editions of current physics textbooks introduce the discussion of STS. Popular science publications provide interesting and useful information.

7. Critical use of new and old educational technologies (laboratory, printed, video, multimedia, software, WWW, etc.). Many teachers do not have access to didactic materials and modern educational technologies. In many instances, the way innovations are introduced does not contribute to acceptance. The modernization of the school does not necessarily mean acquisition of new materials, last generation educational technologies, etc. This aspect belongs to actuality and because of the exponential growth of knowledge, the implementation in large scale should be based in careful research of the educational impact of new technologies. For Mitchell and De Jong, (90) and Thornton (93), good learning requires *constant variation in the purposeful intellectual activities of the learner and a wide range of pedagogical strategies* .

8. Physics Academic New Curricula. In the present world, dominated by a scientific and technological culture, the debate over informal and formal (academic) curricula should be thought in terms of : a) the introduction of modern physics and new ideas to deal with classical physics; b) new approaches to contextualize old curricula in the light of new methodologies and c) making better profit of the information obtained via informal sources : video, television and radio broadcast; books and journals, software's and multimedia, museums, exhibits, etc.

9. Knowledge of results obtained in the field of Research in Physics Education. Probably this is the area that offers the richest of possibilities to modify current teaching practices. Many teachers do not have access to the specific literature; there is a need for publication of journals, bulletins specifically designed to divulge results and instruments used in research, summaries of new books, courseware, video, multimedia, experiments, etc. Is expected that the availability of computer networks in the future could help partially to solve this problem.

V. Actions for teacher's attitudes change

We stress once more a teacher's profile as an active agent, constructing perspectives and taking action. He/she should be encouraged to strengthen his/her capabilities to *make good educational decisions* . The physics teacher could not solely be responsible for the (in)significant learning of physics that goes on in many schools.

Teachers' styles, and mainly their attitudes, are strong context outcomes, rooted in experience and do not become automatic routine conducts, in the sense that they are developed via very slow interactions (action/reaction) and become well established *constructs* for each individual only after some time. In that sense attitudes can be modified only by each individual, when he/she becomes aware, via elements and evidence, that new postures would be better to deal with the world around. We agree with Carr's (90) statement that professional change and educational change are two strongly related problems.

So we could argue about the possibility to modify teaching attitudes by means of teaching programs, as we believe to be true when we teach specific competencies in the pre-service courses. On the other hand, we need to worry about teachers' negative attitudes since they affect a large number of the student population. As quoted by Lederman (95), science illiteracy is very high, ranging up to 90% (developed and developing countries).

According to Nemser-Feinman and Floden (in Wittrock, 86) teachers go through three stages when they start teaching: *adequacy, mastery and impact awareness of the effect of their teaching on the students.* Pre-service courses should prepare the future teacher for *adequacy* and *mastery* . In-service programs should help the teacher to actualize their knowledge with the acquisition of adequate instruments and methodologies to solve problems. Solomon et al. (95) state that *science teachers more than most, require an entitlement to regular re-training in school time, this in addition to pre-service training.*

In order to discuss the possible functions of pre- and in-service training programs for teachers we will refer to the classification about attitudes and competencies, given in Table I.

In our opinion, the teachers belonging to group **c** are obviously a *missing case,* as far as the teaching programs are concerned, since the system has injured them deeply and the efficiency of actions taken to retrieve their interest in teaching is frequently low and wasteful. Most experiences show that individuals in this group do not believe in the educational system, are skeptical in relation to the students and tend to drop out of actualization programs, when they, voluntarily or not, engage in them**.** Paradoxically, those teachers that belong in this category are either very conscious or very naive in political terms, but the fact is that only structural and professional conditions define to a large extent their attitudes and beliefs, reflecting in negative teaching practices and their consequent behavior in the classroom (Sacristan, 89, Leite, 94).

Teachers belonging to group (a) are sensitive to training programs, because those attitudes are closely related to the lack of some specific teaching competence. If pre-/in-service teaching programs are to be successful providing such competencies, then teachers would likely either not show negative attitudes or would modify them as required .

Group (b) presents a challenge for the in-service course. Teachers in this group are generally mature and have good teaching ideas and beliefs, together with unsystematic practices. These teachers need refreshing for competence rebuilding, so their attitudes may be modified by the appropriate in-service programs which take into consideration these favorable conditions. The existence of group (b) indicates the necessity to pay more attention to pre-service teachers education (Elia, 93). As pointed out by Krasilchik (79), pedagogical practices of the pre-service courses do not modify significantly pedagogical practices in primary and secondary schools. Ryu (87) conducted a survey among Japanese teachers, about their opinion of the pre-service educational programs they had at the university in preparation for their future professional performance. The majority of the teachers indicated that the pre-service teachers' programs (courses, procedures and models) were, at best, *of some use* to prepare them for teaching.

On the other hand it is necessary to pay attention to what the in-service programs have to offer. Most of them run pilot courses, didactic materials are constantly reinvented, financial support is mainly temporary, depending on funds and projects. On the positive side it can be mentioned that they provide teachers with new approaches and methods, present current literature and educational technologies and lead the teachers to reflect upon their practices. More efficient models of in-service programs involve cooperative research in the classroom (see, for example Carvalho and Gil -Pérez, 93).

As already stated in the introduction we do not believe in drastic changes and universal recipes. Effective actions to solve the problem of teachers' inadequacies are relative to given contexts and begin by the professional recognition of the teacher. One basic aspect to improve classroom practice is simple: to allow the teacher to identify and reflect about the aspects in their practice that need change. Teachers should be directly involved in defining priorities about what are their real problems and able to select appropriate solutions. (Tobin, 88, Hewson and Hewson, 88). It is easy to establish objectives and policies in education but the implementation of real change teaching strategies in order to put into practice contemporary school reform involves high risks for the teachers and financial costs for the schools (Bybee, 95). It is also important to analyze the consequences of teachers' attitudes. Pre-service courses can benefit from that knowledge and guide the selection of courses and methodologies to insure a good foundation for the future teachers. One possible way to permit a critical evaluation could be putting together the two groups (teachers and students) during the undergraduate training period of the future teachers.

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Education

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ABOUT THE EPISTEMOLOGICAL POSTURE OF SCIENCE TEACHERS

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Teacher: What's an example of a longitudinal wave?

Mike: Uh, a telephone call?

Teacher: Say that out loud.

Mike: When you call someone on the telephone.

Student: Good God! (Students laughing)

Teacher: What is it that goes through the wire when you call somebody?

Student: Electricity.

Teacher: OK, now --that, uh, is not a longitudinal wave. Uh, sorry about that. It's uh --I know you might think that the electricity goes from my house to yours. It really doesn't. The electricity goes back and forth. Uh --you might not believe this, but the individual electrons in a wire travel slower than you can walk.

From longitudinal wave lesson

(quoted in Lemke, 1993, p. 148)

Willingly or unwillingly, consciously or unconsciouly, all science teaching practices embody an epistemological posture, among other things. This posture is what orients in part the process by which students fabricate representations not only of the nature and socio-cognitive impact of the knowledge being taught but of the value of their own variety of knowledge as well. A more or less emancipative relationship to scientific knowledge will thus develop. From this perspective, a key issue in the education of science teachers involves creating the requisite conditions by which teachers can: 1) critically and reflexively problematize their own epistemological posture; 2) consider other potentialities; and whenever possible, 3) break the vicious circle permitting reproduction of traditional school epistemology concerning science (Hodson, 1988).

THE PERVERSE EFFECTS OF AN EPISTEMOLOGICAL POSTURE IN TEACHING

By the time the series of interactions related in the quotation have ended, it is quite conceivable that the student named Mike had learned more than what was being explicitly taught him, even if this was not the teacher's intention. It is probable that he learned in particular that *the knowledge which counts* --i.e. scientific knowledge-- represents an ontological kind of knowledge, that is, knowledge that exists by virtue of itself, that has emerged from nowhere, so to speak. In effect, the language used by the teacher ignores not only the theoretical context which informs and gives meaning to the concepts of wave, electricity and electron but also, and most especially the deliberative activities by which scientists ultimately agree on the relevance of such concepts for solving the questions and problems they are tackling. Actually, the entire sequence of events appears to unfold as though there were a one-to-one correspondence between the concepts under consideration and a number of real entities that could be pointed out and which scientists have simply discovered and named: here we have a wave, here we have an electron (see Sutton, forthcoming). On another level, Mike will have also learned that he does not have *the knowledge that counts* , since he is not asked how it is that he arrived at this idea nor why he thought it was plausible to take up the example of the telephone call to illustrate the idea of a longitudinal wave. His knowledge is simply deemed irrelevant, indeed, the product of a misconception, since presumably the thing called electricity which travels in a wire is not itself a longitudinal wave. In circumstances such as these, and particularly if they are repeated on a daily basis from lesson to lesson, Mike is increasingly likely to disparage the knowledge he has developed in context, to gauge its worth according to official knowledge, and, in the process, develop an inhibiting, indeed alienating relationship to scientific knowledge. A clear illustration of one such relationship may be found in the comments of this other student, who articulates attitudes that are common to other students (Edmonson, 1989; Ryan & Aikenhead, 1992; Driver *et al* ., 1993; Roth & Roychoudhury, 1993):

To me, scientists were geniuses, two or three times more intelligent than us. My idea was that they woke up one morning and said to themselves "Today, I have this problem to solve". They would then sit in front of a piece of paper and their intelligence would function by itself. They then produced scientific knowledge. (Larochelle & Désautels, 1991, p. 169)

The question remains of whether this situation has some bearing on the education of science teachers.

THE CIRCLE LOOPS BACK UPON ITSELF

As studies and research in the field of teacher education lead us to believe, the mode of interaction which was touched on above is no isolated example but in fact reflects a certain form of socialization operating within the profession (Zeichner & Gore, 1990). A number of studies conducted among prospective and practicing science teachers suggest a family resemblance on at least two points. First, there is the same tendency to picture scientific knowledge as *knowledge of something* rather than as knowledge which is socially constructed and negotiated (Robinson, 1969; Guilbert, 1992; Tobin, Tippins & Gallard, 1994). Second, in keeping with this thingifying vision of science (Bachelard speaks of a *chosisme* or a thing-ism), teaching strategies are made use of in which *telling* and *showing* predominate, strategies in other words which are generally little prone to grant students' experience-based knowledge any sort of relevance (Tobin & Gallagher, 1987; Brickhouse, 1990; Geddis, 1988; Ruel, 1994).

Now, even though this vision of science and science teaching is open to criticism, it is reasonable to assume that the teachers who share it *have good reasons* for doing so on account of their own experience as learners in either a school setting or in teacher education programs. It is true that, most often, initial teacher education is narrowly discipline-based (Gallagher, 1991), offering scarcely any kind of opening on to the particularities or stakes of what one might term (after Wittgenstein) *knowledge games* (involving scientific knowledge or everday knowledge); nor, for that matter, does this education open more generally on to that most educational problematic of "how we know what we know." In conditions such as these, teachers, like students, assimilate the representation which is implicit in curricula, namely the empirico-realist version of cognition in general, and of the production of scientific knowledge in particular (Duschl, 1985; Hodson, 1985; Collins, 1989; Roberts & Chastko, 1990; Haggerty, 1992). As Ryan (1982) has pointed out, this is how the cycle extending from primary school to the university loops back upon itself, thus perpetuating a certain notion of science, both within school institutions and society at large.

This is also how a certain relationship to knowledge is perpetuated, in which science teachers teach the way they were taught and subscribe to the widely held interpretation according to which they have been given the single, simple duty of *executing* teaching programs, as thought these programs were simply concerned with factual matters and did not represent socio-political projects in action (Fourez, 1985; Muller & Taylor, 1995-a). But how is this vicious circle to be broken? How are future teachers to be encouraged to develop a capacity for critically appraising the whys and wherefores of their actions, to exercise *reflexive, critical control over what they do and have others do* --in short, to involve themselves in a form of reflexivity that is both epistemological and social in nature?

CONCERNING A NUMBER OF CONDITIONS FOR INITIATING THE PROCESS OF TRANSFORMATION

Helping teachers "to call into question" (Coutinho, 1977) the epistemological posture which partially orients their teaching practice is a process in keeping with a project of professional development that takes into account the various ideological and political stakes involved. As a regulative utopia for our own didactic practices, our project option is based on the concept of critical reflexive teaching. In an admirable article, Gilbert has defined this as "a form of teaching which is capable of taking account of the social and political contexts in which schooling takes place, as well as its technical and practical aspects; teaching which assesses classroom practices on the basis of their ability to contribute to the development of greater equity and social justice" (1994, p. 517). Obviously, this is not an easy project, particularly in light of the conceptual fragility of the models of professional development which have been offered until now; likewise, putting such a project into effect requires a great deal of modesty on the part of its artisans, as we ourselves learned during a recent study on the subject (Désautels *et al.* , 1994). As immediately concerns our argument, the conditions which we present in an abbreviated form hereinafter should be viewed as working hypotheses for initiating breaks in the vicious circle previously alluded to.

In the socio-constructivist perspective we adhere to, all cognition, all learning, is intimately bound up with a context --hence, the resulting knowledge cannot be dissociated from the activities during which it emerged (Lave, 1988; Brown, Collins & Duguid, 1989). Once transposed into the area of teacher education, this option signifies that it is not enough to offer prospective teachers a series of teaching models, however much reflexive potential these models contain: we must also put them into practice. In other words, in our role as educators of teachers, we must develop practices (particularly of a discursive kind) which exemplify our position and foster the creation of a pedagogical context which is consistent with the desired reflexive actions.

Toward that end, we must upset the customary relationship to knowledge (*rapport au savoir*), which, as is most often the case, favors "schemas of docility" (Foucault, 1975) toward established knowledge. Course contents and educational activities ought to be conceived of in such a way as to consider prospective teachers' "spontaneous knowledge" of science, science teaching and science learning from the outset. They ought also to favor explication of spontaneous knowledge and the socio-cognitive positions that this contains, and, on the other hand, confront this knowledge with established knowledge, which stands to undergo a similar process of socio-cognitive psychoanalysis, so to speak. To take the example of specialized documentation concerning science education, it is of cognitive and social significance that students' knowledge should sometimes be considered as an immature or erroneous variety of knowledge (e.g. preconceptions, misconceptions), and then on other occasions as providing evidence of a logic which is every bit as respectable as scientific knowledge, only different, the offshoot of other assumptions and finalities (pupils' paradigms, alternative frameworks) (Gilbert & Watts, 1983; Hills, 1989). In other words, whatever the field involved, established knowledge does not emerge out of nowhere; it serves as standard-bearer for those who have developed it, representing their epistemological postures and their social positions.

However, it is important to add that, if it is difficult for teachers to break with their teaching habits in a school setting and deal with the confusion this may create among students who are used to being told *the* answer, it is no less difficult an endeavour within teacher education programs (indeed, in the short term, it is a fairly thankless experience). As we have observed during our own didactic activities, the past learning experiences of prospective teachers, coupled with the representations of science and science teaching that they have developed throughout schooling of a kind in which "success" has served as watchword, induces them in an educational situation to *re-produce* the same type of relationship toward educational authority and the knowledge being taught. In other words, these prospective teachers have learned a certain way of "punctuating" educational situations and defining their role therein; at that point, they are quite capable of making use of a certain reflexivity and holding forth most instructively on the importance of an emancipative relationship to knowledge, since this is what their professors want!

In short, it is no light undertaking to call upon prospective science teachers to "take a different sort of interest" in what they know (Stengers, 1992), to complexify their relationship to knowledge, and to open this relationship to other potentialities, to borrow Piaget's term; above all, it is an undertaking which cannot be accomplished in only a few weeks' time (Gunstone & Northfield, 1994). The stakes are all the more daunting in that, presumably, these prospective teachers will give up a familiar role as reciters for one which is more active, which exposes them to risks and in which the interest is not immediately apparent: a role, in other words, as *author* of one's own representations and knowledge, hence responsible for these representations and the actions they give rise to. In that connection, the mode of interaction which is favored in a teacher education setting is crucial not only for short-circuiting the traditional "professor-student" pattern, but for avoiding subjectivistic and "psychologizing" varieties of reflexivity. As many researchers have noted (Lampert, 1990; Bauersfeld, 1994), that is why the "classroom culture", and the pedagogical structuring process, ought to leave much room for re-creating, among peers, the deliberations, problems, risks and issues which underlie not only the production of scientific knowledge, but the informed appropriation of this knowledge by students.

Such, in our opinion, are several of the conditions which can contribute to breaking the vicious circle, owing to their capacity to enable future teachers, *as learners* , to evaluate *in vivo* the plausibility and fruitfulness of new modes of learning for organizing their own cognitive experiences (Désautels *et al* ., 1993). There lies a possible avenue for encouraging these teachers to involve themselves in a mode of participation which could incite them to some day play an active and democratic epistemological role in their professional practices. But, as might be suspected, such a teacher education model supposes that the educators also assume responsibility for their own epistemology and that they question the kind of relationship to knowledge that they promote in *what they say, do, and have others do* .

Note: The authors would like to thank Donald Kellough, who, with vigilance and diligence, has provided us this translation.

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Section D3, *About the epistmological posture of science teachers* from: Connecting Research in Physics Education with Teacher Education

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PHYSICS TEACHER TRAINING: ANALYSIS AND PROPOSALS

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Science Education Research has shown the existence of striking differences between the goals of curriculum developers and what teachers actually practice (Cronin-Jones 1991). Those differences have called attention to the influence teachers exert in the implementation of science curricula in high schools. The issue is a major one in a field such as physics that foresees drastic curricular changes (some of which have already been implemented) on this level. On the other hand, there is a high percentage of pupils who fail in physics and pupils' negative attitudes towards science and science learning grow steadily (Yager and Penich 1985).

Those results have broken simplistic views about science teaching as an activity which demands just a sound scientific knowledge and some experience. In other words, those results have made clear that teacher training can not be reduced to just scientific courses , as it has been usually.

A possible solution which has been tried in many countries is to complement the scientific courses with other courses about Education. Which are the results of this orientation?

As McDermott (1990) has shown, university physics courses generally do not provide the type of preparation that teachers should have:

- the lecture format of the classes stimulates passive learning; the future teachers are more accustomed to receiving than to imparting knowledge;

- the standard problems developed in the classroom lead to algorithmic, repetitive, solutions, and fail to stimulate the type of reasoning necessary to approach new situations such as unforeseen issues that students may raise.

- laboratory work calls for sophisticated material not available in secondary schools, and above all, it is restricted to mere verification, like cooking recipes, which gives a reductionist and distorted view of scientific activity.

On the other hand, courses on Education are totally separated from instruction in content, and teachers can not see the interest of those courses in the treatment of their specific teaching and learning problems.

Today, this situation is not acceptable any more since Science Education has experienced an impressive development (Tiberghien 1985, Linn 1987, Viennot 1989), as it becomes a coherent and specific body of knowledge (Gil et all 1991, Hodson 1992). The professional training of physics teachers can be centered on the treatment of physics teaching and learning problems, leading to the acquisition of a theoretical foundation of practice.

Which can be the main implications of science education on physics teacher training?

We shall refer to four points that, according to our way of thinking, are fundamental and clearly constitute a break with the simplistic views of such training. These four fundamental points are: 1) the need of in-depth knowledge of the subject matter to be taught -- knowledge that, by far, surpasses the reductionist overview usually given; 2) questioning of teachers' "common sense" ideas about physics teaching and learning, 3) the acquisition of theoretical knowledge about the learning of physics; and 4) implication in physics education researches and innovation .

1- KNOWING THE SUBJECT MATTER TO BE TAUGHT

No one questions the need for teachers to have in-depth knowledge of what they are to teach. It may seem superfluous to state this point if we take into consideration that, in many countries, teacher training is virtually limited to physics courses plus some pedagogical disciplines (Carvalho and Vianna, 1988). However, we must insist on this point for the reasons pointed out below.

Perhaps as a reaction against the exclusive attention traditionally given to specific content in the teacher preparation, proposals cropped up making these contents relatively unimportant. In most of the on-going teacher training courses, we see that activities tend to focus mainly on innovative methodological proposals, with a striking lack of emphasis on specific content. This attitude sounds like an implicit admission that initial training in this particular is sufficient. However, it is increasingly evident that this initial preparation is insufficient in fact (Krasilchik, 1995), and as Tobin and Espinet (1989) showed in their paper based on science-teacher tutoring and counseling, the lack of scientific knowledge is the main obstacle to teachers' adoption of innovative activities. Pacca and Villani (1992) came up with the same findings when they worked with Brazilian science teachers.

Apart from these points, it is necessary to call attention to the fact that something as apparently simple as "knowing the subject matter to be taught" implies in very diverse professional knowledge (Coll, 1987; Bromme, 1988): knowledge that extends far beyond that traditionally provided in higher education courses. As a matter of fact, knowing the subject matter to be taught should include (Gil and Carvalho 1994):

1.1- knowing the problems that rose the construction of the knowledge to be taught, without which, knowledge seems to have been built up arbitrarily. Knowing the *History of Science,* not only as a basic aspect of scientific culture, but ultimately, *as a means of associating scientific knowledge with the problems that led to the building up of this knowledge* (Otero 1985, Matthews, 1990, 1994; Castro and Carvalho, 1995). Above all, knowing *what difficulties were faced in the building up of this knowledge; the epistemological obstacles involved;* since this knowledge constitutes an essential aid to understanding students' difficulties (Saltiel and Viennot, 1985; Driver, 1994); knowing as well how this knowledge developed and how the various points came to be joined up into one consistent body of knowledge, and , consequently, avoiding static and dogmatic views that distort the very nature of scientific work (Gagliardi and Giordan, 1986);

1.2- knowing the *methodological orientations employed in the construction of knowledge*. In other words, knowing how researchers approach problems, the most notable features of their activity, and the criteria used to validate theories. This knowledge is essential to the appropriate orientation of laboratory practices, to solving problems, and to the students' construction of knowledge (Gil et alli,, 1991);

1.3- knowing *the Science / Technology / Society interactions.* This is essential to give a correct image of physics, since scientists' work is not carried out apart from the society in which they live -- it is affected by the problems and circumstances of the historical moment -- and their actions clearly influence the surrounding physical and social environment. It may appear superfluous to insist on this point, but when we analyze our university teaching, we see that it is reduced to the transmission of conceptual content, devoid of the historical, social, and technological features that marked mankind's development;

1.4- acquiring some *knowledge of recent scientific developments* to transmit a dynamic, non-closed view of physics. It is likewise necessary to acquire knowledge of other related areas to be capable of *approaching the "frontier problems", the interactions among the various fields, and unification* *processes* .

1.5- knowing *how to choose appropriate content* , accessible to students and capable of arousing their interest and given a correct view of physics.

1.6- being prepared to *deepen the knowledge* acquired during the initial teacher training courses contemplating the scientific advances and curricular changes.

2 - KNOWING TEACHERS' SPONTANEOUS IDEAS ON PHYSICS AND ON TEACHING AND LEARNING PHYSICS

Recent research in science education shows that teachers have ideas, attitudes, and behaviors related to science teaching based on a lengthy "environmental" training period -- the period in which they themselves were students (Hewson and Hewson, 1988). The influence of this incidental training is enormous because it corresponds to reiterated experiences acquired in a non-reflexive manner as something natural, thus escaping criticism.

In fact, as Bell and Pearson (1992) have pointed out, it is not possible to change what teachers and pupils do in the classroom without transforming their epistemology, their conceptions about how knowledge is constructed, their views about science. This is not just a question of the well-known extreme inductivism denounced so many times previously. We have to pay attention to many other distortions (Gil 1993; Hodson 1993; Meichstry 1993; Guilbert and Meloche 1993), as, for instance:

2.1- *Extreme inductivism* , enhancing 'free' observation and experimentation ('not subject to aprioristic ideas') and forgetting the essential role played by the making of hypotheses and by the construction of coherent bodies of knowledge (theories). On the other hand, in spite of the great importance assigned to experimentation, Science teaching remains purely bookish, quite frequently, with little practical work. For this reason, experimentation keeps the glamour of an 'unaccomplished revolution'. This inductivist vision underlies the orientation of learning as *discovery* and the reduction of science learning to the *process* of science.

2.2-A *rigid view* (algorithmic, exact, infallible... dogmatic). 'Scientific Method' is presented as a linear sequence of stages to be followed step by step.

Quantitative treatment and control are enhanced, forgetting -or even rejecting- everything related to invention, creativity, tentative constructions. Scientific knowledge is presented in its 'final' state, without any reference either to the problematic situations which are at its origin, its historical evolution or to the limitations of this knowledge which appears as an absolute truth not exposed to change.

2.3-An *exclusively analytical vision* which enhances the necessary division and simplification of the study, but neglects the efforts of unification in order to construct wider bodies of knowledge, the treatment of 'border' problems between different domains. Going in the opposite direction, today there is a tendency to present the unity of nature, not as a result of scientific development but as a starting point.

2.4-A *merely accumulative vision* . Scientific knowledge appears as the result of a linear development, ignoring crisis and deep restructuring.

