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Toward Preparing Students for Change: A Critical Discussion of the Contribution of the History of Physics in Physics Teaching*

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ABSTRACT: In this paper I place physics teaching, and the inclusion of the history of physics into teaching, within a wide context. I start from the conviction that there are considerable changes ahead in the life circumstances of people in western industrial societies. This expectation should influence our aims of education generally, and in particular the aims of physics teaching. The paper does not offer final solutions, but analyses the situation and thereby argues for a change in perspective in physics teaching. The main idea is that physics teaching has to solve the problem of balancing seemingly incompatible needs, for example, conveying a stock of stable, dependable physics knowledge to students, and on the other hand to train them to see their physics knowledge within varying contexts of change. It is argued that the history of physics can be of high value in solving this problem.

1. INTRODUCTION: CHANGES AHEAD – MENACE OR OPPORTUNITY

There is a widespread conviction, which I share, that mankind will undergo considerable changes during the next decades, changes that may even amount to different types of crises. The vast scientific and technological system, which is behind the changes of these past hundred years, is a self-evolving system, which means, it is continually creating new conditions which force it to go on. Karl Marx made the most influential attempt to conceive of this system in a quasi-scientific way, that is, he tried to find the 'equations of motion' of the system of society. It is a pity that not even Rosa Luxemburg's amendments could help. If there are such equations at all, they are of the non-holonomous type. It is a type of motion analogous to the movement of a snowball where we cannot forecast with precision which course it will take. Modern thermodynamics has worked out laws of this sort and described developments governed by them. Of course, history is much more intricate than these thermodynamic systems. All we know points to the conclusion that this scientific-technological system cannot stop, nor can be stopped, though we cannot exclude the possibility that stationary periods may prevail for some time.

I proceed according to the following scheme: First, I analyse types or fields of change ahead in a general way. Second, I take physics as a model. I then try to sketch possible moves for preparing for change and discuss them in relation to physics teaching and the types of change. In this connection I try to come to some conclusions concerning the role of the history of physics in this whole business.

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2. FIELDS OF CHANGE

First I should like to give an overview of the fields of change with which students may be faced.

1. Most conspicuous has been and presumably will be *technological change* together with a change in the material environment. Of course, changes of this sort cannot be looked at in isolation. Many changes in society and in the way of living of individuals will ensue, for instance working conditions including working time. There are models of changes of this sort in the past which I do not need to discuss here, and we are amidst a major change of this type called 'revolution in microlectronics'.[1] Technologists, sociologists, and more and more also educationalists try to analyse the consequences of this revolution. Next to the developments in nuclear physics, electronics is the field where one can see the narrow connection between developments in physics, technological innovation on an industrial level, and consequences for the life of the whole population. Thus a mere teaching of the alphabet of information theory and digital coding, perhaps an introduction to some program language, will not be sufficient educationally.

Present-day technological progress is accompanied by a growing consciousness of destructive side-effects in the material environment. This has been discussed time and again during the last decade. What seems to me more important are the side-effects in what may be called the cognitive, or mental, environment. Computerization, constructing of robots etc. will not only change our material environment demanding new adjustments of living, it also will change our cognitive environment. The computer is going to be the main paradigm of our time, just as the mechanical clock has been in the 18th century.[2] Thinking in terms of computer processes invades thinking about nearly everything and thus confronts us with the serious question about what is truely human. Computers may become more intelligent than human beings, may gain greater learning capacity, finer motor skills, more rapid decision making power, etc. What is man's distinctive quality? I do not feel it my duty to give an answer to this question.

One thing should be clear from what has been said: Concerning our physics teaching it will not be enough to think about how to teach the principles of solid state physics and/or of information theory. We may see from the example of microelectronics one of the reasons for historical and philosophical reflection in science teaching: There is a rapidly rising gap between highly specialized physics knowledge on the one hand, and enormous consequences for the life of men which are only very vaguely known. Under these circumstances, does it suffice to find didactic means to teach 'localized' or 'unlocalized' carriers of charge in different types of solids, or to render understandable the Josephson or Gunn effect, and so on? We have to do that, of course. But we cannot be satisfied by that alone. And there is another question in this connection: Of what help can the history of physics, or science generally, be in fields seemingly unprecedented in history? In a way it is rather trivial that case histories, for example, can enhance our understanding of physics, as a method, as an institution, as a human enterprise, and also as a body of results.[3] But so far we lack an analysis of how historical studies may enhance our understanding of the challenges by the changes we are faced with in the near future.

2. The second type of change to be discussed is much more difficult to evaluate, I mean *scientific change*. In a way at least physicists got used to changes of this type, having seen two 'revolutions' in physics during this century. Though it may be unavoidable to overestimate the stability of the running research results as a going concern of the researcher, there is, nevertheless, a widespread general conviction among physicists that there is always the possibility of a radical change of outlook.

Scientific changes may mean rather different things: Research results in a narrow sense (results of measuring), instruments and apparatus, conceptual schemes (theories), and philosophical frames. It is a standard topic of discussions with left-wing analysts in what way progress in physics can be called 'neutral'. Special results, apparatus and instruments, are looked upon with suspicion. Nuclear weapons are a much discussed example. But even applications in medical treatments are beginning to be looked upon as ambiguous.

Concerning special theories, or conceptual schemes, the most likely prediction is that the gap between understanding in common life situations and scientific understandings will be widened. Mass media will transmit simplified versions of striking new theories, which the lay public cannot judge according to scientific standards. There is a growing consensus by research results (see, e.g., Resnick 1983) in USA, England, France, Italy, Germany and others, that the educated populations do not master the ideas of classical physics. They misunderstand the concept of force, of energy, of gravitation, of current, of voltage, etc. Insofar as a mastering of the conceptual schemes of classical physics is seen as a prerequisite of understanding new theoretical developments: What are our reasons to believe that our physics teaching is contributing to preparing students for change, even in the very narrow sense of following new developments in physics?

Concerning methods and philosophical frames, we may point to the habit of scientists, and a very successful one, to isolate variables and effects, and then using items of specialized knowledge by adding up, which has led them to being blind to holostic aspects. In combination with the technological advances discussed in the foregoing section the net effect of the philosophical frame of science may be boosting a 'message' always connected with science, the message that what we call man is a mere anthropomorphism (Spaemann 1980).

3. So far we have discussed changes in what may be termed material and mental environments. We touched upon changes in the *political* and

societal environment, too, for example, the widening gap between the rich and the poor nations. It must be sufficient here to offer some general commentaries. I myself do not hold, as many educationalists have done in the last decade, that society is the ultimate reason of everything happening to us. It is true that developments in society do influence thinking and doing in science in quite unexpected ways. But the converse is equally true.[4]

Some changes in the political organization can be extrapolated from processes we are observing just now. One example may be termed the end of politics. By politics I mean a set of general aims guiding decisions, aims like free market, free enterprise, or investment planning etc. This is so because governments are faced with an ever growing mass of decisions requiring highly specialized knowledge. General aims will no longer do, because the terms in the aims no longer possess a precise meaning apart from intimate and specialized knowledge. Governments first reacted by founding more and more conmittees, advisory boards and so on, and not only governments, but parliaments, too. This development has recently taken on a new direction in that the political decisions are openly taken on by informal small groups.[5]

4. Changes in the *individual sphere* are strongly tied up with changes in society. Sociologists and psychologists try to find out how changes in society correspond to changes in the family structure, with many consequences for child rearing, the kind of socialization and individuation of the child.[6] One of the most common experiences a child has in western industrial societies is the rapidity of changes, the high value of newness, and the laughter at outdated products. These experiences are not restricted to the material sphere. And this generalization