2.5- A 'commonsense' view which presents scientific knowledge as clear and 'obvious', forgetting the essential differences between the scientific strategies and the common-sense reasoning. This view is characterized by quick and very confident answers, based on 'evidences'; by absence of doubts or consideration of possible alternative solutions; by the lack of consistency in the analysis of different situations; by reasoning which follow a linear causality sequence. The 'conceptual reductionism' of most science teaching contributes to this common sense view forgetting that a conceptual change can not take place without a simultaneous and profound epistemological and attitudinal change.

2.6- A *'veiled' and elitist view* . No special effort is done to make science meaningful and accessible; on the contrary, the meaning of scientific knowledge is hidden behind the mathematical expressions. In this way, Science is presented as a domain reserved for specially gifted minorities, transmitting poor expectations to most pupils and favouring ethnic, social and sexual discriminations.

2.7- An *individualistic view* . Science appears as the activity of isolated 'great scientists', ignoring the role of cooperative work and of interaction between different research teams.

2.8- A *socially 'neutral' view* . Science is presented as something elaborated in 'ivory towers', forgetting the complex STS relationships and the importance of collective decision making on social issues related to science and technology.

In contrast to this vision of science out of context, today there is an opposing tendency, in secondary schools, towards a *'sociological reductionism'* which limits the science curriculum to the treatment of STS problems and forgets the search for coherence and other essential aspects of science.

This teachers' spontaneous epistemology constitutes a serious obstacle to the renewal of science teaching in as much as it is accepted uncritically as 'common-sense evidence'. However, it is not difficult at all, to generate a critical attitude towards these others commonsense views: For instance, when teachers have the opportunity for a collective discussion about possible distortions of the nature of science transmitted by science teaching, they easily become aware of most of the dangers (Gil-Pérez, et al 1991). In other words, the real danger seems to be the lack of attention to what is usually given as common-sense evidence.

This way teachers begin to question the idea that science teaching does not demand any specific training, being enough the scientific knowledge acquired at the university, some experience and common-sense. They became aware of the need of acquiring a specific theoretical body of knowledge about the physics teaching/learning process.

3 - ACQUIRING THEORETICAL KNOWLEDGE ABOUT THE PHYSICS TEACHING/LEARNING PROCESS

We have to refer here mainly to the constructivist approach, which is considered today as the most outstanding contribution to science education over the last decades (Gruender and Tobin 1991, Moutmer 1995), integrating many research findings. Teachers need to understand, very particularly, that:

3.1- pupils can not be considered as 'tabula rasa', They have *preconceptions* or 'alternative frameworks' which play an essential role in their learning process (Viennot 1979, Driver.1986), obliging guiding science learning as a 'conceptual change' (Posner et al 1982) or, better, as a conceptual and epistemological change (Gil and Carrascosa 1990, Dusch and Gitones 1991);

3.2- A meaningful learning demands that *pupils construct their knowledge* (Resnik 1982);

3.3- To construct knowledge pupils need to deal with problematic situations which may interest them; that obliges them to conceive a science curriculum as a *program of activities* (Driver and Oldman 1986), that is to say problematic situations that pupils can identify as worth thinking about (Gil et all 1991; Astolfi 1993);

3.4- The construction of scientific knowledge is a social product associated with the existence of many scientist teams; this suggests organizing pupils in small groups and facilitating the interactions between these groups (Wheatley 1991) and the scientific community, represented by the teacher, by texts, etc

3.5 - the construction of scientific knowledge has axiological commitments: we cannot expect, for instance, that pupils will become involved in a research activity in an atmosphere of 'police control' (Briscoe 1991). This has stimulated research on classroom and school atmosphere (Welch 1985), pupils' (and teachers') attitudes towards science (Schibecci 1984; Yager and Penick 1986) and STS relationships: The construction of knowledge has to be associated with the treatment of problematic situations which appear as *relevant and interesting* to pupils (Gil- et al 1991), enabling them 'to assume the social responsibilities of attentive citizens or key decision makers' (Aikenhead 1985).

The most important thing is that all these contributions constitute related components of an integrated body of knowledge which is generating the emergence of a constructivist teaching/learning model, capable of displacing the usual transmission/reception one. But, how can teachers acquire, effectively, this theoretical corpus of knowledge to be able to replace the reception learning paradigm by the constructivist one? We shall refer to this problem in the next paragraph.

4 - TEACHERS' INVOLVEMENT IN PHYSICS EDUCATION RESEARCH AND INNOVATION

We have already referred to the ineffectiveness of simple transmission of knowledge, through manuals or courses, in the training of teachers. Such procedures have failed to prepare teachers for new, constructivist oriented, curricula (Briscoe 1991). For many, this constituted an unpleasant surprise: How is it possible that motivated teachers, who participated voluntarily in seminars and courses with the intent of mastering new methods and renewing their teaching, go on teaching as they have always done adapting the innovations to the traditional ways? Teachers themselves are frustrated when they have to affirm that things do not work better than formerly, despite the innovations.

This ineffectiveness of the simple transmission means that other strategies of training are required. Investigations into the learning of science provide valuable suggestions of what these strategies might be.

Teachers, like students, have preconceptions. Just as pupils' learning of science is conceived of as conceptual, epistemological and attitudinal change, so should teachers' learning of didactics. Teachers' knowledge, like students', must build on the previous knowledge they have. There is a close parallel between how change occurs in conceptions of science and how it occurs in conceptions of teaching.

The conditions that Posner et al. (1982) identified as necessary for pupils' conceptual change apply equally well to teachers' didactics change:

1. The teacher must be dissatisfied with existing methods:

2. there must be a new method minimally intelligible that

3. must be plausible, even if at first it contradicts the teacher's former conceptions; and

4. it must be potentially fruitful, resolving anomalies and disfunctions and opening new perspectives for solution of teaching and learning problems.

There should not, however, be a mechanical transfer of strategies used with pupils. Constructivist theory led to some teaching strategies and addressed conceptual change explicitly and directly. Driver and Oldham (1986) summarised such strategies as sequences of 1)identifying pupils' ideas; 2) questioning those ideas, using confronting examples to produce cognitive conflicts; 3) introducing concepts elaborated by scientists, that resolve the conflicts; and 4) using the new ideas in various contexts to promote their full assimilation. If a similar procedure were applied in teacher training, we would elicit beliefs about teaching and learning, then create cognitive conflicts to prepare the teachers for new conceptions, which they would have to be shown are effective in practice.

Such a procedure can quickly produce positive results, as it relies on common sense ideas that many accept uncritically as evidence. After the first impact, however, it becomes an "evil" strategy. What is the consequence of having teachers make explicit their ideas and then questioning their validity? It generates a reserve that inhibits the desired change. In the same way, this argument allowed us to appreciate that the strategy is inadequate for changing pupils' conceptions of science (Gil et al. 1991; Gil & Carrascosa 1995), although with pupils the resistance to systematic questioning of their conceptions is not so obvious.

There is another reason why such strategies can inhibit construction of knowledge. They focus on problems, in which prior knowledge and new ideas are brought together in a tentative way. In this process the initial

conceptions might suffer change or even be questioned radically, but this is not the immediate objective - that remains the solution of the problem that has been posed.

This raises an issue concerning the cognitive conflicts: they will not mean an external questioning of the personal conceptions, nor the systematic recognition of the insufficiencies of one's own reasoning, with its consequent affective implications, but a confrontation of personal ideas, taken as hypotheses, with other hypotheses, as personal as preceding ones. We do not propose to eliminate the cognitive conflicts, but to prevent them from appearing as a confrontation between the personal wrong ideas and the scientific correct ones.

Besides, it is important to take into account that the study of preconceptions has aimed, so far, to detect what pupils, and, now, teachers too, answer in an immediate reply to certain questions; more important than that is what they should have answered if they would have time to reflect critically. Actually, if a collective work of certain depth is facilitated, teachers and pupils are able to question those conceptions uncritically assumed and to construct knowledge consistent with that accepted by the scientific community.

The foregoing considerations suggest that a more fruitful strategy for teacher change consists in involving teachers in research in their own classrooms into teaching and learning of science. In this, teachers might be major members of autonomous teams involving researchers and innovators in the teaching of science. Such a strategy would have the following characteristics:

4.1- Be conceived in an intimate connection *with the teaching practice itself,* as treatment of the teaching/learning problems posed by such practice.

4.2- Oriented to favour the *experiencing* of innovating proposals and explicit teaching reflection, questioning "spontaneous" teaching reasoning and behavior, that is, questioning the "natural" character of "what has always been done".

4.3- Designed to:

-incorporate teachers to the investigation and innovation in science teaching and, consequently,

-involve them in the construction of the specific knowledge body of science Teaching and incorporate them to the scientific community in this field.

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COMMENTS ON D2, D3, AND D4

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Although this section of the book is divided into four, all of its parts are closely related. Attitudes to science must influence, and be influenced by, beliefs about classroom practice, and both must affect and be affected by programs of training.

The four chapters in the section were written independently, by authors from widely-separated parts of the world. Such circumstances would increase the likelihood of the chapters presenting unrelated, or even opposed, pictures of what is needed in teaching and the training of teaches. It is significant that they do not; the same theme runs through the chapters by Desautels and Larochelle and by Barros and Elia as through my own with Gunstone, and is consistent with the recommendations that Gil-Perez and de Carvalho make for training.

Such agreement could lead to a bland, uncontroversial section, but instead the implications of these chapters are revolutionary for practice.

Desautels and Larochelle call for fundamental revision of the way that teachers think about science. The main need, they point out, is for teachers to appreciate that science is a human construction. Until teachers do that, they can see no point in taking students' beliefs into account in their teaching, which inevitably will be transmissive with their students docile receivers of established dogma. This is bad enough for science, physics included, but worse when it transfers to students' attitudes to all learning and to their relation to authority. Education has to be a matter of balance. Of course each generation has to acquire the knowledge of the past, but it is tragic if they take that knowledge as settled, final, and the only way of perceiving the world. It would be just as tragic, though in a different way, if they reject the knowledge as sterile, and so throw away all the understanding that their forebears have created.

Barros and Elia discuss how teachers might acquire an appreciation of the nature of science that will foster more effective teaching and learning. They list nine competencies, all of which would be helpful. The ninth is particularly challenging. Of all the professions, I suspect that teaching is the least informed by research. There is no point in complaining about this, or in exhorting teachers to take more notice of research. What could be effective is to *involve* teachers in research, as Gil-Perez and de Carvalho advocate. Two conditions are necessary. One is perception by teachers that they have time. Although teachers are busy, with stressful days, I have seen examples that suggest they are not so overworked that they could not, given support, reflect on their own classrooms. Instances are Swan and White (1994), Baird and Mitchell (1986), Baird and Northfield (1994), Loughran and Northfield (in press), and White and Mitchell (1994). The support is the second condition. University scholars can provide it, and at the same time would fulfil their own obligations to do research and to maintain contact with school classrooms. Their work with the classroom teachers must, however, be a partnership, not a hierarchical relationship.

Student teachers enter courses of training with attitudes in place, formed by their experiences in school and university classrooms. Their pedagogical training is one place where a beneficial shift in attitude can occur. Gil-Perez and de Carvalho emphasise this opportunity. In doing so, they make a particularly subtle point about the danger of applying the often-cited conditions that Posner, Strike, Hewson and Gertzog (1982) specified for conceptual change. Instead, they list three characteristics for programs that promise to be effective in promoting attitude change among both experienced and inexperienced teachers. The challenge for teacher educators is to design programs with these characteristics.

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CURRICULUM DEVELOPMENT IN PHYSICS EDUCATION

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1. INTRODUCTION

In the preface of his famous book "The Process of Education" (1960), the psychologist Bruner wrote about "a conviction that we were at the beginning of a period of new progress in, and concern for creating curricula and ways of teaching science" . He argued that a general appraisal of this progress and concern was in order, so as to better guide developments in the future.

At the time, this same optimism spread to other countries, leading to the well known curriculum wave of the sixties and seventies which flooded the world of science education. Now, 35 years later, it may be appropriate to look back for a while and ask ourselves what progress this curriculum development and related research has brought us.

To guide this reflection, it may be instructive to look somewhat further into what were considered to be the main problems and perspectives in 1960. Let me therefore briefly summarize some of Bruner's main conclusions.

Regarding 'the importance of structure' the following was said: ".. the curriculum of a subject should be determined by the most fundamental understanding that can be achieved of the underlying principles that give structure to that subject. Teaching specific topics or skills without making clear their context in the broader fundamental structure of a field of knowledge is uneconomical in several deep senses. In the first place, such teaching makes it exceedingly difficult for the student to generalize from what he has learned to what he will encounter later. In the second place, learning that has fallen short of a grasp of general principles has little reward in terms of intellectual excitement. (...) Third, knowledge one has acquired without sufficient structure to tie it together is knowledge that is likely to be forgotten."

As far as content choices are concerned, this idea of emphasizing the 'structure-of-the-discipline' seems to fit rather well with what academic physicists usually think to be of importance in teaching about their subject. Bruner, however, added a psychological rationale to this emphasis.

Regarding a second theme, 'readiness for learning', Bruner advanced his famous and much debated hypothesis that any subject can be taught effectively in some intellectually honest form to any child at any stage of development. This hypothesis was said to imply three aspects: the process of intellectual development in children, the act of learning (in particular the act of 'discovery') and the notion of a 'spiral curriculum'. Since then, these aspects have received considerable attention in curriculum development, as we shall see below.

A third theme of Bruner's relates to the fact that "the emphasis in much of school learning and student examining is upon explicit formulations, upon the ability of the student to reproduce verbal or numerical formulae. It is not clear, in the absence of research, whether this emphasis is inimical to the later development of good intuitive understanding indeed, it is even unclear what constitutes intuitive understanding".

"Usually", it is said, "intuitive thinking rests on familiarity with the domain of knowledge involved and with its structure". However, "the complementary nature of intuitive and analytic thinking should be recognized", particularly, as "the formalism of school learning has somehow devalued intuiton".

So, what to do about this? "Will the teaching of certain heuristic procedures facilitate intuitive thinking? For example, should students be taught explicitly that : "When you cannot see how to proceed with the problem, try to think of a simpler problem that is similar to it; then use the method for solving the simpler problem as a plan for solving the more complicated problem?"" In these statements, we see a foreshadowing of the cognitive swing which psychology has undergone since the sixties, a swing which has had much influence on research in physics education.

"In assessing what might be done to improve the state of the curricular art, we are inevitably drawn into discussion of the nature of motives for learning and the objectives one might expect to attain in educating youth", is said to introduce the fourth theme. This discussion is relevant to all levels involved, from the individual teacher and student in the physics classroom to the role of physics education in a society at large. Thus this theme will always demand serious attention.

Finally, regarding 'aids for teaching', it is concluded that "the teacher's task as communicator, model and identification figure can be supported by a wide use of a variety of devices that expand experience, clarify it, and give it personal significance". When we compare the personal computer with the 'teaching machines' of the sixties, we can see how this theme has acquired completely new significance in physics teaching since Bruner first wrote these words.

It is striking to realize how much of the above still applies today. In physics curriculum development and in research on physics teaching we are still struggling with the same problems. Nevertheless, in the past 35 years, a lot of work has been done. Much of the progress that has been made, if it may properly be called so, should be apparent from this volume.

In this chapter, I will restrict myself to the main experiences in physics curriculum development (as I see them). Many questions may be raised. For example, are we now (or still?) teaching the structure of the discipline, as Bruner advocated? Do we have physics curricula that are adapted to the intellectual development of children, and if so in what way? Is discovery learning still on the list of usual teaching strategies in physics? What different goals and objectives do we aim at now, and how do we deal now with motivation to learn ?

In dealing with some of these questions, I will structure my description along three main lines: aims and content, teaching and learning, and ways of curriculum development and implementation.

As we all know, physics education is not a constant but a variable. It changes in direct relation to the developments in the society of which it is a part, to the developments in that society's view on education and science and to developments in physics and technology themselves (Lijnse, 1983). Next to traditional schoolbook writing, professional curriculum development has come into existence as a means to adapt education to these continuing changes. And although in itself it is not usually considered to be part of proper research, it has stimulated the development of many research studies (Fensham, 1994)..

2. AIMS AND CONTENT

2.1. 'The structure-of-the-discipline'

The first major project, the PSSC physics course, primarily meant for "the academically superior collegebound students" (French, 1986), was very influential internationally (PSSC, 1960). As Matthews (1994) describes: "Its intention was to focus upon the conceptual structure of physics, and teach the subject as a discipline: applied material was almost totally absent from the text. Air pressure for instance is not mentioned in the index, it is discussed in the chapter on "The Nature of Gases", and the chapter proceeds entirely without mention of barometers or steam engines, the former making its first appearance in the notes to the chapter". The PSSC way of teaching included lots of experiments, reflecting an aim that the pupil should be 'a scientist for the day'. This latter characteristic seemed to apply even more to the equally influential English Nuffield-Physics projects (O-level, 11-16; A-level, 16-18). These projects all focused largely on teaching the basic disciplinary structure, although in a somewhat different way (Ogborn, 1978). As Rogers (1966), the man behind Nuffield O-level Physics, put it: "And for the things we do teach we should choose topics that have many uses. I do not mean practical applications, but rather linkages with other parts of physics. Science should appear to our pupils as a growing fabric of knowledge in which one piece that they learn reacts with other pieces to build fuller knowledge".

The O-level project aimed to 'teach for understanding' and at 'physics for all'("a course suitable for the general educated man and woman"). Later, however, it was realised that these curricula were not really geared to 'physics for all', but were best suited for the more able scientifically oriented pupils. Therefore, to indicate their rationale, such curricula were better described by one of Roger's own titles 'Physics for the Inquiring Mind'.

One particular aspect of these particular curricula is that they also played an exemplary role in tackling the problem of updating physics teaching from a disciplinary point of view, particularly in relation to the problem of teaching 'modern physics'. French described some of PSSC's main choices as follows: "The most basic and universal features of the physicist's description of nature such matters as orders of magnitude and the effects of changes of scale would be stressed. There would be a unifying theme the atomic, particulate picture of the universe in the presentation and discussion of the subject matter. Also, in the interests of achieving depth of treatment, substantial areas of traditional material (such as sound) would be omitted". And, as the developers of Nuffield A-level said: "One of our basic decisions has been to sacrifice a wide acquaintance with many ideas for a deeper understanding of fewer". In fact, following this principle, they developed really innovative introductions to topics like quantum physics, statistical mechanics and electronics (at an 'advanced' level).

In spite of the immense international influence of these projects, and although similar innovations have been tried in many countries (GIREP, 1973; Aubrecht, 1987; Fischler, 1993), one cannot yet conclude, I think, that, at the secondary school level, the didactical problems of the why, the what, and the how of including basic modern physics have been solved satisfactorily. The more so as, due to the rapid development of physics, we do not only have to deal with basic ideas of quantum physics and relativity. Further new topics are already knocking at the door of the curriculum, like chaos, condensed matter physics, computational physics, high energy physics and cosmology (GIREP,1995, 1993, 1991, etc.). In fact, this rapid development causes the physics curriculum to be under a continuous top down pressure, with the serious danger of becoming ever more overloaded. In this respect, the structure of physics can, because of its largely hierarchical nature, not only be regarded as a curriculum guide, but to a certain extent also as a hindrance, as it is often much clearer what has to be included than what can be left out.

So far, no consensus seems to exist about how to deal with this pressure on the curriculum. In view of the time needed to reach understanding, Arons (1990), for example, still chooses to accept something like the Bohr atom as a useful endpoint for an introductory physics course. "What seems to me to be feasible and highly desirable in an introductory course is to get to the insights gained in early twentieth century physics: electrons, photons, nuclei, atomic structure and (perhaps) the first qualitative aspects of relativity". And even for that, hard choices have to be made: "To achieve this, it is impossible to include all the conventional topics of introductory physics. One must leave gaps, however painful this may seem. How does one decide what to be left out? One powerful way, in my experience, is to define what I call a 'story line'. If one wishes, say to get to the Bohr-atom, one should identify the fundamental concepts and subject matter from mechanics, electricity, and magnetism that will make understandable the experiments and reasoning that defined the electron, the atomic nucleus, and the proton. The selected story line would develop the necessary underpinnings and would leave out those topics not essential to understanding the climax. For students continuing in physics, the gaps would have to be recognized, accepted, kept in mind by the faculty, and closed in subsequent courses".

To my opinion, the problem of how the physics curriculum as a whole can be constructed as a set of usefully intertwined gradually developing 'story lines', now needs renewed attention (Ogborn, 1978). Or, in other words, we have to ask once again how can the structure of physics (in a broad sense) be turned into a better teachable curriculum structure (De Vos et al., 1994))?

2.2. Process and Processes

In the projects mentioned above, much attention was also given to the 'process of physics' and to letting pupils experience the 'process of discovery (or inquiry)'. In the PSSC-texbook "physics is presented not as a mere body of facts but basically as a continuing process by which men seek to understand the nature of the physical world".

But pupils should not only learn about a process that others, in particular 'great' physicists, have gone through, they also should experience this process themselves. To quote Rogers (1966) again: "Practical work is essential not just for learning material content, but for pupils to make their own personal contact with scientific work, with its delight and sorrows. They need to meet their own difficulties like any professional scientist and enjoy their own successes, so that the relation of scientific knowledge to experiment is something they understand".

So, one could say that this emphasis on process was in the first place justified by internal reasons. It is part of understanding physics to know about how knowledge of physics is generated and how it develops. And as physics is an empirical science, it is considered an inherent part of physics to learn about nature by finding out, hypothesizing, testing and experimenting for yourself, i.e. students should be learning physics by doing physics. Since then, the use of "practical work" in physics education has increased enormously as it has become an integral part of many curricula and textbooks. This trend has developed to such an extent that the learning of experimental skills sometimes seems to have become an aim in itself, almost unrelated to the purpose of experimenting, i.e. developing new knowledge (Woolnough and Allsop, 1985; Woolnough, 1989; Wellington, 1989; Hegarty-Hazel, 1990; Hodson, 1993).

It also has become clear, from research on physics learning, that the original idea of discovery learning may have been somewhat too naive (Driver, 1983). On the other hand, learning physics by doing has nowadays almost acquired an extra dimension because of the possibility of modelling 'artificial worlds' that has come into reach by means of the microcomputer (Mellar et al., 1994).

Returning to history, in Harvard Project Physics (1970), another American project that earned much international applause, the attention to the internal process of physics was placed within a much broader intellectual perspective, in that external influences were also considered. In the famous words of Rabi: "I propose science be taught at whatever level from the lowest to the highest, in the humanistic way. It should be taught with a certain historical understanding, with a social understanding and a human understanding in the sense of the biography, the nature of the people who made this construction, the triumphs, the trials, the tribulations". Because of this particular emphasis, it was expected to attract a broader group of pupils (particularly girls). From a physicist's point of view, again, this project developed marvelous curriculum materials. Nevertheless, it not only did not really succeed in attracting significantly more students (French, 1986): for a long time its historical and philosophical approach seems to have been adopted by only a few teachers. Only recently this curriculum focus on history and philosophy, whilst always somewhere in the background, has acquired new impetus (Matthews, 1994). Attention to the 'nature of physics', to its historical, epistemological and methodological aspects, is now becoming a regular part of physics curricula (Aikenhead, 1991; Solomon, 1991). In England, it has even been included in the prescribed National Curriculum, while, e.g., in The Netherlands a new curriculum for "general science" is being developed in which this perspective is given much attention.

Historically, this broader perspective meant that the emphasis was (partly) shifted from teaching as inquiry to teaching about inquiry. An even more drastic shift, I think, was implied by what Shulman and Tamir (1973) called teaching of inquiry. This step was taken to its extreme in a third influential approach, developed by the U.S. project SAPA, which stands for Science A Process Approach. In the words of the psychologist Gagné, this project "rejects the 'content approach' idea of learning highly specific facts or principles of any particular science or set of sciences. It substitutes the notion of having children learn generalisable process skills which are behaviorally specific, but which carry the promise of broad transferability across many subject matters".

Scientific behavior was analysed in terms of its simpler constituent 'scientific process skills', such as: observing, classifying, measuring, communicating, and making inferences, that were thought to be learnable and teachable as such. Since then, the debate about whether one should emphasize scientific knowledge and/or scientific processes has been ongoing (Millar and Driver, 1987). Nowadays, it is even more topical than ever as many cognitive psychologists advocate the learning of even broader 'general skills' (thus not only scientific see below), not only as an aim in itself but also, as already proposed by Gagné, as the appropriate way to deal with the mentioned threat of 'elephantiasis' of the curriculum.

2.3. Broadening of aims

As already indicated above, the curricula that focused on physics-as-a-discipline appeared, both in its rationale and in its cognitive demands (see below), to be more geared to the gifted science interested pupils than to 'physics for all', thereby leaving a curriculum gap for the less able, less scientifically interested pupils. For them, (more) integrated science as well as technology projects were developed (see, e.g., Brown, 1977). These may be interpreted, in line with the spirit of that time, as a shift from discipline centred to more pupil-centred education. A main rationale behind integrated science was that a division in seperate disciplines does not coincide with the way in which pupils experience their world (however, as Black (1985) argued, pupils do not experience their world in an integrated-science way either). As a consequence, integrated science has been implemented in many countries, although some seem to have returned to coordinated science. Other countries, have resisted this trend and have not gone for integration at all.

Early technology projects were mainly developed as add-on activities to the physics curriculum, which reflects an application-of-physics view of technology (e.g. Schools Council, 1975). At present, this view of technology is no longer regarded as adequate, resulting in a gradual emancipation of technology to become a separate school subject (Layton, 1993).

In the seventies, another emphasis gradually developed towards what is now called STS (see, e.g, Solomon and Aikenhead, 1994), although that acronym still stands for a number of considerably different approaches. One of them deals with explicit reflection on the relation of science, technology and society (e.g. the English Science in Society project (SiS)), thus emphasizing social implications and issues. Another approach places more emphasis on relevancy of content for pupils, by teaching science in daily life and issue-related contexts (e.g., the Dutch PLON project for physics; Satis, 1992). Roughly, both approaches have also become known as 'science for the citizen' and 'science for action', or as contextualized science (or physics).

The SiS-project is an example of a project in which the social dimension is treated as an add-on to the regular curriculum. In the PLON project, however, attention for social scientific issues, 'consumer physics' and other 'pupil-relevant' contexts are integrated in the physics curriculum itself. If, however, the boundaries set on the curriculum are such that the physics curriculum should keep its identity as 'proper' physics, such a contextualized approach may result in considerable tension between the knowledge that seems to be relevant for the contexts chosen, and that which demands inclusion from the perspective of physics. Or, in other words, one has to try to find a balance between the 'structure-of-physics' and the structure-of-the-contexts (Lijnse, et al., 1990).

Both approaches, however, imply a broadening of traditional aims (Fensham, 1988), related again to the idea of 'science for all' alhough, in this context, this phrase is now to be interpreted differently from above. In connection to this broadening, in the eighties, new topics, such as environmental education and information technology had to find a curriculum place as well. A matter of discussion was and is whether these should be part of regular physics education, or are should be taught as seperate subjects.

New problems have also arisen from a societal point of view, for example the adaptation of physics education to the needs of girls (Bentley and Watts, 1986) and to the needs of a multicultural society (Reiss, 1993). In fact, how broad can we make our aims and still remain within the borders of physics education? Or even might it be better to remove physics from the school time table?

All this also relates to another trend that is now attracting considerable attention, the new emphasis on scientific and technological literacy for all, including out-of-school ways of educating the general public.

However, next to this broadening tendency (the spirit of the late seventies and early eighties), we see another tendency showing up that focuses less on physics for 'citizenship', and more on the value of physics in the education of a highly qualified workforce (the spirit of the late eighties and nineties). Vocational qualifications are formulated and physics teaching is required to contribute to their attainment. Consequently, we note again a change in curriculum discussions, characterisable as a shift from pupil and relevance centred to 'client' and achievement centred, even with special attention for the gifted child. This trend can lead to pressure to restrict the content of physics curricula to its 'hard core' (preferably described in attainment targets, that can be regularly tested). However, the content of this 'hard core' is now not so much to be decided by 'pure' academic physicists or physics educators (as was done in the past), but by those who form the 'market' for which we educate our pupils (such as employers and institutes for higher education).

This is a very brief and very subjective overview of about forty years of curriculum discussions about aims and content. What may we conclude from this description? Apparently, physics education has had, and still faces now, a continuous stream of 'top-down' innovations. A first obvious conclusion, however, could be that, as far as aims and content is concerned, the same themes seem to show up regularly in a kind of wave motion, driven by changing views on education in changing societies. May we, nevertheless, conclude that physics education is spiralling upwards in some sense that may be called progress (as Bruner expected)? Or should we conclude that physics education is walking around in circles, almost like a snake regularly biting its own tail? Or does this question for progress only represent a 'category mistake', as the late Dutch mathematics educator Freudenthal (1991) argued: "Once, asked by an interviewer whether I thought that attempts at innovating have improved education, I hesitated for a short while, only to eventually stamp it as a wrong question. Pictures of education, taken at different moments in history are incomparable. Each society at a given period got the education it wanted, it needed, it could afford, it deserved and it was able to provide. Innovation cannot effect any more than adapting education to a changing society, or at the best can try to anticipate on the change. This alone is difficult enough". Before going somewhat further into this question, let us first have a closer look at curriculum considerations that have resulted from research on (physics) teaching and learning.

3. TEACHING AND LEARNING

3.1. Behaviorism and 'Piagetianism'

In the above, I have not focused on ways of teaching and learning and on the influence of research on this aspect of curriculum development. Let us therefore paint another broad picture.

In the fifties and sixties, the dominant psychological viewpoint in education was that of behaviourism. It focused on the formulation of educational objectives and aims, distinguishing between knowledge and skills, and organised in learning hierarchies and taxonomies (Bloom, 1956). In fact, Gagné's approach, mentioned above, is an example of this view (SAPA, 1968). Programmed instruction and teaching machines developed into individually paced study systems and mastery learning (Bloom, 1971; White, 1979). Despite research reports about successful implementations, these approaches have largely faded away, although, in some sense, they showed up again more recently in much computer assisted teaching.

According to this position the teaching process should best be split up into smaller and smaller steps, leaving the sequencing of content, however, to continue to follow the 'logical' disciplinary structure. In that sense, in behaviourism, curriculum content is not a variable and it therefore had only a weak link to development of the 'didactics of physics'. Its lasting contribution to physics education has not been spectacular.

Another psychological position which has had much greater influence on physics education is 'Piagetianism'. Thus, Bruner's recommendation, quoted above, has been taken seriously. Piaget's description of concrete and formal operational thinking has been and still is a useful global guide in designing teaching. Apart from having influenced many curriculum projects, (some of which adopted explicitly a Piagetian perspective, such as ASEP, 1974) the Piagetian stage theory has, particularly in the U.S.A., given rise to a wealth of quantitative studies relating pupils' cognitive growth to many other quantitative variables. In the end, this type of research seems to have had little practical influence. More useful was the U.K.-based use of stages as a tool to identify the excessively high demands set by many (newly developed) curricula, as well as a means to match them to assumed age-dependent capabilities of pupils (Shayer and Adey, 1980; Adey and Shayer, 1994). At first, this research played an important role in making 'tangible' the extent to which, and the ways in which, the 'physicist-for-the-day' type of curricula mentioned above were inclined to overestimate the capabilities of 'all' pupils. Thus, 'Piagetian-ism' made the important shift from taking only the curriculum-to-be-taught as the sole starting point for curriculum development, to including also the cognitive development of pupils. That means that from the Piagetian point of view, curriculum content is seen as a 'structural' variable, to be sequenced according to 'developmental logic'.

Later, based on Piagetian reasoning patterns, curriculum materials have been developed, to be implemented as intervention lessons within the science curriculum, that aim not so much at the improvement of science learning in a narrow sense, but much more at the advancement of children's cognitive development itself (Adey, Shayer and Yates, 1989). Nevertheless, the real significance and potential of the Piagetian stage theory is still a matter of debate (Carey, 1985). This is much less the case for another aspect of 'Piagetianism', i.e., its 'constructivist' foundation (Bliss, 1995; Adey and Shayer, 1994): the idea that a learner essentially constructs his own knowledge by acting on his environment. When first formulated, this gave a kind of psychological foundation to the attractiveness of 'discovery learning' for science education, as worked out in several modes of 'learning cycles': exploration (messing around), invention, discovery (application). Alhough, as argued above, discovery learning in its naive sense has disappeared again, constructivism is still around.

It is difficult to say in what way Piagetianism has made a lasting contribution to science education. It is striking that the stage theory is hardly mentioned in current literature. Alhough much literature of the seventies was very optimistic about its value, I think that we may conclude that nowadays most research is only globally influenced by Piagetian stage theory. Or maybe we should say, nowadays research in physics education does not try any more to develop its potential (see, however Lawson ,1994, for a new interpretation).

3.2. Constructivism

This change must be linked with the spectacular rise, since the late seventies, of what I like to call 'didactical constructivism'. Using this term, I'm referring to what started as the 'alternative framework' movement, as it is sometimes loosely called. This movement may be regarded as also having its roots in the (early) work of Piaget. In fact, it did build on the way in which Piaget investigated the content of children's ideas about specific phenomena, but not on his analysis in terms of hypothetical underlying logico-mathematical structures that led to the stage theory mentioned above. At first, this focus on children's content specific reasoning led to numerous diagnostic and descriptive research reports about all kinds of pupils' concepts and ideas about situations (Driver, Guesne and Tiberghien, 1985). This has since been extended to pupils' ideas about experiments (Carey, et al. 1991), about learning and teaching, and about their epistemologies (Butler Songer and Linn, 1991). Subsequently, the same has been done done for teachers' ideas and opinions (Tobin et al., 1990). Also developments in time of pupils' and teachers' conceptions have been studied, be it during a number of lessons, or over many years (Driver et al, 1994).

Apart from the usual 'implications for teaching' that seem to be an almost obligatory endpoint of too many research studies, experimental classroom studies have been and are done to find concrete ways to improve the teaching of certain topics, or to find more general and better teaching strategies (CLIS, 1990). Such studies make clear that this research field has important implications for curriculum development, that are still to be developed to their full potential. It even implies a certain change of view on how we think about a curriculum. As Driver (1989) writes: "Curriculum is not that which is to be learned, but a programme of learning tasks, materials and resources which enable students to reconstruct their models of the world to be closer to those of school science". An important consequence of this view is that "the curriculum is not something that can be planned in an *a priori* way but is necessarily the subject of empirical enquiry".

Theoretically, the dominant position in this "paradigm" is that of 'constructivism and conceptual change'. Much research is aimed at explaining processes of conceptual change in terms of individual or social processes, and at finding general strategies to let such change take place. Part of these strategies is their emphasis on "higher order thinking skills" and metacognition (Baird and Mitchell, 1986). This reflects a strong link with present-day cognitive psychology. Many meta-level discussions are taking place examining different opinions about constructivism and related ideas about knowledge and epistemology (Matthews, 1995). In itself this may be very interesting, but it does not (yet?) lead, I think, to much progression in the practice of physics education .

In my opinion, the main importance of this paradigm lies in the fact that now learning of physics content itself has become a major variable in much physics education research. Research results are no longer, in the first place, only to be interpreted within a far-away psychological perspective that is often seen by many practitioners as something that, whilst not irrelevant, is mostly unusable. In my experience, these content-specific research outcomes seem to have a much more direct appeal to teachers, didacticians and curriculum developers, as they question precisely their level of intuitive practice-built expertise.

This is again a very rough description of research on teaching and learning. Did this research influence practice so far, and if so, in what way ? The main theories have certainly influenced the above described development of curricula. Writing about the period up to the early eighties White and Tisher (1986) nevertheless concluded as follows: "The great amount of energy that went into research did not spill over into seeing the results affected practice." Is the situation for the period since then different, or is it too early to judge? As said, the misconceptions-wave got much attention from a wide audience of didacticians. It has also had some impact on the formulation of curriculum attainment targets, in the sense that concepts have to be developed now more gradually in steps. It is my impression that much effort has also been expended in trying to get the messages across to teachers (e.g., CLIS, 1990). However, what was the message? So far, teachers often get the impression that they are not doing well enough, that they do not succeed in making pupils understand sufficiently what they teach and that they should take more account of pupils' misconceptions. At first sight, that seems to be a rather negative message, which makes it understandable that many teachers are not very eager to listen. So, how could we do better? General strategies for conceptual change do not really function for physics teachers as long as they cannot be translated into concrete practice.Furthermore, researchers do not yet have much to offer at that level (e.g, Tobin et al., 1994), a failing of which they seem to become increasingly aware (Fensham, Gunstone and White, 1994). Fortunately, I would say, because otherwise, in my opinion, research in didactics of physics would, after an encouraging period, be in danger of stagnation again.

4. WAYS OF CURRICULUM DEVELOPMENT

4.1. University based approaches

In the part two above, I described some main trends in physics curriculum development as far as content and aims are concerned. In part three, I did the same for research on teaching and learning physics that has had more or less strong implications for curriculum development. In doing so, implicitly I have also touched upon some major developments in ways of curriculum development, related to problems of curriculum implementation and of use of research results in practice. In this part, I will elaborate this theme more explicitly, as it is my conviction that Bruner's expected progress has very much to do with the way in which we will be able to solve these problems in the future.

A first thing to note, however, is the difference in time scales between large scale curriculum development and "fundamental" research on teaching and learning. Curriculum projects often have to produce, within a limited time, teaching materials that can and will be used in schools. By contrast, research on teaching and learning often aims at longer term development of understanding, to be framed in applicable theory. A second remark concerns the fact that curriculum implementation is, in the first place, also very much a matter of educational politics. If, for instance, the political situation in a country is such that the government decides to implement a new curriculum for all schools from a certain set date, quantitatively the implementation will be necessarily "successful", even although in terms of quality the situation may be quite different. The other extreme of the spectrum is when the political situation is such that schools, or even individual teachers, are very much free to choose whether or not they will adopt a new curriculum. Then, as past experience has shown, curriculum implementation is quite another matter.

Most of the first curricula were developed in project teams, in which university physicists, educational specialists and physics teachers cooperated (e.g., French, 1986; Raizen, 1991). This meant a fundamental change from the usual method of textbook writing by one or two authors, not usually practising physicists themselves but experienced teachers. At least in the US, a "fundamental axiom of the program was that the improvement of curricula needed to enlist outstanding research scientists" (Raizen, 1991). Or, as Matthews (1994) writes, in the first wave, the scientists were put "firmly in the saddle of curriculum reform, teachers were at best stable-hands, and education faculty rarely got as far as the stable door. The PSSC project epitomized "top-down" curriculum development : its maxim was: "Make physics teacher-proof." This description makes clear that in general most emphasis was laid on the up-dating of scientific content, that the translation of general theories of teaching and learning into curriculum materials and classroom practice mostly resulted in considerable 'slippage' (as Fensham describes it), and that the role of teachers was restricted to"trying out" and not so much to "participating in" As Welch (1979) wrote: "Scientists were usually hesitant to accept the criticism of their "science" from school teachers unless very convincing substantiating data were provided."

Nevertheless, such top down projects developed in general beautiful and very original and innovative curriculum materials, both for students and teachers, that have had a broad and considerable influence. For example, French (1986) describes the PSSC course as being characterized "by originality and freshness of approach", and the same characteristic applies to many other curricula developed in that period.

Another main characteristic of the first wave was that it was characterised by a mainly university-based development. Central project teams of specialists developed marvellous materials, to be tried out in a limited number of schools, to be implemented top-down and on a large scale afterwards. However, probably precisely because of their innovative character and high standards, this implementation appeared not to take place as expected. Quite often adoption of curricula did not necessarily mean adoption of their spirit, or of their recommended teaching methods. Indeed , the problem appeared to be one of dealing with curriculum-proof teachers, rather than of implementing teacher-proof curricula.

Fensham notes that in the 1970s "evidence accumulated that many or most of the hopes and good intentions of the reformers were not being achieved in schools" And, according to Matthews: "Now, in the 1990s, when school science reform is once more on the agenda, it is timely to know how much of this failure and confusion was due to the curriculum materials, how much to teacher inadequacies, how much to implementation and logistic failures, how much to general anti-intellectual or anti-scientific cultural factors and how much to a residue factor of faulty learning theory and inadequate views of the scientific method that the schemes incorporated."

This is not the place to discuss all these factors extensively. The important thing that I want to stress here, is that it now seems that a centralized-expert-project-team format of curriculum development, although seeming very reasonable at the time, is bound to very much underestimate the intricacies of curriculum implementation, and in particular of the teacher's role in it. As French (1986) noted: "the crucial ingredient for the success of any educational innovation is the classroom teacher."

4.2. School-based approaches

It is therefore understandable that a quite different school-based approach to curriculum development emerged. It seems probable that this arose in part as a reaction to the problems described above, and in part because, in tune with the spirit of the seventies and eighties, teachers became much more emancipated in general and more concerned about physics, about education and about physics education. As Eggleston (1980) writes in the preface of a book about the situation in Britain: "School-based curriculum development has, in the early 1980s, become the dominant form of the curriculum development movement. After a decade in which the main effort has been focused on the national project, we have come to realise that if change in the schools is the objective, then the initiative must also come from the schools. The result has been a gradual resurgence of curriculum development that arises directly from the needs and enthusiasms of the schools, of their pupils and of their teachers".

This "bottom-up" kind of curriculum development generally results in rather different types of materials, with different aims and pretensions. These emphasise use of teaching methods that are manageable by teachers, give less emphasis to the scientific content of physics and more to its possible relevance for students, are less glossy and more down to earth, and in some sense are less innovative and original but more usable and locally adaptable.

In terms of research, this change in the model of curriculum development more or less coincided with an advocated change in educational research attitude, away from academic research focusing on the development and subsequent application of general educational theories, and towards action research that was meant in the first place to support and help teachers in the direct achievement of their goals, thus leading to exemplary practices to be taken over by others.

Both of the "idealized" models of curriculum development described above have complementary roles to play. University-based projects, be it with scientists or teachers, may develop very innovative curricula that may not be directly implementable on a large scale. Nevertheless, their influence in the long run may be considerable and indispensable. In school-based, teacher-centred ways of curriculum development, attention is often given to more direct concerns of teachers, so that the development becomes an important mechanism for getting teachers involved in the direct improvement of their own teaching situation, leading to the availability of flexible and in principle rather easily implementable curriculum materials and experiences. It has often turned out that part of this improvement lies in a locally manageble adaptation of the products of large scale more innovative projects, which means that this knife may cut both ways.

4.3. Developmental Research

In my opinion, however, another third model also needs consideration, not to replace the two models described so far, but to fulfil another essential role, for which the first two models do not provide. The need for this model has to do, in my view, with the explicit linking of research on teaching and learning to curriculum development, and in that sense with bridging the gap between educational theory and curriculum practice. In the main projects of the past, as already described, general educational theory often only had its influence somewhere in the background, or in the curriculum rhetoric. In fact, in my opinion, that is not an unlucky coincidence, but has to do with the very nature of such theory. In reality, the actual development of such curricula was much more based on the intuitive content-specific didactical knowledge, views and experiences of the developers. The same applies, in fact, to school-based curriculum development. In fact, action research often results much more in action, than in development of empirically supported didactical theory. So, both models have, in my opinion, resulted in many important differences in and improvements of educational practice, but not in a systematic research-based way of making curricular progress.

At the same time, however, the described growth of research on the learning and teaching of physics seems to promise that such progress is within reach, provided that we succeed in making research on learning and curriculum development shake hands in a joint long term approach.

This can best be done, I think, in a rather pragmatic empirical process of closely inter-connected small scale research and development, that I like to call 'developmental research' (Lijnse, 1995), in which researchers (physicists, didacticians of physics) and physics teachers closely cooperate on a basis of equality. I envisage a cyclical process of theoretical reflection, conceptual analysis, small scale curriculum development (including teacher training and test development), and classroom research into the interaction of teaching-learning processes. The final, empirically based, description and justification of these interrelated processes and activities constitutes what we may call "possible 'didactical structures' " for a particular topic under consideration. A detailed description and justification of such structures may be given in terms of learning tasks, of their interrelations, and of the actions that students and teachers are supposed and expected to perform. In fact, such descriptions can be considered as empirically tested domain specific didactical theories (Klaassen, 1995), that are based on an explicit view of physics and of physics teaching. Reflection on such theories for various topics may lead to 'higher level' didactical theories. In the long run, as the disciplinary structure of physics is not the most suitable starting point for instructional design, developmental research should also lead to empirically supported didactical structures for teaching the whole of physics. As Freudenthal (1991) argues, the term 'implementation of results' may not be an adequate description in the case of developmental research. It asks much more for a gradual and continuous process of dissemination, use, reflection and further development of ideas, in order to establish change at all levels.

This third, additional model of developmental research is not a theoretical fata morgana, but a way of both pragmatic and reflective working that, in various ways, already takes place at quite a lot of places. In fact, it means that curriculum development and didactical research are merged. The CLISP-approach (Driver and Oldham, 1987) is a well known example that comes close to what I have described. The PEEL project in Melbourne has taken a similar route, though not focusing on the teaching of particular subject matter, but on the development of metacognition. In recent European summerschools for PhD's in science education, it turned out that many activities were dealing with the teaching of X, where X stands for a particular topic (Lijnse, 1994, 1996; see also Psillos and Meheut, this volume). In the US, some physics educators (e.g. McDermott and Shaffer, 1993) seem to be working along similar lines.

At the same time, however, this list reveals a particular weakness of the advocated approach, i.e. the absence of models and/or examples of ways of cooperating and building on one another's concrete experiences. This requires that detailed descriptions of research and curriculum materials be made available, descriptions which will have to be much more detailed than is common in the usual research literature. Could modern facilities, like the Internet, take that role in the future? `

5. CONCLUSION

Let me finish by briefly summarizing the above in terms of what I think to be the main conclusion. Starting from Bruner's description dating from the late fifties, regarding the expected progress in curriculum development, I have tried to describe the main trends in physics curriculum development. Much work has been done in trying to keep our physics curricula both conceptually and educationally up to date a task that will never be finished.

At the same time, and largely resulting from the first main curriculum effort, research on physics teaching and learning has shown that the difficulty of designing understandable curricula and teaching has been strongly under-estimated in the past. This points to a second long-term task that also needs unending attention in the future.

In both tasks, different participants, physicists, physics teachers and researchers of physics education, have different, but equally important, roles to play. As I have argued, in the past, these different roles have more or less led to three different models of physics curriculum development, that in some sense are equally important although aiming at different functions. For the future, the long-awaited realisation of Bruner's predicted curricular progress will, in my opinion, very much depend on the extent to which we will succeed in steering work in these different perspectives so that they can contribute, in a co-ordinated and cooperative way, to the development of new physics curricula and new ways of teaching.

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COMMENTS ON E1: CURRICULUM DEVELOPMENT IN PHYSICS EDUCATION

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This survey of curriculum development raises for me three main issues . One is an expansion of a point discussed briefly in section 2.3 concerning 'integrated science'. There have been important developments in several countries aimed at teaching the sciences in some co-ordinated or combined way. For some, this is ideological - they believe the separate sciences to be an anachronism and that there is only one single science. Others, including myself, disagree with this, but nevertheless feel that the sciences should be taught within a closely co-ordinated pattern - so that, for example, pupils are not taught about energy in three different ways between physics, chemistry and biology lessons. Others who are constructing their curriculum around issues or themes, point out that some of the most interesting issues cut across the inter-science boundaries. In all of these debates, physics educators ought to develop a clearer stance about how they see the specific role of physics - and I do not see this being done at present.

My second issue links to the first but is a broader problem which is touched upon at several points in the chapter. The pupil's interests, daily life outside school, concerns about his or her future, are all centrally important if a curriculum is to be matched to the pupil. To be sure, there is discussion about matching to cognitive development, but this means that the pupil is treated only as a 'brain on legs'. In all aspects of education, including physics, we have to give more emphasis to the rapid changes in society which affect the life of our pupils whatever we do in schools. A notable example is that some now spend more time in front of the TV than in school classrooms - the media enrich their passive reception of information, but impoverish their experience of practical action and their development of human relationships. What does this imply for the role of schooling ? Similarly, concerns about the environment, or about changes in the patterns of employment are often far more important to young people than to their teachers - how should the curriculum respond.

This leads to my third issue - for the life of young people is changing rapidly and will continue to change. Here, the quotation at the end of section 2 from Freudenthal is very appropriate. However, I would like the idea to be thought out in a more positive way. As society changes, education must change to respond. The task is to continually review to try to ensure that the curriculum best serves the needs of young people and is optimally attuned to their outlook - even if it should aim to change or expand that outlook. How can we bear such continual change - given that it is very hard for any teachers to change the topics, let alone the pedagogical methods, with which they have built up familiarity and confidence. A strategy for promoting and supporting teacher change may be at the heart of our needs - much of the argument near the end of this chapter suggests or requires this, but the issue has to be brought out more boldly.

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Section E, *Comments on E1* from: Connecting Research in Physics Education with Teacher Education

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EVALUATION AND ASSESSMENT

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1 INTRODUCTION

The purposes

Assessment in education has three main functions. The first is to record the achievements of individual pupils for the purpose of certification. The second is to record the achievements of groups, classes or schools, for broader policy purposes. The third is to serve teaching and learning.

The first function produces records which are passports - to better jobs or to higher education for a pupil leaving school. To fulfil this function, assessment has to command public confidence. In such assessment, there is also an aim of appraising a pupil's work as a whole, so that it can be described as summative.

The second function is characterised by emphasis on the public accountability both of individual schools, and of an education system at national or state level. The aim here is to inform policy by collection and analysis of evaluative information. Various regional and national monitoring systems, and international comparative studies, serve this purpose.

The third function arises because any learning system needs feedback. To serve this purpose, the assessment information has to provide information about each pupil's learning on the basis of which action can be taken to meet each pupil's learning needs. Such assessment may be called formative or diagnostic.

Ideally, each of these three functions requires assessment information of a different type from the other two. In practice, it is often necessary to use the same information to serve the different functions. Such multiple usage is attractive because it is economical, but it is not always feasible and there is always tension between the needs of the different functions.

Social and political context

Differences in history, in traditions and in social and political needs have combined to produce systems which reveal on comparison, very different patterns of practice between different countries (Black 1992, Britton and Raizen 1996). For example, in some countries school-leaving certificates are entirely in the hands of each school, whilst in other countries such trust in teachers would be unthinkable and certificates are based entirely on external tests.

Such differences have developed historically. Social movements aimed at producing a more egalitarian society have in the past found ways to offset the advantages of privileged schools by use of assessment procedures. In such a venture, the external nature of the assessment system, and its lack of organic connection with the teaching system in schools is an essential feature. Conversely, in societies where equality of provision and status between schools has been achieved, it becomes possible to move from external and objective systems and to rely on each school's own role in assessment. However, a well-developed public and universal system of education becomes a very large user of public funds so that the justification of its budget claims becomes an important political issue. This pressure has led to demands for monitoring and accountability.

Such features affect the ways in which external examinations constrain the development of teaching and learning. Against complaints that they stifle and distort learning must be set the fact that, properly developed and applied, they can be powerful agents of reform.

The place of physics in the "high-stakes" certification assessments linked to university entrance is likewise very variable. In the university procedures of most countries, performance in several subjects, rather than in physics alone, is taken into account even for admission to specialised physics courses. Where there is a broad range of subjects taken at the top end of secondary school, there can be rules of aggregation which so operate that a student can be admitted to study in physics when the physics performance has been very low - as in Brazil Where the entry examination is based on only a few subjects - as in the UK.- it is possible to place great weight on the physics result, partly because this can be examined by an extensive exercise which would be impracticable for candidates taking more subjects.

Structure of this chapter

This chapter will discuss in turn the three main functions, i.e.. for certification, for accountability and to serve learning. Inevitably, in consideration of the first of these, many general issues which apply to all three will have to be explored. A final section will review the interactions between these functions in attempting an overview of state and national systems.

2 ASSESSMENT FOR CERTIFICATION

Methods - written tests

Paper and pencil tests have long been used as the main media in assessment in education. Conventional written tests in physics comprise a collection of items requiring definitions, standard explanations or derivations, accounts of standard experiments or applications, and a few problems, usually of a routine nature. The following example illustrates the combination :

- A sample of a Thallium element 207 / 81 Tl of 16 gm emits beta radiation and is converted into an isotope of lead (Pb). The half-life of the decay process is 5 minutes, answer the following questions:

- What is meant by each of the following terms: isotopes - isobars - isotones ?

Give examples for each.

- Explain what is meant by "a half-life of 5 minutes for such a decay"

- Find the mass of the Thallium element 207 / 81 Tl left in the sample after 1/3 hour.

- Calculate the decay constant of the Thallium element 207 / 81 Tl

- State (without explanation) two methods for radioactive waste disposal.

(Egypt - Wassef pp.57-68 in Black 1992)

Tests may be composed of shorter questions, treating the knowledge and the problem-solving aspects separately. the following in a typical example of a short problem style :

A compressed spring pushes apart two trolleys having masses of 0,2 kg and 0,3 kg, respectively, in such a way that the trolleys that were initially at rest are separated by 60 cm in 5 s. The mass of the spring and friction are negligible. What is the velocity of the trolleys? (Hungary - Radnai pp.84-100 in Black 1992)

Such short problem items need not necessarily be quantitative, as in this example : -

How does an electric dipole behave both in a uniform electric field and in a radial electric field? (Poland - Plazak and Mazur pp.125-139 in Black 1992)

More test items per unit time, and enhanced reliability in marking, may be secured with use of multiple choice items, which test problem solving abilities as well as knowledge, as in the following example : -

The points O, P, Q, R, S lie in a vertical line with equal intervals between them. An object is released from O with no initial velocity to fall freely.

The average velocity between O and T is equal to the instantaneous velocity at a point which is in the following interval : -

(a) between O and P; (b) between P and Q; (c) between Q and R; (d) between R and S; (e) between S and T.

(Japan - Ryu pp.101-123 in Black 1992)

Because of the large number of such items which pupils can attempt in a given testing time, such questions can achieve greater coverage and greater overall reliability. Their disadvantage is that they can give no direct evidence of a pupil's reasons for their choices, and some studies have shown that up to a third of pupils who choose the correct response may do so for a wrong reason (Tamir 1990). Exclusive use of them can lead to neglect, in teaching, of the discussion and argument which is a valuable and valid aspects of scientific enquiry. In public examinations, they have long been dominant in testing in the USA, are used as a minority component in some countries (e.g. UK, Sweden) and are not used at all in others (e.g. France)

All of the above examples involve a combination of knowledge of physics combined with skills of selecting and applying that knowledge. Where longer questions have a structure - as in the first example, that structure helps the respondent, both by presenting the selection of the knowledge needed for the problem, and by giving guidance for the sequence strategy needed to tackle it.

It is not necessary to rely entirely on remembered knowledge. Some written tests present a pupil with information in the form of a short article about a physics topic, and then assess the capacity to understand and apply by questions about it - either short open questions or multiple choice questions (see Black 1992)

Assessing "process skills"

There have been attempts to assess "skills" separately from their physics knowledge. The problems that this raises can be illustrated by practical tasks set out to assess measurement skills. One problem is that of context - many pupils who seem able to use measuring instruments and procedures when required directly in artificial and isolated contexts do not deploy this ability when asked to undertake an investigation, even when provided with measuring instruments; they use only a qualitative comparison even when they have shown, in a different context, the ability to use the instruments. It is essential here to formulate a more comprehensive view of the skill involved. The ability to read accurately off a scale and to set up or adjust instruments is not enough. A scientist has to be clear about what to measure - for example measuring 'rate of flow' requires the understanding that a co-ordinated pair of measurements is needed. Furthermore, the investigator has to judge when to measure, which requires a judgement that the powerful tools of quantification can and should be applied to the problem (Black 1990).

Thus an assessment of skill with instruments and scales is not, on its own, of any great value, because such skill can only be useful if deployed in the light of a conceptual model of the system under investigation and of the variables involved. The same is true for other "skills" - for example observation, which is not passive reception but an essentially selective activity guided by assumptions about what should be selected. It follows that questions which test specific "skills" in isolation may not convey any useful information about a pupil's ability to use the skills in scientific work.

Other methods - oral and practical

Oral tests are an important component of public examinations in physics in several Eastern European countries, but elsewhere they are seldom used. In the assessment of practical work, the logistic and other problems of using equipment in assessment exercises have led to attempts to use paper and pencil tests of practical work as substitutes. Such an approach can have undesirable feedback effects on teaching, and correlations between pupils' performances with real equipment and their responses to "equivalent" written tests are low. However, very few countries, notably the UK and Israel, use direct tests with equipment as part of public examination procedures (Britton and Raizen 1996).

One common form of practical test has been to specify set routines with given equipment and require certain types of response in terms of measurements taken and analysis of results. The tight constraints thus imposed improve reliability, but such skills as experimental design and choice of equipment are neglected. The "experiment" is indeed a vehicle for testing certain specific skills relevant to experimental science. An alternative approach has been to organise very short exercises, each testing a specific skill in its own set context. Examples of skills tested are the taking of accurate measurements with pre-set instruments, and making and recording qualitative observations of an unusual phenomenon.

Concern that out-of-context tests can be misleading has led to attempts to assess with open-ended and complete experimental tasks. If comparability and imposition of conventional examination conditions are required, then the best that can be done must be very limited. An additional constraint of such conditions is that, because all members of a group have to work simultaneously over a limited time, assessment has to be based on pupils' written records. Their actual actions, and their reasons for what they did, cannot be observed or interrogated directly. Also, since no system could handle more than a very few (probably one or two) such extensive tasks, generalisability of the results is a severe problem (Shavelson et al. 1993).

Such severe limitations can be overcome by assessment of extended pieces of work undertaken under normal working conditions. A written record of such work may hide some of the very important aspects of capability that a pupil may have exercised, which could only be appreciated if the process by which the pupil's work proceeded were observed and understood. The only feasible solution to such problems is for the teacher to be involved as assessor, allowing for such important features as the precise way the problem was posed, the effects of group collaboration and the constraints within which the pupil had to work and the reasons for a pupil's decisions about his or her strategy. Such attention requires careful training of teachers, and time and opportunity for them to observe individual or group work carefully.

Of course, there is a paradox here. As the aims of physics education become more real and less artificial, they lead to activities which reflect more of the complexity and untidiness of real life, and so become less susceptible to any reproducible assessment process.

Such difficulties do not apply only to assessment of practical work. Some of the many types of written tasks that are in use are severely constrained by the time constraints of external test routines. If discussion of ideas, and the use of these, suitably selected and interwoven to bear on a new issue, is an important aim, then test procedures must work with responses in prose produced after adequate time for thought and planning.

Combining methods

All methods of assessment suffer from shortcomings, and the best choice may often depend on the particular educational or social context involved. For example, availability of equipment, or the possibility of adequate monitoring to prevent unfair practices, may vary greatly from one situation to another. It is also necessary to consider that a combination of methods may be needed, both to reflect a range of aims, to enhance reliability and to offset the bias effects that any one technique is bound to introduce.

The range of methods used is very varied in some countries and very restricted in others. At one extreme is the exclusive use of multiple choice questions, as in the U.S.A. for those using one of the testing agencies, whilst at the other is the spectrum of eight types of task included in the Nuffield examination in the United Kingdom (Black 1992). If there is a most popular pattern, it seems to be a mixture of multiple choice questions and short problems.

One reason why such variety is found is that familiarity with certain methods and a tradition of using them can inhibit the possibility at looking seriously at alternatives. For example, there is a tradition in some countries that the mathematical theoretical question is the most significant test of ability as a physicist, so these are given far greater prominence than, say, ability to tackle problems experimentally or to write critically about the subject.

Another reason may be a belief that some methods cannot give reliable results : some think that multiple choice questions, with their objective marking, pre-testing checks, and possibilities of statistical analyses of large numbers of questions, give results which are so much more reliable than other types that they should be the only method used.

A third reason may be cost. For examinations with a large entry, the expense of preparing good multiple choice questions is justified by the possibility of securing reliable marking at low cost. To set and mark several other types of question makes heavy demands on the time and expertise of examiners. In particular, assessment of practical work is usually ruled out on grounds of cost and practicability.

Reliability

The question of whether or not the range of types of questions really matters is a more complex one to address. The main factors involved are reliability, validity, feedback, quality and bias. Reliability is the simplest to tackle. An examination can be reliable if one can have confidence that the same results would be obtained with a parallel examination, i.e. one set and marked according to the same aims and methods. It is possible to obtain a measure of reliability by testing the internal consistency of responses, but this is only appropriate where there is a reasonably large number of questions and where it can be assumed that they should give homogeneous results. A more strict test is to set parallel forms to the same students, or at least to give some students large numbers of questions in the same domain of testing and to determine from the results the minimum number of questions needed to reduce the error below a given limit. Such tests are hardly ever carried out - the faith of university and school examiners in the reliability of short external test papers is usually unjustified in that it is not based on evidence. Reliability of marking is also an issue in public examinations - careful training of examiners and cross-checks on their marking are essential.

Validity

A broad concept of validity is both necessary and cogent in any attempt to improve the quality of assessments. The opening statement of Messick's (1989) review gave an authoritative definition :

Validity is an integrated evaluative judgement of the degree to which empirical evidence and theoretical rationales support the adequacy and appropriateness of inferences and actions based on test scores or other modes of assessment.

Thus, if a test is meant to show whether or not a pupil is competent in measurement, it is a matter for expert judgement whether it calls for use of those abilities in measurement which are of value in science. If a test is designed to help predict potential for future attainment, this can be appraised, after the event, by studying correlation of its results with those which it was designed to predict. The closer an assessment activity can come to the actual activity to which its results are to be considered relevant, the more likely it is to satisfy validity criteria. In this light, classroom assessment has a better chance of success than formal timed written tests.

Effects on learning

One focus of concern about testing is its effect on learning. Research is showing that preparing pupils for multiple choice tests can be inimical to good learning practice. This is expressed by Resnick and Resnick (1992) as follows : -

Children who practice reading mainly in the form in which it appears in the tests - and there is good evidence that this is what happens in many classrooms - would have little exposure to the demands and reasoning possibilities of the thinking curriculum. . . .

Students who practised mathematics in the form found in the standardised tests would never be exposed to the kind of mathematical thinking sought by all who are concerned with reforming mathematical education . . .

Assessments must be so designed that when you do the natural thing - that is, prepare the students to perform well - they will exercise the kinds of abilities and develop the kinds of skills that are the real goals of educational reform.

Quality

Of the various features that affect the quality of testing and assessment, one that stands out here must be about the time taken for external tests. If one country invests over eight hours in tests in one subject to determine future career prospects, how can another perform the same function in under two hours ? Any test is meant to sample the several domains of performance that are important in the subject - the A.P.U. Science monitoring at Age 13 in 1984 used 35 one-hour tests to obtain reliable results over the domains judged important for science (Johnson 1988).

One tactic to overcome the difficulty is to narrow the range of the domains assessed, but this narrows the scope of subject aims which the examinations exhibit and thereby, because of their high stakes in most systems, the aims that they impose on school learning.

A related issue pertaining to quality lies in the balance between questions which can be answered by routine procedures using learned algorithms and those which require thoughtful translation and application of principles and procedures. In many country's systems, the analysis shows that the balance is very much in favour of the former, and this must in part be due to the limitations of test times. The very difficult task for most test setters is to develop questions which demand thoughtfulness rather than rote learning, at a level where the average pupils can have a good chance of success.

Bias

Any assessment process is an interaction between certain questions, items and/or procedures, and the pupil being assessed. There are many ways in which this interaction may operate defectively, so producing bias or flaws in the results (Gipps and Murphy 1994).

One example that has been well researched is gender bias. An issue of comparable importance is the problem of cultural or ethnic bias. Difficulties arise in the language used in teaching the subjects, in the range and nature of "everyday" examples used and in cultural assumptions inherent in western science.

There are also many ways in which individual pupils even within the same gender and cultural group, can be unfairly affected by the presentation, context, or language, of assessments. Some pupils who produce strange and apparently worthless responses can, in discussions reveal that these were sensible responses to a misinterpretation of the question (Gauld 1980).

Norm and criterion referencing, aggregation and profiles

The dominant tradition in education at all levels has been to use norm-referenced tests. Where these are used, the emphasis is on comparison of any one pupil or group with the whole population entered for the assessment or test. The alternative approach is to give priority to criterion referencing, so that an assessment result implies that a pupil has satisfied certain defined criteria irrespective of the achievements of other pupils (Gipps 1994).

A related issue is that of the agglomeration of results. A common approach is to take results of marking questions, on different topics and assessing different abilities, and to sum these to give each pupil a total score. This approach can be compared to attempts to obtain a composite measure of chalk, cheese and the smell of a rose. One solution is to report results as a profile in which separate elements are kept apart. It may then be possible to say that scores on each component have meaning in relation to success on given criteria.

One outcome of such discussion is to cast doubt on whether the conventional practice, of setting tests with questions ranging over a variety of contexts, knowledge and skills and adding marks to produce a single norm-referenced number, is valid i.e. can give meaningful results and can be justified in relation to uses made of them.

Teachers' assessments

In principle, a teacher who can record a pupil's performance over time and in several contexts, and who can discuss idiosyncratic answers in order to understand the thinking that might lie behind them, can build up a record of far better reliability than any external test can achieve. Similarly, it also seems that the need to secure validity by assessing pupils skills in the context of tackling realistic problems, and to do this over several different problem contexts, can only be met by teachers' assessments.

The obvious difficulties are the lack of teachers' assessment expertise, the lack of comparability of standards between different schools, and indeed between teachers in the same school, and the dangers of prejudice and dishonesty. None of these obstacles can be overcome quickly or cheaply.

Comparability between schools can be secured by exchange meetings between groups of schools in which criteria are discussed and examples of student work are exchanged. Such meetings have been found to be very valuable for the development of the teachers involved, often revealing how isolated teachers have been in respect of their standards and expectations. There are other methods of moderating standards between schools, notably using external visitors to inspect procedures and submitted samples of work (Black 1993).

The UK. seems unique giving weight in public certificate examinations to marking by the students' own teachers of work done outside formal examination conditions. For this to be acceptable, in commanding public confidence, there have to be very carefully specified rules, and a system which, by drawing samples from schools and checking their standards, can ensure the integrity, and comparability of the results. Sweden is also unique in a very different way. There, the teachers' assessments are the foremost element in determining the whole result. The external examination serves to calibrate the schools distribution as a whole, but leaves the teacher free to decide about individual students (Black 1992).

3 ASSESSMENT FOR ACCOUNTABILITY

The aim involved here is to inform public policy by collection and use of evaluative information. Where public certification results are accumulated for use as performance indicators of schools, the data lacks necessary detail. However, for this purpose there is no need to produce reliable and complete results for any one individual, different pupils can be given different tests and performance can therefore investigated in much greater detail.

If relationships between performance outcomes, and other factors that can be adjusted by public or school policy, are to be explored, information on these factors has to be collected Thus the task involves selection and collection of data on such features as class size, home background of pupils, time spent on learning, laboratory equipment, and so on, to supplement the pupil performance data. The analysis of possible relationships within the data then becomes complex because multiple correlations have to be carefully explored. Any one factor (e.g. type of school) can be correlated with, and so appear to cause, performance variations when it is really only a surrogate for a different factor (e.g. attainment of pupil on entry to the school) with which it is associated. The interpretation of relationships is also difficult because correlations even when properly isolated by statistical means cannot by themselves offer proof of causes (Woodhouse and Goldstein 1996).

Any national monitoring has to reflect a structure of aims and criteria. Insofar as it produces good quality test items and comprehensive data about these aims and criteria, it will attract the attention of teachers and influence their work. Thus, in the national science monitoring in the UK, the structure chosen emphasised process aims in science and influenced teachers to give more emphasis to such aims as observation and the design of practical investigations (Black 1990). Thus the monitoring became prescriptive, and it could be said that the exercise was as much a curriculum development project as an assessment project because it moved ahead of current practice. Thus monitoring can provide an opportunity to promote innovation, just as it can be a powerful conservative force if it only reflects established aims and procedures.

4 SUPPORT FOR LEARNING - FORMATIVE ASSESSMENT

Introduction to the issues

Formative assessment requires the use of a diverse set of data for a purpose. That purpose is the modification of the learning work to adapt to the needs that are revealed by the evidence. Only when assessment evidence is acted upon in this way does it become formative. Such response to feedback may range from the immediate classroom response to a question, through to a comprehensive review of a variety of data in order to appraise progress over a whole topic or theme. In terms of control theory, the use of feedback in this way would seem to be an obvious necessity.

Several common features emerge from surveys research into formative assessment in many countries (Black, P.J. 1993). One of these is that there is substantial evidence that carefully designed programmes of formative assessment do lead to improvements in pupils' learning. A common characteristic is that the renewal of assessment practice is part of a wider change in teaching strategy and not merely an added supplement.

Another feature is that assessment generally, and formative assessment in particular, ranks low in teachers own practice and priorities. Furthermore, where extra emphasis on teacher assessment has been prescribed, as with the national curriculum in England and Wales, the requirements have been widely misunderstood. Research evaluations have established that most teachers, particularly those in primary schools, have interpreted teacher assessment as summative assessment only. Recent surveys have also reported that there was very little formative assessment to be seen in science work (Russell et al. 1994).

One outstanding reason for this weakness is that summative assessments, notably external testing, often dominate teaching because their results command greater esteem than those of other forms of assessment. This has many damaging consequences. External tests create models and images for the whole of assessment and testing which are misleading. For example, a common teaching practice is to set an end-of-unit or end-of-term test which resembles the external tests as closely as possible, and to record the results, perhaps even make them public. Since the data are not used to modify teaching and learning, there is no formative assessment. Thus a practice of more or less frequent summative assessment is set up, so that assessment is equated with testing and acquires the negative overtones, of ordeal by fire for pupils, and of onerous and unproductive labour for their teachers.

However, there are other reasons for the weak development of the practices of formative assessment. They are to do with the many practical difficulties of collecting and recording evidence in the midst of all the other demands of everyday teaching, and with the challenges presented by the prospect of amending, or repeating, or differentiating teaching to respond to assessment evidence.

Two examples

Two specific examples, each about the development of practice in a school in England will serve to illustrate some of the issues. In the first school (Parkin and Richards 1995), the science teachers wanted to use pupils' self assessment and subsequent teacher/pupil discussion as the basis for their assessments. For each module of the course, target criteria were expressed in language accessible to pupils. For each lesson, every pupil had a sheet setting out the criteria with a space opposite each in which the pupil had to state whether the criterion was clear and had been achieved; pupils were also asked to write in other comments - for example about enjoyment or interest.

The teacher subsequently annotated each of the criterion responses with one of three code letters as follows : **A** - for full understanding achieved, **P** - for a partial understanding achieved, **V** - where the work had been no more than 'visited' by the pupil.

It took about a year from the first introduction of this scheme for pupils to learn to use it productively- many at the start wrote very few, and very vague, comments, but during the year these change and become more explicit and perceptive and so more useful. Pupils were not accustomed to thinking of their own learning as purposeful in relation to target criteria. They were also had to break away from treating the assessment as a formal testing.

Some pupils, especially the less able, did not like to admit failure and sometimes said that they understood when they did not. Teachers tried emphasise to each pupil that the record was a private document aimed to help the teacher to see the pupil's problems so that help could be given where needed.

In the second school (Fairbrother 1995), a teacher of physics to a class of 12/13 year-olds wanted them to approach a unit on electricity and magnetism in a more responsible way. He aimed to help them to

put each lesson into the context of the whole unit,

have a summary of what they had been doing for revision purposes,

see what was to come next in the unit of work.

He gave each pupil a "revision sheet" for the unit containing about 25 target statements, for example : -

Know how to make an electromagnet and how to vary its strength

Know that a complete circuit is needed for electrical devices to work

Know that a wire carrying a current in a magnetic field will try to move

Know how switches, relays, variable resistors, sensors and logic gates can be used to solve simple problems e.g.. burglar alarm, frost warning, automatic street lights

Most of the pupils had little idea of how to use this list, for example to check the notes in their exercise book against its contents, or to check whether they did know what was required. Some of the less?organised pupils simply lost it, others simply stored it away and were not referring to it.

The teacher's explanation of this failure was that these pupils were being given too much teaching only about the subject and not about how to learn. The revision sheet was intended to address this issue but the teacher had not realised at the beginning how much actual teaching on how to use the sheet would be needed. For example, when pupils were told as a homework to "revise for the test", most of them were floundering. There seemed to be two main reasons for this. The first was that pupils do not know how to extract from everything they do that which they are supposed to know and understand. Teachers know the difference between the *ends* which they want to achieve and the *means* by which they are trying to achieve them. The pupils do not see this difference. A second reason was that pupils did not know how they would be expected to show their knowledge and understanding. Most of them learn by experience something of what is required of them, and for many pupils this experience is hard and dispiriting. Some of them, usually the weakest, never do learn.

Developing Good Practice

The traditional dominance of the summative function means that formative assessment struggles for its status and development (Fairbrother et al. 1995). Attempts to enhance teacher assessment can too easily reduce in practice to greater use of that assessment for summative purposes, and to more frequent application of teacher assessments, with collection and storage of the results becoming a burden. The summative function can inhibit the growth of the formative function in teachers' assessments in several ways. Summative practice can mislead because external tests are accepted as the model for teachers' assessments so driving these towards techniques appropriate only for summative use. External tests are a poor model for formative assessment because : -

- in summative testing the need for a single overall result means that quite disparate data (e.g. for practical and for theory) have to be added in ways that are often arbitrary: formative assessment does not have to do this

- summative assessment has peculiar problems with criterion referencing, partly because of the need to aggregate, partly because it cannot rely on personal judgements in deciding about the application of broad criteria to the work of individual pupils; such problems are far less serious in the practice of formative assessment;

- summative work has to insist on standards of uniformity and reliability in collection and recording of data which are not needed in formative work and which inhibit the freedom and attention to individual needs that formative work requires;

- whilst summative processes have to be seen to be "fair", formative practice, with its priorities of identifying and helping to meet the learning needs of each pupil, can treat different pupils very differently;

- summative purposes can demand documented evidence for results - e.g. for any auditing review - and so add to workload and distort formative practice, whereas formative work calls for action on the data rather than storage of it;

An outstanding source of difficulty in developing formative assessment is that it cannot just be stuck on to existing schemes of work, it has to be built into the scheme, if only because its use to guide pupils' learning according to their different needs can only happen if the teaching plans allow the extensive time for planning and organisation that such use requires.

Effective use of assessment feedback requires teacher judgement, and the confidence and flexibility in management of a curriculum plan that can only come from ownership of such a plan. Thus is seems that, ideally, any scheme for incorporating good formative opportunities has to be constructed by teachers' for themselves. In such construction, teachers' have to handle two innovations - the need to implement new methods for differentiation and flexibility in learning and the need to learn, perhaps invent, a new technology for producing the appropriate evidence of pupils' achievements.

Use of formative evidence is perhaps the most challenging aspect. There are 'macro' responses, in terms of streaming and setting, but these do not deal with immediate needs. Some teachers have responded by organising units of work into a core and extension, with the extension work varying widely, from advanced new topics for high attainers, to repetition of the basics for those in serious need (Black, H. 1993).. Others indicate less formal and more flexible approaches, building in revision or re-visiting opportunities in later work for those in need. Affecting this last issue is the extent to which teaching programmes are flexible rather than rigid.

The technology of collecting data on pupils' progress is only just beginning to develop. Most teachers have always used a variety of sources in an informal way - it is essential to sharpen this practice with a view to eliciting more usable data. The sheets described in the first example above show one way to do this; the outcomes are distinctive in that they produce detailed information in relation to statements about specific aims - i.e. they are quite naturally implementing criterion referencing because this is what formative assessment inevitably needs. Furthermore, because these provide written evidence in a systematic way, they relieve the teacher from the pressure of noting and recording entirely from the ephemeral evidence of classroom events. Such ephemeral evidence can however have its own unique value: some have found it especially useful - and surprising - if they suspend their active teaching interventions for a time - making clear to a class what they are doing and why - and concentrate only on looking and listening with a few pupils (see Cavendish et al. 1990, Connor 1991).

When an assessment activity is so closely built into a learning programme, it would be foolish to prevent pupils from commenting on their results, from challenging them, and from repeating assessments if they so wished to improve their performance. Thus formative assessments become both informal, and pupil driven, as a consequence of their role in supporting learning. The prominence given to pupils' self-assessment is a notable feature and experience shows that pupils cannot play an effective part in their own assessment except within a long-term programme designed to help them achieve and sustain an overview of their learning targets and to apply the criteria which comprise it to their own progress. As both of the examples above make clear, pupils have to be taught how to assess their own progress. An important part of this work is the translation of curriculum aims into language that all pupils can understand, and down to a level of detail that helps them relate directly to their learning efforts. It also follows that targets have to be both attainable in the short term, and adequately modest in relation to the learners' prospects of success. These requirements come out in particularly sharp forms in providing for pupils with special learning difficulties - but they are important for all.

Teachers who have developed pupils' self-assessment report on several advantages which follow - that pupils can direct their own efforts more clearly and effectively, that they can be more actively involved and motivated in relation to their own learning progress, that they can then suggest their own ways to improve their attainment, and even that they can challenge assessments which they believe to be unfair.

Clearly, pupils' involvement can make it more feasible for teachers to carry through a programme of formative assessment. However, this involvement also changes both the role of the pupil as learner and the nature of the relationship between teacher and pupil, making the latter shoulder more of the responsibility for learning. Quite apart from the needs for improved assessment, the prior need for improved learning demands such changes. Indeed, some have argued that meta-cognition, by which they mean awareness and self-direction about the nature of their learning work, is essential to pupils' development in concept learning, and the work described here is clearly serving that purpose (see Brown 1987, White and Gunstone 1989, Baird and

Northfield 1992).Thus improved formative assessment can lead to changes which are of much wider significance - changes which should be a powerful help with pupils' personal development and which should also be part of any programme to help them to be more effective learners.

5 SYSTEMS AND ROLES

Good summative assessment requires the involvement of teachers, so there seems to be no alternative to developing ways in which teachers can carry both summative and formative roles, using at least some, but not necessarily all, of their evidence for both but distinguishing carefully between the methods and needs which relate to the two purposes. Carrying two roles in this way would be very demanding . On the one side, there are the learning needs of their pupils, which it must be their first concern to serve. On the other side are the pressures and constraints that come from outside . National and regional high-stakes systems create pressures for teachers to work within a framework which drives both their school policies and parental expectations. The teacher has to hold the boundary between the different pressures coming from these two sides.

The main reason for emphasising this issue is that some of the most important aims of physics education cannot be reflected in, and so supported by, assessment systems which rely only on short external testing. Reform of national summative testing is a serious necessity In 1992, at the end of a review of national tests in physics in eleven countries, I wrote the following in a closing summary : -

One conclusion that I draw from this study is that the range of methods used, and the range of abilities assessed, by these physics examinations is too narrow and that they are probably having a seriously narrowing effect on the development of school physics and on the recruitment of physicists. There are many reasons for this. Shortage of resources, together with other system constraints, may account for the willingness of physics examiners to work with systems which they judge to be, at best, far from ideal and perhaps seriously damaging to the future of physics.. Perhaps this situation is accepted too readily by all of us.

(Black 1992)

Public examinations have particular power over the future of physics. By setting the targets and framework within which high school teachers feel they must work, they determine the structure and the image of the subject in the eyes of the young. If such examinations do not call for or promote activities which are important and attractive to physicists and if they convey a very narrow image of the subject, they will attract too few specialists, and give all adults a negative view of physics.

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COMMENTS ON EVALUATION AND ASSESSMENT

(P. J. Black)

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Reading Black's paper, I realised how closely it is related to my own paper on curriculum development and how little explicit attention I have paid to curriculum evaluation, and to the role of assessment. Both in large scale curriculum development and in the design of a single lesson, one starts usually with thinking about what one wants to achieve, i.e., with thinking about (new) aims and about how to reach them. However, it is the function of evaluation and assessment, at the endpoint of the spectrum of educational activities, to reveal to what extent such aims and ways to reach them have been realistic. Much evaluation has shown that many curriculum projects had only moderate success, and one of its reasons could well be that, often, too little attention has been given to the role of assessment. For many teachers, and particularly for teachers who have to work within the constraints of some kind of centralised school and examination system, it is the final assessment for certification that, in the first place, decides what to teach and how to teach it. In those centralised assessments, it is operationally made clear what all the usual curriculum rhetoric is supposed to mean in practice; which, and to what depth, concepts and skills are supposed to be understood and learned. Could one say that curriculum philosophy drives the written curriculum, often, it is the testing practice that drives curriculum practice. Thus testing is an essential instrument for curriculum change and implementation, that not always has got enough attention from curriculum developers. In fact, quite often it appears to be rather difficult to design objectively scorable tests, as are often desired in such certification assessments, that do real justice to all the advocated new aims, be it in the form of conceptual understanding, new skills, or new attitudes. And if new aims are not properly tested, usually teachers do not teach them. The influence of testing on the curriculum may even go a big step further, in the sense that what cannot be objectively tested, should not be part of the curriculum. E.g., in the Netherlands, a successful experiment with the introduction of some Quantum Mechanics in our secondary schools has not led to its adoption in the official curriculum, as, at that level, though the topic was considered to be teachable, it was not considered to be sufficiently testable. So far, my remarks have primarily dealt with summative testing. However, Black quite appropriately also on the role of formative testing in providing teacher/pupil feedback on the teaching/learning process. Again, what he describes is, I think, an essential addition to what I have described at the end of my paper under the heading of developmental research. If we develop new teaching/learning-research-based curricula, we also have to develop new ways of testing that fit into and even strengthen such approaches. The described formative testing procedures aimed at 'developing good practice' seem to be precisely able to play that role. In fact, these formative ways of providing teacher and pupil feedback could be a most essential instrument in keeping the required teaching/learning processes as much as possible on the right track. If we could develop ways of testing that are accepted and can be used both by pupils and teachers for this purpose, instead of the usual 'mark-dominated' testing procedures, than classrooms could become to look much more like mature communication communities, in which teachers and pupils really cooperate in the learning and teaching of physics and in which the detrimental motivational effects of 'the continuous stress of having to work for tests', could be avoided.

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Section E, *Comments on E2* from: Connecting Research in Physics Education
with Teacher Education

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DESIGNING LEARNING SEQUENCES ABOUT PRE-QUANTITATIVE PARTICLE MODELS

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1 INTRODUCTION

To teach some notions about the particle structure of matter from the first years of secondary schooling (or even earlier) seems nowadays unavoidable. This can be related to the increase in everyday-life of linked technologies, such as "electronics" or "nuclear" power for example, and to the diffusion through the media of particular words and images.

In such teaching, we have to be careful with the "concrete" character of these models and to pay attention to their theoretical contents. The need for caution has been shown by evaluations of the results of teaching in this field, and didactical research (Dow, Auld & Wilson, 1978 ; Novick & Nussbaum, 1978 ; Pfundt, 1981 ; Méheut, 1982 ; Brook, Briggs & Driver, 1984), which have brought to light some difficulties and misconceptions relative to

- the existence of vacuum,

- the separation between the sensible properties of matter and the mechanical properties of atoms.

These difficulties can be easily understood if we recall some specific features of the historical development of atomic models. The particle theories of the structure of matter developed from a philosophical assertion rather than from empirical evidence, namely the immutability of matter under transformations and its unity under various aspects. Atomist philosophers considered sensations as misleading ; they asserted that reality remains concealed and can be reached by reason, rather than by direct perceptions. So, matter can be coloured, fluid, compressible, combustible, and so on, whilst atoms have invariable shape, have dimensions, and can only move, collide and aggregate.

" Atoms have no more phenomenological qualities than heaviness, size, shape (...)*. Because all qualities can change, the atoms can't change anyway* (...)*"* or *" They have nothing of the changing nature ; they have necesarily permanent mass and shape.".* (Epicure, quoted by Bensaude-Vincent & Kounelis, 1991)

Errors and misconceptions revealed by didactical research indicate that students are rather reluctant to agree with such "arbitrary" hypotheses. Let us remember the objections that these viewpoints encountered, either in the early stages of atomism or at various moments of its development (Kubbinga, 1983, Bensaude-Vincent & Kounelis, 1991 ; Pullman, 1995). Let us give only as an echo of these debates some words of Ostwald just before atomism was accepted by the international scientific community.

"Everywhere it is repeated, as an axiom, that only the mechanics of atoms can give the key of physical world. Matter and motion are the two concepts to which the most complex natural phenomena are reduced in final analysis (...)*. Nobody usually takes care to note how much this point of view, so widespread, is quite hypothetical, quite metaphysical."* or *" Then,*

atoms, or mechanics, what image of the reality will we keep ? But we don't need any image, any symbol (...). *To establish relationships between realities, that is tangible, measurable variables,* (...)*, this is the task of science and science doesn't fulfil it when concluding with a more or less hypothetical image."* (Ostwald, quoted by Bensaude-Vincent & Kounelis, 1991)

Similarly, there is Boltzmann's answer, justifying atomism as a powerfull instrument for thinking, on the grounds of its capacity to offer unifying descriptions and predictions of observable phenomena, and not as truth devoid of any arbitrariness or hypothesis.

"And to elaborate images to represent facts so that they make it possible to predict the course of similar phenomena, this is the first aim of any exact science (...). *Images will be modified and completed so that they will suffice to describe old and new phenomena. To conclude, I will not hesitate to support, albeit with some reservations, that to contain some arbitrary elements comes from the intrinsically figurative nature of images and that to go beyond the observed facts is indeed unavoidable if one wants to explain even one additional fact "* (Boltzmann, quoted by Bensaude-Vincent & Kounelis, 1991)

Designing teaching-learning sequences, we tried to put into play some of the following characteristic features of particle models of matter:

- rational rather than empirical origins,

- "instruments for thinking" rather than "observable reality",

- mechanical properties which make concretization easy.

The aim is to develop models as cognitive tools in order to unify descriptions and then to predict physical phenomena, the models getting more and more precise in relation with the questions. In this approach, we did not suppose that students would be able to infer a particulate nature of matter by observation and interpretation of some experimental facts (Nussbaum & Novick, 1982 ; Johnston, 1990).

AN UNIFYING MODEL FOR PHYSICAL TRANSFORMATIONS OF MATTER

Characterizing the model

The experimental field and the functions of the model

During a first sequence, we proposed to students that they could interpret physical phenomena (compression of a gas, mixing of gases by diffusion, change of state) as changes of the spatial organization of immutable particles. The models thus elaborated remain quite rough : they provide a coherent interpretation only of the conservation of matter in these phenomena. Using such models one needs to separate space and matter in order to be consistent with the existence of vacuum and the immutability of particles. We also expected that students would propose permanent and multi-directional motion of particles in order to explain the mixing by diffusion of two gases.

The "concretization" of the model

We introduced this sequence through the production and the discussion of iconic representation. This method of representation implies constraints due to its static nature ; on the other hand, t share of initiative in the choice of the significant features that they use. One can thus make a variety of the possible representations appear and elicit the pertinent variables of the model by discussing the meaningful or meaningless nature of the different aspects of the representations made by the pupils. Some samples of working sheets are presented in the annex.

The didactical experiment conditions

We were able to repeat this experiment in each of two years with about three hundred 13-14 year old third formers, viz eleven forms. The learning took place for an hour and a half per week over a six week period, in the usual form groups and in the normal time table. Frequent meetings with our teaching colleagues taking part in the experiment allowed us to work out a precise protocol and to take into account the students' cognitive skills and the normal operating routines of the school.

We defined an accurate protocol with the teachers in order to collect the data during the classes. The data were the pupils' written productions (in every tested form) and tape recordings of the teachers' interventions and of the discussions of several groups of students (in three forms). After the sequence, we assessed by means of written questionnaires various aspects of the individual model building evolved during the learning sequence.

Some results

The invariance of particles

We have chosen to impose invariance as a guide line in the elaboration of the model. This constraint is generally well respected by pupils, who were found to be sensitive to a contradiction.

In the course of this sequence the pupils used the particle shape as a parameter of the model, so allowing the modelling of different substances. The answers to the final questionnaires show that a vast majority of pupils (about 80%) then prove able to establish the idea of invariant shape. Yet one can remark that a low percentage (about 10%) of pupils misinterpret the increase of volume during a thermal expansion process as being a swelling of the particles ; a majority (about 60%) interpret it properly as an augmentation of the distances between particles.

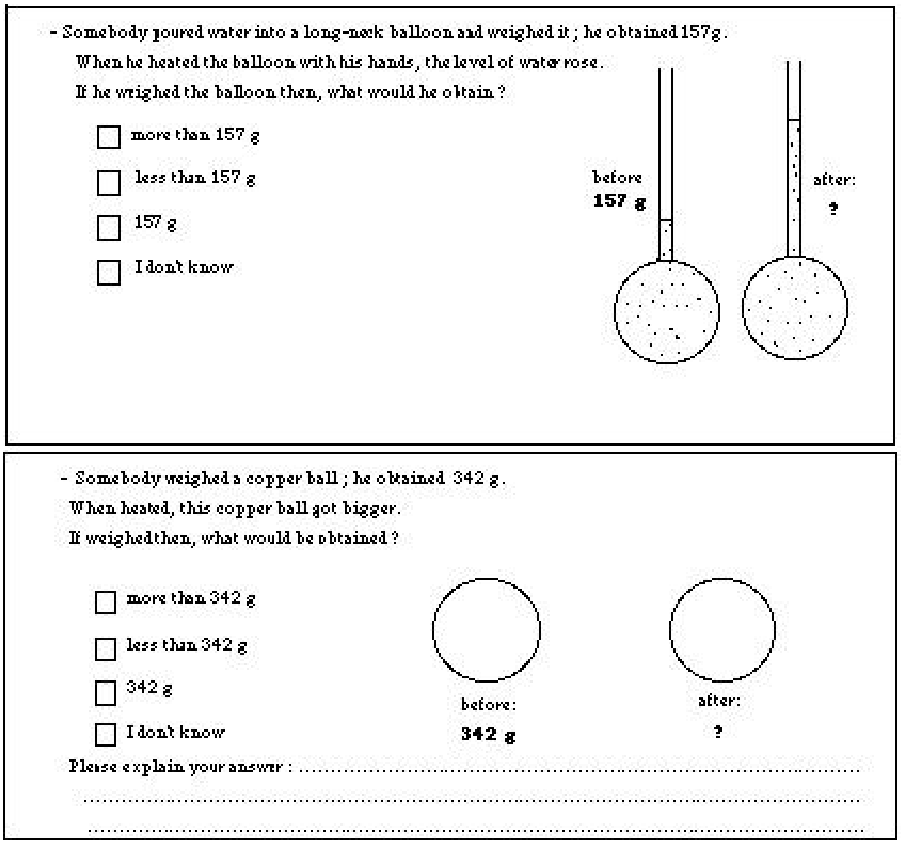
Separating space and matter

The variability of interparticulate distances makes it possible to separate mass variations from volume variations. It is put forward by a great number of pupils in order to explain the compression of a gas sample. It's then used again not only as an explanation of the greater or lesser compressibility of gases, liquids and solids, but also of the miscibility of gases and liquids.

It seems, however, that some pupils were somehow reluctant to conceive of a region devoid of matter. So, in order to model a gas they draw contiguous particles, with no interstitial space (4%), or particles superimposed upon a continuous background (7%). Later on, in order to model a solid they focus on the properties of non compressibility, cohesion, or non miscibility of solids in order to avoid accepting the existence of such empty spaces (15%).

To what extent did the sequence help to achieve a better dissociation of the two concepts of mass and volume ? We can compare the answers given, before and after the sequence, to questions about a thermal expansion process, a phenomenon that was not interpreted during the sequence (see figure 1).

progress in the affirmation of the mass invariance and in the dissociation of the mass and volume concepts. A third of the pupils use particle arguments exclusively in order to justify this invariance of mass.



	Expansion of water			Expansion of copper	
Mass	Before *(N=113)*	After (*N*=*151*)		Before *(N=113)*	After (*N*=*164*)
increases	19%	4%		28%	7%
decreases	8%	1%		9%	1%
no variation	68%	93%		59%	91%
no answer	5%	2%		4%	1%

Conservation of mass during an expansion process; the evolution of pupils' answers

Figure 1: An unifying model for physical transformations

Motion

We also expected that students would propose a permanent and multi-directional motion of particles in order to explain the mixing by diffusion of two gases. Only a few pupils (less than 1%) met this expectation. About one quarter of them evoked the mobility of particles, without specifying the conditions and the nature of such a motion.

Discussion

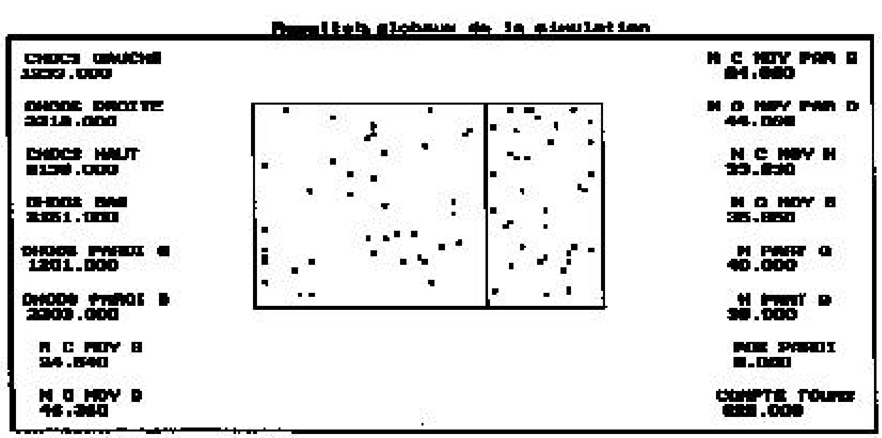
Our students worked on modelling physical phenomena by immutable particles. In this first step, only some limited aspects of these transformations were taken into account. Nevertheless students were given the opportunity to discuss necesary complements to the initial hypothesis : the existence of vacuum, the variability of distances and of arrangements of particles. The analysis of data (Chomat & al., 1988 ; Méheut & Chomat, 1990a ; 1990b) makes clear that more specific learning sequences have to be developed in order that students put into play kinetic, dynamic and thermodynamic aspects of particle models, which are necesary for more effective modelling of physical phenomena.

A PREDICTIVE MODEL FOR THERMOELASTIC PROPERTIES OF GASES

Characterizing the model

The "concretization" of the model

We developed a computer simulation in order to introduce and explore the kinetic and dynamic aspects of particle models. This program generates images of moving entities in a rectangular box (see figure 2). Entities move according to the kinetic theory of gases, except for some procedures related to the low number of entities (about one hundred particles) and the discrete treatment of some variables (position, speed : magnitude and direction) (Chomat, Larcher & Méheut, 1990). The dimensions of the frames are modifiable. It is possible to obtain two boxes with a common side ; this side can, if desired, move in relation to the impacts of the particles. The user can set the number and the "speed" (mean square speed) of the particles in each frame. He can also choose to display the values of parameters of the simulation and of some variables : the number of particle impacts against a side of the box (for the whole length of the side or by unit of length) for a given duration and, when the common side is moving, the position of this side at any insteant, and the mean position of this side for a given length of time.



"Concretization" of the model; a sc

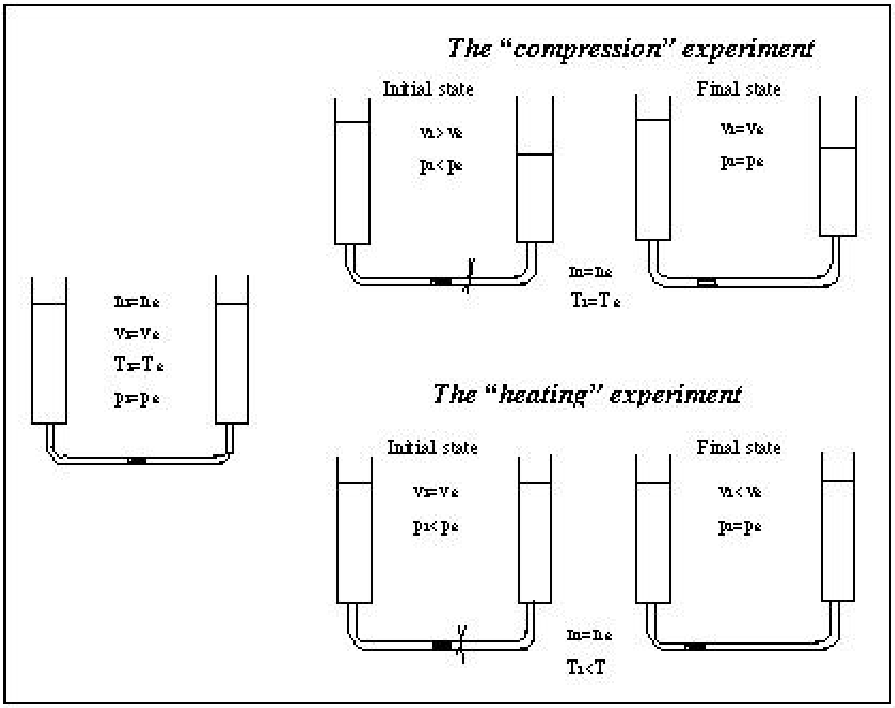
Figure 2 : A predictive model for thermoelastic properties of gases

The experimental field and the functions of the model

During this second sequence, our aims were to help students to develop kinetic and dynamic particle models. The expected ways of thinking require the use of relationships between the number of particles, the occupied space, the speed of particles, the frequency and the "force" of impacts. Such models make possible the explanation and the pediction of phenomena related to the thermoelastic properties of gases ; they give an interpretation of relationships between the volume, the temperature and the pressure of a gas.

We chose the phenomena and the questions so that students could be in a position to bring into play progressively more and more variables of the model. We also took into account some results of didactical research about teaching pressure (Séré, 1985) and specific ways of causal linear reasoning in elementary thermodynamics (Rozier & Viennot, 1990 ; see also part C, chapter 3 in this book). Moreover we wanted to ensure that during this sequence models could be used to make predictions. That is the reason why we searched for phenomena about which students at this age have difficulties making predictions or explanations. So we opted for making the students work first with phenomena without variations of temperature ; the variables of the model are therefore the dimensions of the frames, the number of entities in each box, and the frequency of impacts of particles on the sides of the boxes. Phenomena with variations of temperature are then proposed in order to put students into a position to bring into play more kinetic and dynamic aspects of the models : the speed of entities and the "force" of impacts.

We used an unsophisticated device (see figure 3) in order to make the relationship between the elements of the experimental device and those of the simulation as easy as possible. This device is made of two syringes (containing air) connected by a length of rubber tubing ; a drop of coloured water is placed in this tubing. This tubing can be blocked with a clip or a tap ; the plungers of the syringes can be locked. The experiments consist of creating a difference of pressure between the two quantities of air (the tubing staying blocked) and then letting the system evolve towards a new equilibrium by removing the clip. The difference of pressure can be created by shifting a plunger (*com* experiment) or by heating one syringe (experiment).



The device and experimental situations

Figure 3: A predictive model for thermoelastic properties of gases

For each phenomenon, pupils were asked to predict first, then to observe and to explain the features they observed, without any use of the model ; the questions concerned the shifting, and the stopping of the coloured drop.

1. What will happen if the tap is opened ?

2. Will the drop move ?

O yes O no O I don't know

Why ?

3 . Why did the drop move ?

4. Explain why it stopped . (Where did it stop ? Under what conditions ?)

A second step included the use of the computer program in order to build a model of the system and to simulate the observed phenomena. For this purpose, we asked pupils to discuss the validity of a simulation proposed by the teacher. The aim of these first questions was to put pupils into a position to consider and to choose the values of the parameters of the model : the number of entities in each frame, the dimensions of the frames, and the speed of the entities in each frame in relation to the macroscopic parameters : quantities of gas in each syringe, volumes and temperatures.

1. Does this simulation represent the situation adequately , before the tap is opened?

O yes O no O I don't know

- *If you say "yes", please explain why it is well adapted.*

- *If you say "no", please explain what must be changed, and why.*

2. Is the simulation adapted to representing the situation immediately after the drop stops ?

O yes O no O I don't know

- *If you say "yes", please explain why it is well adapted*

- *If you say "no", please explain what must be changed, and why.*

After obtaining a suitable simulation, pupils were asked to explain the shifting and the stopping of the drop with the help of this simulation.

3. According to the simulation, why did the common side (representing the drop) move?

4. Explain why it stopped. (Where did it stop ? Under what conditions ?)

Teachers could then opt for displaying the number of impacts or for using a simulation with a moving side in order to help pupils to develop the expected relationships between the variables of the model.

The didactical experiment conditions

The aims of the experiment are on the one hand to obtain information on the feasibility and the effectiveness of this learning process and on the other hand to test the hypotheses underlying the choice of phenomena and questions. The experiment included several stages. The first stage consisted of interviews of five pairs of students ; these interviews were divided into two sequences of nearly three quarters of an hour each and they were tape recorded. The second stage was the implementation of a nine hour learning sequence in sixteen 2nd year classes in French secondary schools. We gathered data all along the sequence by written work : nine sheets for each student. The analysis concerned the work of ten randomly selected students out of each class (ie 160 students). In a third stage, two years after the development of this learning sequence, we gathered some additional information for two purposes. The first was to ascertain and to clarify some results obtained by the analysis of the data gathered during the interviews and the classroom sequence ; the second was to assess the long-term effects of this learning process.

Some results and discussion

The analysis of the data collected during interviews provides information about the way students took into account the different variables of the model in relation to the phenomena and the questions (Chomat & al., 1990 ; Méheut & al., 1994).

- About the *compression* experiment, students seemed interested first in representing density variations and differences ; let us giv

Jonathan and Stanislas

J: I should like to reduce the dimensions of the box.

S: And to divide it approximately into two parts.

...

S: With small particles more closed up than the others.

...

J: The right one more reduced than the left one and equal numbers of particles in both boxes.

To explain the shifting of the drop, some of them considered the impacts of particles against the sides of the boxes ; they explained the shifting and the stopping of the drop by comparing the frequencies of impacts on both sides.

Olivier and Pascal

- the shifting

I: And on the screen, how is the push of the air represented ?

O: The air, it rebounds ; the small points rebound against the wall, here more because they have less room so they collide more against the walls.

P: We say, as they have less room, they rebound more against all the walls and as they move with the same speed, they collide more against the walls.

- the stopping

O: They will collide as much because they will have as much space.

- About the *heating* experiment, all the students managed to translate an increase of the temperature of the air into an increase of the speed of particles. So, this was suggested by some students before the interviewer asked them to work with the computer simulation (see for example*Olivier and Pascal*) . It was accepted by the other students after trying other possibilities : particles expanding, multiplying, repulsive forces between particles.

Olivier and Pascal

They seem to feel first some difficulty in predicting what will happen. Pascal then makes a good prediction by using an idea of expansion.

P: The air will expand and then, when one opens it, it will push ; it will push the drop more than ...

After observing, he went from this idea to an increase of the speed of the particles

P : The air was more ... The particles were more distant in the same place, they collided much more quickly.

...

P: What ! They collide much more quickly. It isn't exactly that they are more distant but ... They collide much more quickly, they move much more quickly.

...

P: By heating, one speeded up the moving of particles.

Olivier says very little until this moment. Commenting on a picture, he develops the idea that particles expanded.

O : (before heating) There are as many particles in each syringe and they collide as much ; they collide both as much against the same wall, so the wall keep still and , in the second situation (after heating), particles expand , so when they collide against the wall, it makes a bigger collision than when small particles collide against the wall.

Pascal then recalls the hypothesis of immuability of particles. Olivier then agrees with Pascal's explanations.

This question of interpreting an increase of temperature comes back when using the computer simulation.

P : We should have to try to heat, what !

...

P: We should have to try to recreate when heating.

O: On the computer, would it be possible to represent when heating ?

The interviewer sends back this question to the students.

I: How would it be possible to do that ?

P: If what I said is right, we would have to be able to speed up the particles in this one (box).

This relation was more or less used according to the group. Some students related the speed of particles and the *frequency* of impacts, but didn't consider the *force* of impacts ; so they explained the equilibrium by the equality of the frequencies of impacts on both sides. Other students succeded in considering both the *frequency* and the *force* of the impacts.

Jonathan and Stanislas

J: As it goes faster on the left, the "force de frappe" if we can call it in this way, is higher than this one on the right. But, as it's hitting the wall more from the left, everything is balanced.

Jean- Michel and Flo

JM: The impacts are more violent because molecules are faster.

I: So, when do you think the wall should stop ?

JM: For example, if an impact of a blue molecule has a value of ten and there are ten impacts, and if an impact of a blue molecule has a value of five, it should be twenty impacts of black molecules for ten impacts of blue molecules ; then the wall will stop.

The analysis of the data collected during the classroom sequences gives some information about the short-term and the longer-term efficiency of this learning sequence. For example, in order to assess the efficiency of the particle model built by students as the outcome of this sequence, we gave students experiments that were a little different from those they simulated during the sequence. For both experiments, the number of students reasoning in a particulate way was a little more than a half. Among these, the greatest number (34%) compared the frequencies of impacts. The predictions were correct for a great majority of students (more than 80%). Two years later, students who attended this learning sequence used a particle model more than students who did not attend it.

Analysis of the data can provide evidence about the hypotheses underlying the choice of phenomena and questions. For instance, in choosing the questions, we formulated the hypothesis that students will take into account and compare actions exerted by two systems more for a stopping than for a shifting. The analysis of the data are in accordance with this first hypothesis (table 1).

Table 1 : Testing H1 hypothesis

Situation	compression *N= 145*		heating *N= 160*	
Explaining / Taking into account	the shifting	the stopping	the shifting	the stopping
one sample of gas	96 %	69 %	88 %	56 %
both samples of gas	4 %	28 %	10 %	37 %
no answer	0 %	3 %	2 %	7 %

In choosing the phenomena, we made the hypothesis that phenomena related to temperature were more problematic than elastic properties, when temperature is not put into play. This second hypothesis can be seen as preliminary to a third one, that the model will seem more useful to students for thermoelastic properties and then they will use it more than for elastic properties. The analysis of the data is in accordance with the second hypothesis (table 2), but we didn't observe the expected effect related to the third hypothesis. We now consider that the questions we chose were not sufficient for students to feel the need of such a model and use it more than alternative phenomenological types of explanation. We have to remember that a major quality of the particulate model is its unifying power. Establishing this characteristic on a sec ong process !

Table 2 : Testing H2 hypothesis

Situation Prediction	compression *N= 79*	expanding *N= 77*	heating *N= 79*	cooling *N= 77*
right direction shifting	77%	53%	22%	21%
no shifting	11%	12%	39%	40%
wrong direction shifting	11%	31%	22%	25%
no answer	0 %	4%	17%	14%

CONCLUSION

In order to design these teaching sequences, we took into account some specific features of atomic models and some students' misconceptions and ways of reasoning. For both sequences, we chose the "theoretical" content of the model in close connection with the phenomena and the questions. The didactical experiments enabled us to test the hypotheses underlying the design of these "didactical structures" (Lijnse, 1994) and provided precise information about the effectiveness of the expected learning process. Thus, they threw light on some limitations of these structures in relation to our expectations and suggested some directions for improving the design of such sequences.

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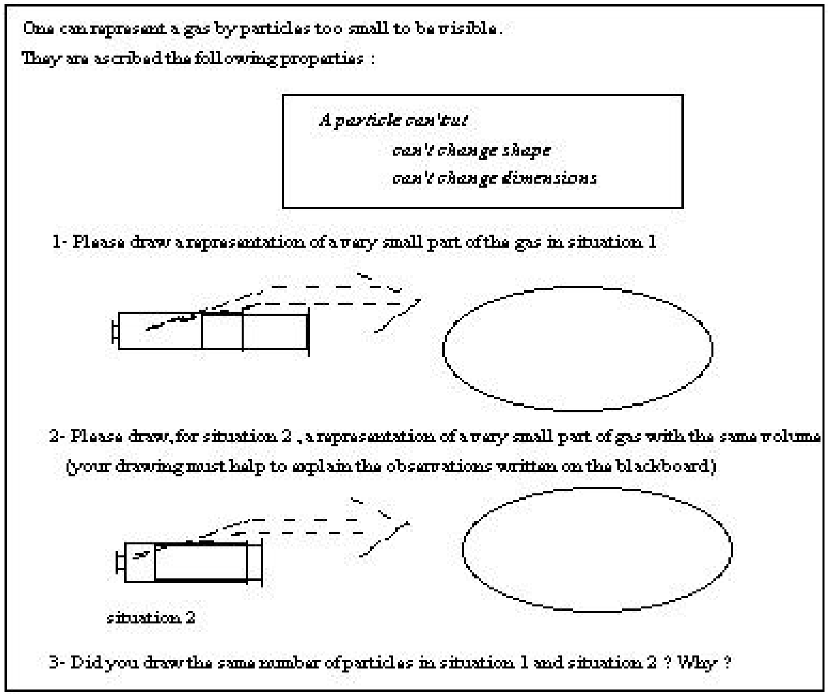
APPENDIX:

A UNIFYING MODEL FOR PHYSICAL TRANSFORMATION
Some working sheets



One can represent a gas by particles too small to be visible.
They are ascribed the following properties :

A particle can't cut
can't change shape
can't change dimensions

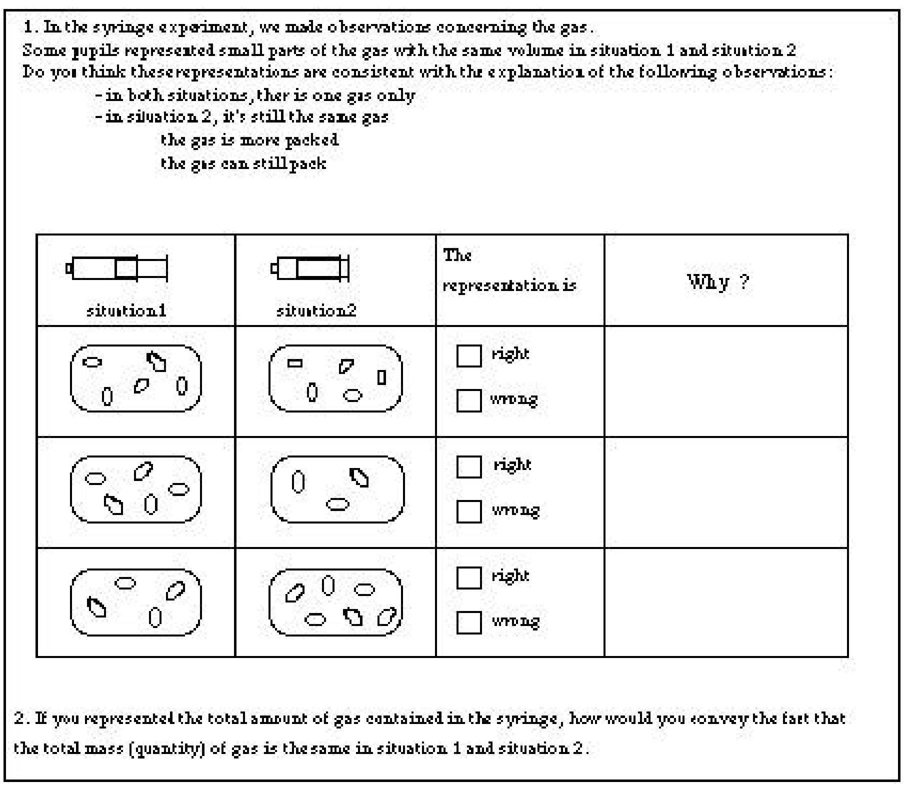
1- Please draw a representation of a very small part of the gas in situation 1

2- Please draw, for situation 2 , a representation of a very small part of gas with the same volume
(your drawing must help to explain the observations written on the blackboard)

situation 2

3- Did you draw the same number of particles in situation 1 and situation 2 ? Why ?

Figure 1a: Interpretation of the compression of a gas



1. In the syringe experiment, we made observations concerning the gas.
Some pupils represented small parts of the gas with the same volume in situation 1 and situation 2
Do you think these representations are consistent with the explanation of the following observations:
- in both situations, ther is one gas only
- in situation 2, it's still the same gas
the gas is more packed
the gas can still pack

situation1	situation2	The representation is	Why ?
		☐ right ☐ wrong	
		☐ right ☐ wrong	
		☐ right ☐ wrong	

2. If you represented the total amount of gas contained in the syringe, how would you convey the fact that the total mass (quantity) of gas is the same in situation 1 and situation 2.

Figure 2a: Discussing the interpretation of the compression of a gas

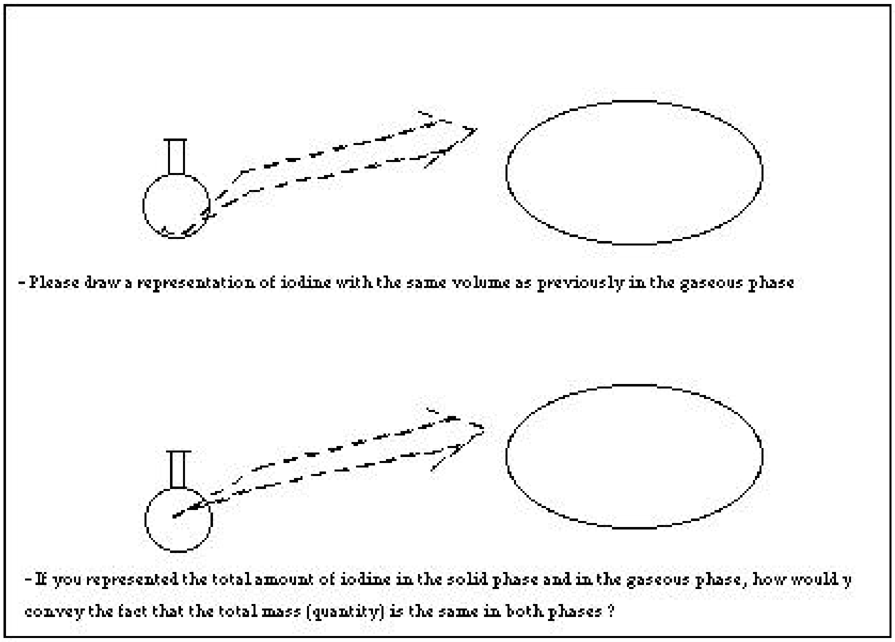


Figure 3a: Interpretation of change of state

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Section E3, *Designing learning sequences about pre-quantitative particle models* from: Connecting Research in Physics Education with Teacher Education

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COMMENTS ON E3: DESIGNING LEARNING SEQUENCES ABOUT PRE-QUANTITATIVE PARTICLE MODELS

(M.Méheut)

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Méheut's paper is concerned with facilitating student's understanding of some aspects of the structure of matter. This is an important teaching and learning issue since models regarding the structure of matter are included in several science curricula world wide. Méheut takes into account results on students' conceptual difficulties and historical developments of atomic models in attempting to develop research based teaching which is adaptable to students' reasoning. In this sense Méheut meets with several other researchers who attempt to develop small scale thoroughly investigated curriculum projects which may contribute to the elaboration of a content based theory of teaching and learning science.

The specific characteristics of Méheut's proposal are related to her epistemological and learning assumptions put forward either explicitly or implicitly in her paper. For Méheut, modeling of the phenomena is an essential function of science as a discipline which should be fulfilled by science teaching too. This position is reflected in the materialization of her teaching sequences in which the models suggested to the students are conceived as "tools to unify descriptions and predict phenomena". These tools have to be taught to the students, they are not supposed to derive from observation of experimental data, and this is one distinctive characteristic of Méheut's approach as compared to other sequences on this and other topics.

Méheut suggests two types of models for the structure of matter both aiming at enabling students to develop a unifying account of a set of observable phenomena. The first, simple model, involves students in interpreting physical transformations of matter as changes in the spatial organization of immutable particles while the second, more advanced model, makes potentially possible the interpretation of thermoelastic properties of gases by the students. In essence, Méheut suggests the explicit linking of the proposed models to a corresponding experimental field, an approach taken also in the teaching sequence on electricity presented in this chapter. I believe that this is an important development to which considerable attention should be given in both research and teaching since it may facilitate our understanding of the cognitive demands put on the students as well as the limits of the taught knowledge. An issue emerging from such a position is how to design teaching sequences leading to increased levels of understanding. In the topic of electricity I suggest that a hierarchy of models, corresponding to enlargement of the experimental field, should be presented to the students. In the topic of the structure of matter a similar approach seems to be taken, in which simple and advanced models form a developmental hierarchy rather than independent teaching pathways.

Another important issue in Méheut's paper concerns the representation of scientific knowledge specifically for teaching and learning purposes. In both sequences qualitative models are used for introducing conceptual scientific knowledge and it is as far as that, that the models on the structure of matter go in line with the aims of teaching. In a broader perspective, I consider that students should acquire a capacity to handle qualitative or semi quantitative models and then they should be taught quantitative ones which are compiled forms of knowledge distant from students' reasoning.

Understanding the structure of matter involves students in handling abstract models so Méheut uses still pictures and parametric simulations to "concretize" microscopic entities and process. I consider that relating such "concretized" models to simple experiments may provide the experiential basis which is necessary for meaning making and for constructing links between observable phenomena and underlying microscopic process. Finally, another crucial issue is how to make students put into play microscopic models instead of complying with phenomenological explanations. It appears from Méheut's paper that students initially carry out experiments, afterwards they are taught aspects of the models and then they are guided by appropriate questions to provide explanations of the observed experiments in terms of the models. This is a rational approach in line with Méheut's learning assumptions the learning results of which are encouraging. An alternative could be the creation of a need in the students to be involved in such a constructive activity. In the sequence on electricity meaningful cognitive conflict is a strategy used for engendering a search by students for an explanatory microscopic mechanism. One wonders whether such a strategy would be effective in the topic of the structure of matter as well.

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Section E, *Comments on E3* from: Connecting Research in Physics Education
with Teacher Education

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TEACHING INTRODUCTORY ELECTRICITY

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The teaching and learning of electricity, a topic often included in primary and secondary curricula, has been the object of many investigations, books and conferences (Duit et al, 1985; Calliot, 1992). The emerging picture world-wide is not promising given that an adequate knowledge of, for example, electrical circuits has rarely been acquired by students by the end of secondary education. Research results provide a fairly clear view of a variety of students' topic-specific alternative ideas (an extensive review is presented in Section C of this volume). Moreover, it emerges that students encounter deep-level conceptual and reasoning difficulties in understanding introductory electricity which the usual or innovative teaching tends to ignore rather than explicitly take into account.

Briefly stated, students demonstrate learning difficulties with regard to:

i) Developing systemic reasoning

Linear causal reasoning is employed by students to account for the functioning of electrical circuits. In simple circuits, causal models are of a source-consumer type resembling, from the scientific perspective, an energy view of simple circuit operation. Often, following the teaching of resistance, sequential models develop, according to which any disturbance travels in one direction affecting circuit components in succession. Linear causal reasoning is fundamentally different from the systemic reasoning which is necessary to understand the electrical circuit as a closed system in which all components interact with each other and any disturbance extends in all directions.

ii) Conceptual differentiation

Students confuse features of current and energy; voltage being considered a property of "current" indicating its "strength". All the scientific concepts collapse under the global-undifferentiated notion of "current/energy".

iii) Establishing phenomenological relations

Students do not relate the phenomenologically different areas of electrokinetics and electrostatics (Frederiksen & White, 1992). For the students, there are no obvious common features between the attraction/repulsion of electrified bodies and the lighting of a bulb.

iv) Linking different models

The establishment of relations between several models - qualitative with quantitative ones, macroscopic ones with underlying microscopic mechanisms - is another source of difficulty for the students (Eylon and Ganiel, 1990).

It is worthwhile noting that students' difficulties such as the above are not specifically limited to electricity but appear across several other topics involving physical processes (Driver et al, 1994; Viennot, 1993).

1. Pathways for teaching electricity

It appears that the consensus which has been achieved gradually among researchers concerning students' learning difficulties has not brought about a consensus on the appropriate pedagogy. Thus in the search for remediation, several research-based pathways have emerged following a constructivist perspective on teaching and learning, according to which the learner is an active agent of his own knowledge construction and the learners' domain-specific prior knowledge is a crucial factor in acquiring new knowledge.

In one pathway, proposals question the feasibility and the educational value of pursuing understanding of the mechanism of the electrical circuit by the students. Since adequate understanding of electrical circuits is difficult, the argument goes, teaching of electricity should focus on important applications, for example electricity at home and/or electrical energy saving (Berg & Grosheide, 1993). In another pathway, however, several proposals focus on effective strategies to render learnable the essential features of more traditional subject matter such as that of understanding of function of electrical circuits.

Within the second pathway, some proposals rely on analogies and analogical reasoning as a vehicle for inducing conceptual change in the students. For example, water analogies are suggested in order to facilitate understanding of the electrical circuit as a closed system (Schwedes, 1995). Yet other approaches use confrontation strategies (Scott et al, 1993) as a means of facilitating conceptual change in the students (Shipstone et al, 1988; Licht, 1991). The above categorisation does not entail the mutual exclusivity of strategies and means employed in several pathways. For instance, the use of some type of analogy seems unavoidable in order to render intelligible current conservation. The differences lie in the relative emphasis put on these strategies as well as in the purposes they serve.

In this context, the present paper outlines key aspects of one approach to teaching basic electrical concepts in secondary general education utilising confrontation strategies. This is one of the teaching sequences developed in a research and innovation programme, concerning various aspects of teaching electricity, carried out over a peroid of several years by the Science Education Group at the School of Education in the University of Thessaloniki (Psillos et al, 1987; Koumaras, 1989).

2. Scientific knowledge

Any approach to teaching and learning science is influenced by epistemological considerations concerning the structure and the object of the scientific knowledge to be taught. We accept here that modelling of the real world is a main function of scientific knowledge (Hestenes, 1992). The core of scientific knowledge comprises models of real objects and processes that are elaborated and shared by the scientific community in order to interpret nature. Models are embedded in theories and are testable in an experimental field (Bunge, 1973). The process of creating theory and models does not consist of an extraction of the common factors from a set of observations, as empiricists would claim (and as has been adopted in several physics curricula and teaching practice). According to constructivist epistemology there are strong links between the questions asked of nature, observations and the theoretical framework.

Questions that are relevant within one theoretical framework are meaningless in a different one. In electricity, enquiry into the nature of the electrical fluid (Stoclmayer and Treagust, 1994) is irrelevant in the context of the Drude model. Any theoretical approach refers to one experimental field and is instrumental in structuring it. For instance, the unification of electrostatic and electrokinetic phenomena was possible only after the work of Ohm and Kirchoff and the employment of surface charges in electrical circuits. Explanations are embedded in a theoretical framework the evolution of which implies a change in the type of explanation and causality accepted by the scientific community. Following Faraday and Maxwell, the electromagnetic field provides the basis for explaining the unified electromagnetic phenomena in classical electrodynamics.

In the development of scientific knowledge, there is a continuous interplay between experimental field, models and theory which shows the need for validating and establishing links between these different levels. Such a creative process requires considerable intellectual effort and is usually the product of collaborative activity producing objective models in the sense that they have been validated and are publicly accepted. Thus scientific models and theories transcend personal idiosyncratic views which students hold as products of everyday interaction with phenomena and ideas. They become part of a shared culture implying a particular way of "seeing" nature.

3. Assumptions about science teaching and learning

Briefly stated, the following assumptions have been taken into account for the development of the teaching sequence on electricity which is outlined in the present chapter. These assumptions do not make up for a comprehensive model regarding the teaching and learning of science, but concern important issues in matching students' learning difficulties with our epistemological perspective.

First, we consider that teaching science should involve all levels of scientific knowledge, namely theory, models, experimental field (Tiberghien et.al,1995). However, scientific models are different in scope and structure from students' personal views of the world. On the one hand, this means that comprehension of scientific models and involvement in modelling activities may imply a conceptual change for the students. On the other, scientific models must not be too distant from students reasoning in order to be intelligible. This implies that a transformation of scientific knowledge in order to be adapted to students' causality is necessary in several cases.

Second, in science teaching, there should be a coherence between the models to be taught and the corresponding experimental field which provides the experiential basis for meaning making. A corollary of this thesis is that the enlargement of the experimental field to be taught should imply the successive presentation of more powerful conceptual models.

Third, in science teaching models should be treated as hypothetical constructs. This, in turn, necessitates a validation process as an essential ingredient for the development of scientific knowledge.

4. The development of models

We outline key aspects of a teaching sequence in introductory electricity, demonstrating the gradual enlargement of the experimental field as well as the successive development of the corresponding models. Various versions of this sequence have been used with samples of students at the end of compulsory secondary education in Greece (15yrs). At this level, physics is taught as a compulsory single subject for two years. Electricity is also taught at primary school, in the context of a two-year course in natural sciences.

The conceptual objectives of this sequence included description and interpretation of circuit behaviour and electrostatic phenomena in terms of the physical quantities V, I, R, E, Q and t. The cognitive objectives included the differentiation of the concepts of V, I and E, the development and use of appropriate models to account for electrical phenomena, the linking of electrostatic to electrokinetic phenomena and the development of a systemic view for the electric circuit.

The sequence has been structured in four parts. The parts form a developmental hierarchy in terms of the questions raised, models which are taught and the corresponding experimental field. Subsequent models are self consistent, but are linked with each other leading to deeper levels of understanding electricity. For example, the concept of resistance is not introduced in the first, phenomenological, part. It is introduced qualitatively in the conceptual macroscopic part, then is related to a microscopic mechanism in the third, the microscopic, part and finally is studied quantitatively at the fourth, quantitative, part.

i) The Phenomenological part

The Phenomenological part has been designed as a long familiarisation period which is characteristic of constructivist approaches in electricity and elsewhere. The Phenomenological part, deals with questions meaningful for the students. These are formulated at the level of phenomena which refer to familiar objects and events and are in line with students' source consumer model, e.g., how does a bulb shine or what do we pay to the electricity board.

Batteries, bulbs and familiar applications such as a torch or Christmas tree lights make up the experimental field. Our research results (Koumaras, et.al) led us to an important decision concerning the experimental field; namely, to include events related not only to the intensity of lighting but also to its duration. This choice enlarges the experimental field, which usually includes only steady state situations in both traditional and constructivist curricula. As a consequence, events such as the duration of lighting or the "life" of a battery, which are familiar to students, are extensively treated in the sequence. We call these situations evolutionary ones.

In our case, scientific concepts are not introduced at this level. At the end of the phenomenological part students are expected to have become familiar with electrical phenomena and experiments, understand the closed circuit, construct causal relationships with respect to 'instantaneous' events referring to the brightness of the bulb and with events extended over time regarding the duration of lighting, for instance " batteries in parallel imply illumination for a longer time".

From the beginning of the sequence students are offered opportunities to experiment with batteries, bulbs and several materials in order to understand the closed circuit and classify materials as conductors and insulators. The knowledge gained about the continuous pathway is further validated for the students when they attempt to interpret familiar but not obvious situations. Thus, for example, a real bicycle is brought in the classroom and students are asked to predict and interpret the circuit of its dynamo.

In the next step, students are involved in experiments in which they manipulate the number as well as the type of connections between batteries and the bulbs. Teaching at this level is limited to the establishment of relations between observable variables, namely the number of batteries and bulbs, the circuit configuration and variation of lighting. Students learn that lighting depends not only on the number of batteries and bulbs but also on the configuration of a circuit. Both the intensity and the duration of lighting are considered as important effects. This facilitates the intelligibility of the new knowledge and the construction of causal models for circuit functioning, as the following extract from one classroom shows.
Task 1 (Fig.1) was presented to the students during the teaching of parallel connection of batteries and bulbs which followed the treatment of closed circuit and the series connection of batteries and lamps.

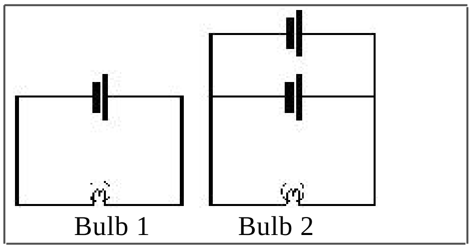
Q1		The bulbs, batteries and wires in both figures are similar. Will bulb 2 shine more, less, or equally brightly than bulb 1? Justify.

Figure 1.

Initially the students were asked to make their predictions.

Most of them answered that Bulb 2 will be brighter than Bulb 1:

"because in the second circuit there are two batteries while in the first there is only one".

After carrying out the experiment the students in one classroom were asked to provide their interpretations of the equal brightness. In the course of discussion with the teacher, several students introduced the duration of the lighting as follows:

".. With this kind of connection we do not have much brightness but it (lighting/battery) must keep on for more time."

".. With this connection of the batteries we gain time, that is the bulb will be on for double the time than if it were connected with only one battery".

Similar responses were noted in other classrooms, suggesting that when the experimental observations were different from their predictions, several students used the evolution of the functioning of the circuit in their interpretations of the data. By reasoning in terms of time/duration, these students managed to provide plausible, for them, explanations about steady-state tasks. Our research suggests that this is an ingenious reasoning strategy which students use effectively to reduce the conflict between their predictions and experimental results (Koumaras et al).

Finally, It may be noted that it is anticipated that students will persist with their source-consumer model by the end of the phenomenological part. For example, the bulb remains a consumer in students' minds; it has not acquired the status of a resistor.

ii) The Conceptual Part

Once the students have acquired an understanding of electric circuits at a phenomenological level, our results suggest that they are expected to raise conceptual questions of the type "what(quantity) changes when the connection of two bulbs changes?

More powerful models corresponding to an enlarged experimental field and capable of providing answers to conceptual questions are developed at this level. Our choice is on the one hand to repeat a set of phenomena encountered in the phenomenological part such as series and parallel connections of batteries and bulbs so on. On the other to enlarged the experimental field to include, voltmeter and ammeter readings and resistors. Domestic electric appliances such as hair dryers are among the several applications students deal with.

In our case, the conceptual part is based on the modelling of electrical phenomena at a macroscopic level including the concepts of voltage (V), current (I), energy (E), resistance (R), time (t). Simple use of microscopic entities (charged particles, electrons) is made only in response to students' questions regarding "what is flowing". With regard to the conceptual structures we may note that at this level domain knowledge has to be adapted to students' reasoning in order to be intelligible. Taking into account students' causality, the domain knowledge is decomposed into two partial causal models in order to account for brightness and duration of lighting. The first is the flow model, which puts into play the physical quantities V, I, R and their interrelationships. The second is the energy model, which puts into play the physical quantities E and t.

The starting point for conceptual modelling of electrical circuits is an issue on which not all researchers agree. In the present case, voltage and energy are presented as the entrance to the cluster of concepts V, I, E for two reasons. First, we consider that the reconceptualization of "current" towards a scientifically acceptable concept involves conceptual differentiation mainly between the concepts I and E which has a considerable cognitive cost for the students. Such a conceptual change requires substantial preparation in order to occur and may be assisted by the acquisition of preliminary knowledge about voltage and energy (see also Episode 1). Second, the early development of a voltage concept may assist a causal account of electric circuits, render students more "voltage than current minded" and facilitate the formation of links between electrokinetic and electrostatic phenomena at both a macroscopic and microscopic level (Psillos, Koumaras and Tiberghien, 1988). Following voltage, the next step is to introduce current and then resistance. Our data suggest that facilitating the construction of the concept of resistance plays a prominent role in the development of a macroscopic flow model and provides a bridge towards the microscopic model. This is why emphasis is put on the teaching of resistance.

As a first step towards the development of conceptual models, students are involved in various activities, presented in Episode 1. In the next step, students are involved in experimentation with bulbs and ammeters taking qualitative and semi-quantitative data. In addition to bulbs, ammeters are used as current indicators, their readings suggesting that current along the circuit remains the same. Conservation of current alongside the circuit is discussed with the students thus pursuing further the I, E differentiation.. The well known experiment with bulbs and ammeters in series is used to indicate equal readings across the circuit. However, our results lead us to speculate that several of the students consider the ammeter as a consumer of energy like the bulb and thus may assimilate equal ammeter readings in their source consumer model (Psillos, et. al. 1987). A water analogy including a pump, water circuit and a mill provides a useful visualisation of a closed system in which one quantity (water) is circulating and conserved while energy is transferred from the pump and used in the mill. At this point the flow model of current starts progressively developing. Ammeters, even zero point ones, are not used to show current unidirectionality, they are not convincing for the students. The same applies to magnetic needles. Elsewhere we have argued that magnetic effects are interpretable in terms of the source consumer model and should be used only after the development of a current concept (Psillos, et.al 1987) . Metaphors are utilised for inducing unidirectionality such as "in the rivers the current travels only towards one direction". In addition to the above, students are also experimenting with batteries of different volt indication which show them that for the same circuit current depends on voltage.

In the next step the students are engaged in activities and experiments regarding resistors. They are confronted with a difficult task, namely to relate resistors to bulbs and ascribe two functions instead of one to these two objects i.e. users of energy and regulators of current. This is a crucial step where the flow model of current may acquire meaning for the students, i.e., the flow of "something" may develop into the flow of invisible "material" particles. Students often develop a sequence model and this signifies their conceptual progress. In Episode 2, aspects of a confrontation strategy regarding the teaching of resistance are presented.

At the end of the conceptual part students develop a new relation between E, I. They are involved in a series of experiments which suggest that the rate of energy transferred depends not only on the amount of current in a circuit but also on voltage. For example, in one experiment one torch bulb is connected to one 4.5V battery and one house bulb is plugged plugged to a socket. The ammeters in both circuits have the same readings but the bulbs light differently.

iii) The Microscopic Part

Questions regarding microscopic entities and mechanisms emerge when students start developing the concept of current conservation and particularly the double function of resistors as both energy users and current regulators. For example, the following dialogue has been recorded during a classroom discussion:

Ss Sir, if we measure the current just before a bulb (in a battery-bulb circuit), the ammeter should read more.

T: Why?

Ss Because the electrons accumulate as they to pass through the

resistor. After the resistor the current is less because fewer electrons pass through.

This model has been called a "packed crowd" model for current and is in line with the sequential treatment of changes in an electrical circuit. What matters for our argument is that the students seek an explanation at the level of a microscopic mechanism in order to account for the function of a resistor and current circulation. In the microscopic part, qualitative causal models are developed which provide answers to such questions, enhance macro-micro links and pursue an understanding of the electric circuit as a system.

The experimental field is enlarged considerably to include the interaction of electrically charged bodies, electrostatic machines and conductivity in liquids. Teacher-led experimental demonstrations and discussions are carried out regarding charging, attraction and repulsion of charged bodies, and electrostatic machines as well as about the function of a prototype battery.

A crucial issue at this level is how to relate electrostatic and electrokinetic fields, seemingly separate for the students. Experiments, analogies and metaphors, concepts and conceptual structures are used to establish links at both the phenomena and the model levels.
For example, in one experiment the measurement of voltage between the arms of the Wimshurst machine is related to the measurement of voltage between the battery terminals. Another experiment (see Fig. 2) is used to facilitate links between charging, charged body movement, lighting and ammeter reading. The explanation offered is that an electrostatic machine can accumulate different charges on its poles and hence establish a voltage value between them. Under the appropriate conditions, i.e. one closed circuit consisting of one bulb, the machine and one light movable body between the poles, an electric current may be created.

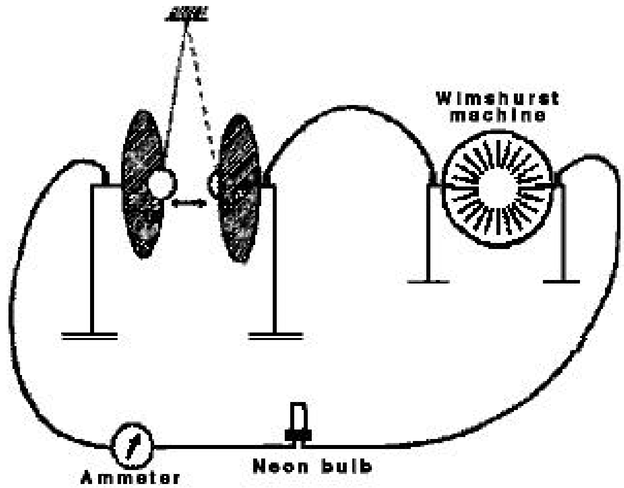


Figure 2.

Crucial aspects of the microscopic mechanisms for battery function are illustrated by analogies, for example the charge separation and accumulation in the arms of the Wimshurst machine are related to the charge separation and accumulation in the battery terminal. Voltage and charge are presented as unifying concepts of electrostatic and electrokinetic phenomena both at the micro and macro level. Voltage is linked to the differential charge accumulation at both the battery poles and the terminals of a Wimshurst machine. Causal explanations are provided for the students in order to make processes intelligible. For example when somebody turns the Wimshurst machine crank, one can observe the deviation of the voltmeter needle; the faster you turn the lrger the voltage indicated.

A simplified causal microscopic model is used to provide an explanatory mechanism for the operation of an electrical circuit. This model is battery centred and voltage corresponds to the surplus and lack of electrons created by chemical reactions on battery terminals. Attraction and repulsion forces are consequently exerted on the free electrons setting them into movement and thus current is established. Lack of space does not permit detailed description of the model. It is important to note however, that such a model is appealing to students because it provides a causal explanatory mechanism of what happens in the circuit. The macroscopic variables I, V, R acquire a microscopic representation which facilitates macro-micro relations.

iv) The Quantitative Part

In the previous parts students have acquired a strong qualitative basis, have obtained semi-quantitative measurements and have explored covariations of the physical quantities V, I and R. At the quantitative part are taught quantitative relations among V, I, R in order to answer questions such as "if we double the resistance value how much will the current decrease in one circuit containing one ammeter, resistors in series and one 4.5 V battery ? ".

The experimental field is enlarged in the quantitative part to include series and parallel connection of resistors, ohmmeter readings and specific resistance. A quantitative macroscopic model is introduced including Ohm's law and the relation R = ñ.l/s. Variation of resistance changes with temperature, are also presented.

Students are engaged in activities in which they use instrument readings to investigate quantitatively various aspects of the functional relation V = I.R. For example, having acquired a qualitative concept of resistance and a microscopic representation of this concept students are involved in direct measurements of resistance obtained by an ohmmeter. Then they compare these data with calculations about the same resistance value which derive from voltmeter and ammeter readings in a circuit consisting of one battery and two resistors in series. Measurements are also taken in order to construct a graphic representation of the I = V/R relationship.

One specific feature of this part is that students are involved in experiments designed to facilitate realising that a local change such as increase in resistance value implies a global change in the whole circuit - for example the value of current in the circuit - thus enhancing the systemic view of the circuit. For example, students are involved in experiments in which they are asked to predict and interpret variations in ammeter readings when a parallel branch including one resistor is added to a circuit containing one battery connected to one resistor:

When we add the resistance the ammeter shows more because there is a parallel connection...we have two circuits the battery has to give more (current).

5. Teaching Strategies

Several teaching strategies and techniques have been applied to facilitate students' constructive activities aiming at understanding the above models. Normally students were involved in collaborative guided experimentation and discussions in order to elicit their views, predict and interpret phenomena. Aspects of two confrontation strategies which have been applied are presented in the next session.

5i). Episode 1: Facilitating conceptual differentiation

In introductory electricity the development of scientific concepts implies students' differentiating the features of current, voltage and energy from the initial global notion "current/energy". Essential steps in facilitating conceptual differentiation by students may be the upgrading of those conceptual features that are weak in students' initial knowledge; the discrimination between the features of different concepts; the establishment of new relations among the concepts (Kariotoglou et al. 1995). This strategy has been applied in the case of voltage which is a weak concept subordinate to current. A teaching unit on voltage and energy has been included in the conceptual part, aiming at upgrading the voltage concept and commencing current-voltage and current-energy discrimination. Aspects of this teaching unit are presented below.

Changing the level of questioning

By the end of the phenomenological part students potentially raise conceptual questions such as : 'What changes occur in a circuit when we connect two batteries in series or in parallel?' The introduction of the voltage and energy concepts aims at facilitating students' use of features of voltage and energy to provide answers to such questions.

Enlarging the experimental field

The experimental field includes batteries and bulbs, as mentioned before. In addition to this, the field is enlarged to include voltmeters and their readings.

Validating new knowledge

In this unit students take and use qualitative and semi-quantitative data to validate the conceptual models. Thus they have the opportunity to use and relate the unknown voltmeter readings with familiar objects or events. For example, the students read 4.5V on a battery and check that a voltmeter indicates 4.5V, or they note that two batteries connected in series might imply 9V and check it with a voltmeter. Measurements are not related to a formal definition of the physical quantities voltage and energy but are utilised as a means to describe the attributes of these concepts.

Introducing meaningful models

As mentioned in section 4ii, the two partial models of energy and flow are gradually put into play at the conceptual level. The level of causal relations changes; from dealing with objects and events students are asked to describe and interpret similar phenomena in terms of physical quantities. In the flow model voltage is introduced as a primary concept with direct reference to the battery, signifying its potential to establish 'current' in a circuit. Voltage is causally related to the generation of current. In the energy model, energy is introduced as a primary concept too by the property of 'storability'. Energy is related to the volume of the battery (for batteries of the same type), in the sense that a battery is a container of energy. In terms of the energy model, energy stored in the battery is causally related to the duration of the lighting. This approach is radically different from several traditional ones in which voltage and energy are introduced by relational equations and is in line with research suggesting that students understand properties of objects better than relations between concepts.

Elaborating the models

The new knowledge about voltage is introduced by using what is familiar to the students, namely, volt indication on batteries. At the beginning of the unit students compare the brightness of identical bulbs connected with batteries of different volt indications. At this point the students are informed that volts measure a new quantity voltage. Then they compare variations in brightness by using batteries connected in series and in parallel and repeat the same experiments using the voltmeter. Essential steps in the evolution of their reasoning are presented below.

Classroom results show that initially, the number of volts indicates for several students the quantity of "current" stored in a battery, either functioning in a circuit or not:

T: After all you have seen in this lesson up to now what do you think that volt indicates?

S3: It is the quantity that a battery has

T: What quantity?

S3: Current

T Do the others agree?

Ss: Yes

It seems that the students conceptualise only the "quantity stored" in a battery, the amount of which determines how much "current" is "given" to the bulb. A possible schema applicable for the students is " the more I have, the more I give, ". Thus two batteries in series have more "current" therefore they may "give" more "current" to the circuit hence brightness increases. In this way experimental results are interpreted in terms of students' source consumer model.

In a second step two teacher-led demonstrations are used to facilitate discrimination between voltage/energy and voltage/current. The first involves two batteries of the same voltage but different size. These are connected to similar bulbs. In this experiment, students are asked to predict and interpret the brightness of each bulb and the duration of its lighting. Classroom data show that in step two, some students (see S3) relate the volume of a battery to the "quantity stored", which they distinguish from voltage

T: If we connect these two batteries (same V, different size) with two similar bulbs will the brightness be the same?

S3: Yes.

T: Are you sure, this one is very big?

S3: It does not matter since the volts are the same the batteries have the same force. This one (the small) will finish quickly, the big one will finish later.

S2: Both (batteries) will finish at the same time.

S3: The big one has got more energy it is bigger.

S2: If it has more energy the bulb will bright more.

S3: Quantity, eh, not force.

Here the students conceptualise voltage as determining the "strength/force" of the "current given" by the battery to the bulb. These conceptions are more elaborate than the previous schema and are partially correct. However, the students do not quite distinguish the use of these conceptions as a second variable which conditions the interaction between the battery and the bulb, when they function in a circuit. Students still relate voltage to "current" and, possibly, the volt is a unit of "current" measurement.

In the second experiment, a voltmeter is connected in series with a bulb and a battery. Classroom data show that the students ascribe voltage to battery when trying to interpret the reading of a voltmeter connected in series to a battery and a bulb which, in this case, does not glow.

T: Do we have current in the circuit

S3: No

T: How do you know this?

S3: The bulb does not bright

T: Does the volt measure the current?

S2: No

T: Why?

S2: If the volt measured the current the bulb would bright

Voltage now indicates the "strength/force" of the battery. It appears that, in a third step, voltage is conceptualised as a permanent characteristic of the battery which holds when it either functions in a circuit or not. With the help of metaphors (employing the Greek term for voltage, "tassi" which also means tendency, disposition to do), the students relate Voltage to the disposition of the battery to "give current" to the bulb and not to the "current" it "has" or "gives", in line with the objectives of the unit:

T: Okay, can any of you tell us what you think you have learned today.

S1: We learned that voltage is first and then current, the voltmeter does not measure the strength of the current, it does not measure the quantity, it measures the volts.

S3: Voltage

S2: Eh..,voltage

T: What does this voltage mean? Whose feature is it?

S3: The battery, which gives energy to the bulb.

S4: Disposition of the battery to give current to the bulb.

This step is a difficult one which takes time to become meaningful, so reversals between the steps have been noted in students' conceptions during and after the unit. In the next teaching units conceptual discrimination is enhanced while new relations are developed between voltage, energy and current so that students are helped gradually to differentiate and develop the scientific meanings of these concepts.

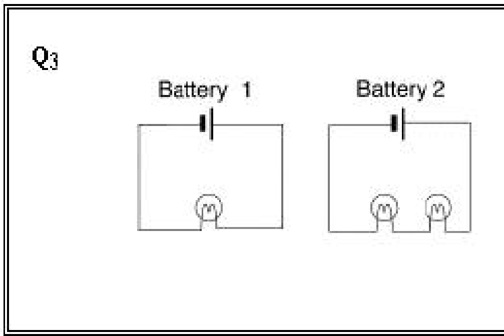
5ii) Episode 2: Inducing meaningful cognitive conflict

We present here aspects of a cognitive conflict strategy aiming at facilitating students' construction of a model for resistors and resistance. As we have argued elsewhere (Koumaras et. al, 1995) this strategy is based on: the acquisition of preliminary knowledge by the students; the confrontation with recognisable counter-evidence; the concurrent presentation of a better alternative explanation; the application of new knowledge. One crucial feature for the effectiveness of such a strategy concerns what may count as counter-evidence for the students.

An essential part of this strategy comprises the gradual acquisition of initial knowledge regarding resistance. Students, for example, are involved in experiments observing the co-variation of the length of a resistor, ammeter readings and bulb brightness connected in series to one battery. Also they touch and feel that the temperature of a resistor, such as a nichrome wire, increases as current passes through but not that of a conductor, such as copper wire. This approach is different from usual teaching, which often treats the thermal effects of current separately from resistors. Students realise that a bulb is a resistor by experimenting, problem solving, discussing and exchanging views in group work. Our results suggest though that such knowledge is still interpretable in terms of the source- consumer model. For example, in the above experiment, the resistor warms up not because it is an obstacle but because it consumes more energy. Hence both the brightness of the bulb and ammeter reading decrease:

"In the nichrome wire experiment, the current becomes lower because it is consumed in order to get the wire hot, so less current arrives to the bulb, which gets dimmer. In the copper wire experiment, the brightness of the bulb and the reading of the ammeter remain the same, while the copper wire doesn't get any hotter. The (copper) wire does not consume any current and all of the current gets to the bulb which lights a lot." (typical response from 28/56 students)

Having acquired the prerequisite knowledge, students are then involved in a conflict situation, in which they are asked to predict the duration of lighting in two circuits. One circuit includes one battery and one bulb and the other circuit includes one battery connected in series with two bulbs. This experiment is counter-intuitive because results cannot be predicted nor can it be interpreted in terms of students' causality. If students had been asked to compare the brightness of the bulbs, the result could have easily been predicted. With regard to duration, one bulb has a constant capacity to receive current, two bulbs are predicted to have double capacity and, hence, they will go out earlier. Taking into account the diminished brightness, students' predictions might go as far as to suggest the equal duration of lighting in the two circuits as classroom data have shown.
.S: "... (this result) cannot be explained. Normally, the other battery should finish first (the one connected to two bulbs), or, at least, they should finish simultaneously".



All bulbs, batteries and wires in both figures are similar.

Battery 2 will wear out together, earlier or later than Battery 1?

Justify.

Figure 3.

The above experiment satisfies the following criteria. First, it is meaningful for the students since it is based on questions arising from the source-consumer model. Second, experimental results are recognised as challenging because they are not consonant with students' causal reasoning according to which two bulbs should consume more, hence lighting should continue for less time. We argue that the extension of the experimental field in the teaching sequence to include duration of lighting i.e. evolutionary tasks, made it possible to change one conventional experiment into a recognisable counter-intuitive one (Koumaras et.al).

An integral part of the strategy is the presentation, concurrent with the dissatisfaction created in the students, of a resolution provided by a better alternative explanation for the two functions of the resistor, as a pathway for current and user of energy, in terms of a unifying microscopic mechanism. (The mechanism is simple at this level; electrons are presented as particles moving around and warming up the wires by friction). The construction of the desired knowledge about resistance is further facilitated by the interpretation of previous results and extensive new applications in terms of new knowledge.

6. Some results

A range of techniques, such as semi-structured interviews, classroom recordings and written questionnaires have been applied to monitor students' conceptual evolution during and after teaching. In this section, we briefly present comments based on results from post tests administered to 156 students who were taught the sequence during several years. Some comparisons are also made with results obtained from a large reference sample comprising 313 students who attended the official curriculum (Koumaras et al 1991).

The great majority of the students answered correctly tasks on the closed circuit. Tasks focusing on the value of current in circuits including batteries and bulbs were given to the students. Over half of the students utilised the scientific model of current, discriminating current from energy and accepting current conservation. However, about one-fifth of the subjects still reasoned in terms of the source- consumer model in many tasks and did not differentiate current from energy. The majority of the students answered correctly questions regarding what is the volt, what does the quantity voltage indicates and how is it measured. The correct answers to propositions concerning voltage-current relationship were from half to two- thirds of the students.

Concerning reasoning patterns we may note that about half of the students recognised that a change in one circuit implies changes in all circuit parameters in circuits involving change of resistance values. It worth noting that several of our subjects developed a local view of the electric circuit when they were taught about resistance. Later during teaching, they abandoned local in favour of a systemic view but over one- third kept the instruction originated local view. Similar achievements were obtained in tasks regarding series and parallel connections of batteries and bulbs in which experimental subjects used the taught knowledge instead of causal rules based on the source consumer model, which were used prior of the teaching. All these results were significantly better than the ones obtained in the reference sample comprising students attending the lower and the upper secondary school in Greece. For example, the majority of upper secondary students demonstrated sequential models after instruction but did not show systemic reasoning.

The experimental results allow for two views to be taken. The pessimistic one takes into account that alternative conceptions appeared to a number of students despite their involvement in an extended specially designed constructivist teaching sequence. Also some of the alternative conceptions were possibly created by the interaction of the teaching with students' knowledge. The cautiously optimistic view takes into account two results. First, considerable progress was made during and after teaching. Second, the results are significantly better if compared with existing practises, at least in Greece, even when compared with upper secondary school students.

7. Concluding remarks

Teachers and researchers are concerned with the teaching of electricity since this topic appears in primary and secondary curricula world wide. Diagnostic research has been fruitful in identifying students' learning difficulties. Research on teaching is based on a constructivist approach and has focused on alternative pathways which may facilitate the construction of scientific knowledge by students. A notable shift of emphasis is that the teaching of electricity attempts to make up for students' difficulties, not simply to present content in appropriate ways.

In our case we decided to extend the experimental field to include not only steady states but evolutionary situations as well; to link electrokinetik and electrostatic phenomena; to develop causal models adapted to students' causal reasoning; to commence conceptual modelling by voltage and energy, introducing these concepts as primary and not relational ones; to present a hierarchy of models capable of answering progressively sophisticated questions and leading to increased levels of understanding. Research results allow for a cautiously optimistic view to be taken regarding the effectiveness of this sequence.

We suggest that traditional representation of knowledge which is content based should change towards a representation of knowledge that is pedagogical valid to be taught in introductory electricity. Such a process, though, may imply a conceptual change on the part of curriculum designers, teacher trainers and teachers in order to materialise and to render instruction in electricity intelligible for their students.

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Section E4, *Teaching Introductory Electricity* from: Connecting Research in Physics Education with Teacher Education

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COMMENTS ON E4: TEACHING INTRODUCTORY ELECTRICITY
(D.Psillos)

Martine Méheut
LDPES, Université Denis Diderot , Paris, France

The papers presented in chapters E3 and E4 bring to light the extent of the work underlying the design of teaching-learning situations. Taking into account the conceptions and reasoning of the students, closely connecting cognitive contents with problematic situations, and referring to scientific knowledge are the broad lines of the design of the sequences described .

Defining the cognitive objectives of the teaching-learning process, both researchers refer to scientific knowledge ; they try to characterize precisely the "distance" between scientific knowledge and the desired students' knowledge. So, in the sequence about electricity by D. Psillos, the choice of models to be taught is discussed with regard to both scientific models (relations between energy, voltage, intensity, resistance, time) and to the students' causal reasoning . In the sequences about the structure of matter, the desired models are defined with regard to students' conceptions and to specific features of scientific particle models (the "elementarity" of particles, the existence of vacuum in particular). One can remark that if the students' linear causal reasoning is taken as a constraint to be respected in defining the knowledge to be taught in the sequence about electricity, one aim of the second sequence concerning the structure of matter is to put students into a position to go further and to bring into play multi-variable reasoning. So students' reasoning is seen in the first case as a support for conceptual development, in the second case as an obstacle to go beyond (Viennot, unpublished)**.**

For both authors, building concepts is seen as a long-term process, bringing into play more and more properties to adequately solve problematic situations ; elaborating questions and choosing the phenomena as objects of these questions are important aspects of elaborating these problematic situations. In the sequence "electricity", the main aims are the differentiation of the concepts of intensity, voltage and energy from an initial global notion "current/ energy" and the development of systemic viewpoints. In the sequences "structure of matter", the main aim is to elaborate more and more efficient particle models (in terms of predictive and unifying power), by addition of new properties (static, then kinetic and dynamic ones) to particles initially defined by a few invariable properties (shape and dimensions).

The epistemological references put into play seem not so different ; both authors consider scientific work as elaborating and using models as cognitive tools. So these projects can be included in a didactic research current which developed in close connection with the epistemology of models (see for example Martinand *et al*. 1992, Méheut *et al*. 1988, Méheut and Chomat 1990, Tiberghien *et al.* 1994, Tiberghien *et al* 1995)**.**

The teaching-learning strategies make use of different "driving forces" : contradiction, analogy, unification. In the sequence D. Psillos presented, cognitive conflict is used for engendering a need for a better explanation ; it plays the part of a driving force for the desired learning process. In the sequences I presented, the justification appears rather a posteriori , as the "winning of a bet", in terms of unifying phenomenologies and increasing predicting capacities. Can these different viewpoints be linked to the concerned fields of physics , to the historical development of concepts in these fields ? Or are they the expression of some differences between the epistemological and psycho-cognitive individual roots of the researchers ?

The methodology of the research project developed by D. Psillos is developed in order to "monitor the conceptual evolution" of the students and to compare the effectiveness of the experimental sequence with the "usual" teaching with respect to the cognitive aims of the teaching-learning process. This methodological viewpoint is put into play also in the research project I presented ; the comparative character is somehow less systematic. Another type of methodology has been developed here, i.e. using the sequence as an experimental device to test hypotheses related to the part played by some problematic situations in the learning-process.

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Biographical sketches

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These brief biographical sketches, furnished by the authors, are arranged in alphabetical order.

Jorge Barojas
Introduction

Jorge Barojas received his Ph.D. in molecular physics at the Universite de Paris in 1970, and has contributed to research in this field and in statistical mechanics. He has taught at the Universidad Nacional Autonoma de Mexico and at the Universidad Autonoma Metropolitana-Iztapalapa. Author of textbooks and articles in physics and physics education, he has also produced literary works (stories and essays). Barojas has been editor of the "Contactos" journal, principal organizer of the International Conference on "Cooperative Networks in Physics Education" in Oaxtepec in 1987, and editor of the proceedings of that conference. He has also been a member and served as Secretary of the International Commission on Physics Education of IUPAP, and has held a Senior Education Fellowship at the American Institute of Physics. In Mexico, his native country, he has served as Director of Education at the National Commission on Energy Efficiency and as consultant for the "Colegio de Ciencias y Humanidades" high school system and for the "UNIVERSUM" museum of Science.

Paul J. Black
Preface, E2 Evaluation and assessment, Comments on E1

Paul J. Black started his career as a physicist with research interests in crystallography using X-ray and gamma-ray scattering. After six years at the Cavendish Laboratory in Cambridge, he spent twenty years in the Physics Department at the University of Birmingham (England). His interests gradually shifted to science education and in 1976 he came to London to be director of the Centre for Science Education at Chelsea College, which merged with King's College London in 1985. He retired in 1995 and is now Professor Emeritus in Science Education at King's. His interests in development and research have been focused mainly in curriculum development and in policy and practice for assessment and testing. He is currently (1998) the chair of the International Commission on Physics Education.

Anna Maria Pessoa de Carvalho
Section D Introduction, D1CComment on D1 D4 Analysis of training programs

Anna Maria Pessoa de Carvalho is Professor of Physics Education at the University of Sao Paulo. After graduating in Nuclear Physics she obtained her Doctorate in Science Education. She teaches pre-service and in-service courses for Physics teachers, and has been involved in physics curriculum development for primary school. Her research interests have been focused mainly on Physics Teacher Education and on curriculum development. She is the Brasilian representative at the Inter-American Council for Conferences on Physics Education and is currently (1998) Secretary of the International Commission on Physics Education.

Jacques Désautels
D3 About the epistomological posture of science teachers

Jacques Désautels is a tenured professor in the Faculty of Education of the University of Laval, and a member of the research staff at CIRADE, the Interdisciplinary Center for Research on Learning and Development in Education at the University of Québec, Montréal. He is concerned with the didactic and ideological aspects of science teaching. He is the author or co-author of many publications on the subject, among which is the book written in collaboration with Marie Larochelle "Qu'est-ce que le savoir scientifique? Points de vue d'adolescents et d'adolescentes" (Presses de l'Université Laval, 1989). Recently he has co-authored a chapter on student epistemology for the International Handbook of Science Education, edited by B. J. Fraser and K. Tobin (Kluwer, 1998).

Rosalind H. Driver (1941-1997).
C5 Teaching for conceptual change: a review of strategies

Rosalind H. Driver was educated at Nottingham High School for Girls and the University of Manchester. She taught for several years before going to the University of Illinois where she received her Ph.D in 1973 on the representation of conceptual frameworks in young adolescent science students. In 1974 she was appointed as a Lecturer in Physics and Science Education at the University of Leeds, as the senior research fellow (1977) and as Deputy Director (1979-82) of the Assessment of Performance in Science Unit (APU). She was Director of the Children's Learning In Science Project (1982 - 1989) and the Children's Learning In Science Research Group (1990 - 1995). Among her publications: *The Pupil as Scientist? (1983* , Open University Press), *Children's Ideas in Science* (with Andree Tiberghien and Edith Guesne) (1985, Open University Press), and joint author *of Constructing Scientific Knowledge in the Classroom* (Educational Researcher, 1994) and *Young People's Images of Science* (Open University Press, 1996). In 1986 she was appointed to a Readership, and in 1989 appointed as Professor of Science Education at Leeds. In 1995, she became Professor of Science Education at King's College London. She was instrumental in working with science educators in Europe to establish the European Science Education Research Association (ESERA). In 1997 she received the award of the National Association for Research in Science Teaching (NARST) in Chicago for Distinguished Service to Research in Science Education.

Reinders Duit
C2 Learning and understanding key concepts of electricity

Reinders Duit is Professor of Physics Education and a member of the Physics Education Group at the Institute for Science Education (IPN) at the University of Kiel, Germany. He earned his Ph.D. in 1972 investigating long-term changes of students' knowledge structures in the domain of heat phenomena. His main research interest has been difficulties in learning basic science concepts and incorporating constructivist ideas into mainstream secondary school classrooms. His research includes studies on students' learning processes in the domains of electricity, energy, entropy, heat, and, more recently, non-linear dynamics (i.e. chaotic systems, fractals and self-organizing systems).

Marcos F. Elia
D2 Physics teacher's attitudes

Marcos F. Elia, Associate Professor at the University of Rio de Janeiro, graduated from the University of Brasilia, Brasil and his first interests in physics were in the field of Solid State Physics (ESR), during his graduate studies at the Brazilian Center for Physics. Becoming a teacher at the university he gradually got involved with science education, collaborating to create a new laboratory model for the basic physics courses, and produced his doctoral work - at Chelsea College, University of London - on "Evaluation of objectives, assessment and student performance in a University Physics laboratory course". He has been doing development and research in Information Technology in Physics Education, having produced a series of courseware materials, using a constructivist approach, for the secondary level. This work was followed by a systematic research of the effect on learning physics in the school. His main research interests nowadays lie on the effective use of information technologies in education, evaluation and assessment. He is currently involved in the development of a modern undergraduate physics laboratory for a new course of Applied Textile Engineering .

Anthony P. French
B1 The Nature of Physics

Anthony P. French received his bachelor's degree (1942) and his Ph.D. (1948) from Cambridge University. He was on the faculty of Cambridge University from 1948 to 1955, teaching undergraduates and doing research in nuclear physics. From 1955 to 1962 he was at the University of South Carolina. Since 1962 he has been at MIT, working chiefly on undergraduate physics curriculum development. He has published 6 textbooks (4 of them in the MIT Introductory Physics Series). From 1975 to 1981 he served as Chairman of the International Commission on Physics Education, and in 1985-1986 he was President of the American Association of Physics Teachers. He received the Bragg Medal of the Institute of Physics in 1988 and the Oersted Medal and the Phillips Medal from the American Association of Physics Teachers in 1989 and 1993 respectively. He is interested in the history of physics and has edited a centenary volume (1979) about Albert Einstein and co-edited (with Peter Kennedy) another centenary volume (1985) about Niels Bohr. He retired from MIT in 1991 and now holds the rank of Professor Emeritus.

Daniel Gil Perez
D4 Analysis of training programs

Daniel Gil Perez is Professor of Science Education at the University of Valencia (Spain). Our group is interested in overcoming the conceptual reductionism of many researches. We are doing researches on: conceptual learning, practical works, paper and pencil problem-solving, STS interactions, Attitudes towards science and science learning, assessment... We intend to contribute to the displacement of the reception learning paradigm by a model of science learning as an orientated research, it is to say, as a treatment of problematic situations that pupils can identify as worth thinking about. We are also interested in the displacement of the usual teachers' "spontaneous" conceptions (and behaviour and attitudes) about science teaching and learning by a more correct and founded view.

Richard Gunstone
D1 Teacher's attitudes about physics classroom practice

Richard Gunstone is Professor of Science and Technology Education at Monash University. He has undertaken extensive research on learning, teaching and assessment in physics, with particular interests in metacognition and the learning of physics with understanding. Most of this research has been in high school contexts, with some at undergraduate level. Before joining Monash he taught high school physics, science and mathematics for 12 years.

E. Leonard Jossem
Introduction

E. Leonard Jossem received his Ph.D. in Physics from Cornell University in 1950. Joining the faculty of the Department of Physics in The Ohio State University he continued his research in experimental condensed matter physics and was responsible for building the advanced undergraduate physics laboratories in the department. He served as Chairman of the department (1967-80), and became Professor Emeritus in 1989. His activities in physics education include service as Staff Physicist and Executive Secretary of the Commission on College Physics (1963-1965), and as Chairman of the Commission (1966-71). He has served as a member of : the Board of Directors of the Michigan-Ohio Regional Educational Laboratory (1967-69); the U.S. National Advisory Committee on Educations Professions Development (1967-70); the Council of the American Association for the Advancement of Science (1967-70); and the Physics Survey Committee of the National Academy of Sciences/National Research Council (1967-1970). He is a past president of the American Association of Physics Teachers, and continues to serve on several of its committees. The AAPT has awarded him its Oersted Medal and its Phillips Medal. He has served also with the International Commission on Physics Education of the International Union of Pure and Applied Physics both as its Secretary and as its Chairman (1981-1993), and was awarded the Medal of the Commission in 1995. He has been a member of the Committee on the Teaching of Science of the International Council of Scientific Unions, and of the UNESCO-Physics Action Council working Group on University Physics Education.

Martin H. Krieger
B2 The physicist's toolkit

Martin H. Krieger is a professor of planning in the School of Urban Planning and Development at the University of Southern California. His Ph.D. is in Physics (Columbia,1969), and he has taught at Berkeley, Minnesota, the Massachusetts Institute of Technology, and Michigan. He has been a Fellow at the Center for Advanced Study in the Behavioral Sciences and at the National Humanities Center, and has held grants from Exxon Education Foundation, Lilly Endowment, and Russell Sage Foundation. His books include Advice and Planning (Temple, 1981), Marginalism and Discontinuity (Russell Sage Foundation, 1989), Doing Physics: How Physicists Take Hold of the World (Indiana, 1992), Entrepreneurial Vocations: Learning from the Callings of Augustine, Moses, Mothers, Oedipus, Antigone, and Prospero (Scholars Press, 1996), and The Constitutions of Matter: Mathematically Modeling the

Most Everyday of Physical Phenomena (Chicago, 1996).

Marie Larochelle
D3 About the epistomological posture of science teachers

Marie Larochelle is a tenure professor in the Faculty of Education of the University of Laval, and a member of the research staff at CIRADE, the Interdisciplinary Center for Research on Training and Development in Education at the University of Québec, Montréal. She is interested in epistemological problems related to learning of scientific knowledge. She is the author or co-author of many publications on the subject, among which is the book written in collaboration with Jacques Désautels "Autour de l'idée de science. Itinéraires cognitifs d'étudiants et d'étudiantes" (Presses de l'Université Laval & de Boeck-Wesmaël, 1992). She has also coedited the book "Constructivism and Education" published by the Cambridge University Press (1998).

Piet Lijnse
E1 Curriculum Development In Physics Education, Comments on E2

Piet Lijnse is professor of Physics Education at Utrecht University. After having done a Ph.D in molecular physics in 1973, he became a member of the physics education group at Utrecht University, which is now a part of the Utrecht Centre for Science and Mathematics Education. He was involved in several curriculum development projects, among which the PLON-project. Gradually his interest has shifted towards research in physics education, with particular emphasis on how such research may improve teaching practice.

Lillian C. McDermott
C1 Student's conceptions and problem solving in mechanics, Comments on C2

Lillian C. McDermott is a Professor of Physics and director of the Physics Education Group at the University of Washington. She did her undergraduate work at Vassar College and received her Ph.D. in experimental nuclear physics from Columbia University in 1959. She is a Fellow of the American Physical Society and of the American Association for the Advancement of Science. She has been a Councilor of the American Physical Society and a member of the APS Executive Board. In 1981, Dr. McDermott was a recipient of the Distinguished Service Citation of the American Association of Physics Teachers. In 1990, the AAPT recognized her contributions to physics education research with the Robert A. Millikan Lecture Award. Under Prof. McDermott's supervision, the Physics Education Group has for many years been engaged in research on the learning and teaching of physics and in applying the results to the design of curriculum. Graduate students in the group may earn the Ph.D. in physics by doing research in physics education. In addition to the instruction of mainstream physics students, the Physics Education Group conducts special programs for the preparation of prospective and practicing teachers of physics and physical science. The curriculum used in these courses, *Physics by Inquiry* (John Wiley & Sons, Inc.), was especially developed for this purpose by Prof. McDermott and her group. A similar project, *Tutorials in Introductory Physics,* is under way for the introductory calculus-based physics series, and a preliminary edition of this curriculum was recently published by Prentice Hall.

Martine Méheut
E3 Designing learning sequences about pre-quantitative particle models, Comments on E4

Martine Méheut taught physics and chemistry in secondary schools from 1974 to 1990; she did a Ph.D. in physics education (1982). For 1990, she is lecturer at the Teacher Training Institute of Creteil (France). She teaches Thermodynamics and is responsible of vocational dissertations. Her main research interests are the common sense conceptions and the design of teaching-learning situations about physical and chemical transformations of matter and the particle models."

Robin Millar
C4 Student's understanding of the procedures of scientific inquiry, Comments on C3

Robin Millar is Professor of Science Education at the University of York. After graduating in theoretical physics from the University of Cambridge, he moved to Edinburgh to do a Ph.D. in medical physics, before training as a teacher. He then taught physics and general science for eight years in secondary schools in the Edinburgh area, before moving to the University of York in 1982. He teaches on pre-service and in-service courses for science teachers, and has been involved in several major science curriculum development projects, including the Salters' Science project for which he was a member of the management and writing teams. His research interests include pupils' learning in science, the role of practical work in science education, and the public understanding of science.

Dimitris Psillos
E4 Teaching Introductory Electricity, Comments on E3

Dimitris Psillos is Professor of Didactics of Science at the School of Education of the University of Thessaloniki, Section of Technologies, Science and Mathematics Education (TESME). He received his Diploma from the Physics Department of the University of Thessaloniki in 1972, his MEd in 1978, and Ph.D. in Science Education in 1983 from Exeter University, UK. He taught physics and didactics of Physics at the Physics Dept. for eight years and then moved to the School of Education of the University of Thessaloniki. He is involved in pre-service and in-service education of teachers and is responsible for the postgraduate course on Didactics of Science. He has been involved in research and development activities and projects at the local and international level including the Labwork in Science Education project funded by the European Union. His research interests involve modeling of students, conceptual evolution and laboratory practice as well as the design and development of research based teaching sequences. He is the President of the European Science Education Research Association (ESERA) for the period 1995-99.

Christoph von Rhöneck
C2 Learning and understanding key concepts of electricity

Christoph von Rhöneck born 1940, Ph. D. in theoretical physics (1969), since 1971 professor for physics and didactics of physics at the college of education (Paedagogische Hochschule) in Ludwigsburg, Germany. Research interests: students' alternative frameworks and psychological aspects of learning

Susana de Souza Barros
D2 Physics teacher's attitudes

Susana de Souza Barros is Associate Professor of Physics at the Federal University of Rio de Janeiro, Brasil. She graduated in Physics and Mathematics at the University of Buenos Aires. She did research in Cosmic Radiation at the High Altitude Laboratory of Chacaltaya, and high energy physics during her postgraduate studies at Manchester University. During a long period living in the United States, she moved to the study of magnetic properties of paramagnetic crystals at low temperature and started her long and lasting interest with physics education, getting involved with minority students in pre-university programs. Back in Brasil she developed several programs to work with the difficulties students entering the university have in learning physics, a task that took her to research on the role of the laboratory and problem solving approaches. She became involved in the pre-service education of physics teachers, curricular development and in- service courses for high school physics teachers. Her current interests are primarily in how to teach physics (science) for primary teachers and how to develop scientific literacy for the educated citizen, via formal and informal education. The role of the laboratory at high school level is also a primary concern, trying to understand how new technologies can contribute in reaching this objective and also the function of demonstrations and low cost equipment.

Roger Stuewer
B3 History and Physics

Roger Stuewer is professor of the history of science and technology in the School of Physics and Astronomy at the University of Minnesota. He received his Ph.D. in the history of science and physics from the University of Wisconsin in 1968. He has published numerous articles and has written, edited, or co-edited seven books, including The Compton Effect: Turning Point in Physics (1975), Nuclear Physics in Retrospect (1979), and The Michelson Era in American Science (1988). His current area of research is on the history of nuclear physics between the first and second world wars, with particular reference to the various nuclear models that were proposed during that period. He helped organize the APS Forum (then Division) on the History of Physics. His other professional activities have included serving as Secretary of the History of Science Society (1972-78), Member and Chair of the Advisory Committee on the History of Physics of the AIP (1978-93), Co-Chair of an international Commission on the History of Modern Physics (1993-present), Chair of the History and Philosophy of Science Section of the AAAS (1993-94),

Andrée Tiberghien
Introduction

Andrée Tiberghien is Director of Research in the National Center of Scientific Research (CNRS). She obtained her Ph.D. in condensed matter physics from the University of Paris 6 in 1972. She is currently Head of the COAST Research group (COmmunication et Apprentissage des Savoirs Scientifiques et Techniques) of the GRIC laboratory; Member of the "Scientific Committee" of the National Institute of Pedagogical Research (INRP), and chair of the Scientific and Pedagogical committee of the University Institute of Teachers Training (IUFM). She is in charge of the physics science option of the "Formation Doctorale : Didactiques des Disciplines Scientifiques" (Université Lyon 1 et Grenoble 1) ". She has been a Member and Vice-Chair of the International Commission of Physics Education (ICPE) of the International Union of Pure and Applied Physics (IUPAP). Her research is focused on the relations between the students' evolution of knowledge during learning in the physics domain and the conditions of learning and, more specifically, the content and the way in which the taught knowledge is introduced. Her approach requires taking into account the meaning of the concepts involved.

Laurence Viennot
Section C Introduction, Comments on C1, C3 Experimental facts and ways of reasoning in thermodynamics: learners' common approach
Laurence Viennot after five years of research in astrophysics, moved to didactics of physics in 1971. Now a professor at University Denis Diderot (Paris 7), she teaches "pure" physics and didactics of physics. Here research is more specifically focused on students' and teachers' reasoning in physics. She is responsible for the "Laboratoire de Didactique de la Physique dans l'Enseignement Supérieur" in Paris, and as been for five years (1990-1995) a member of the French National Curriculum Council.

Richard White
Section D Introduction, D1 Teacher's attitudes about physics classroom practice, Comments on D2,D3,D4
Richard White is professor of Psychology in Education and Dean of the Faculty of Education at Monash University. His many journal articles and his books - especially Learning Science, The Content of Science (with Peter Fensham and Richard Gunstone) and Probing Understanding (with Richard Gunstone) - address how teaching and assessment can be arranged to foster understanding. Sailing, cycling, painting, reading, computer games and growing Australian plants keep his mind fresh for work.

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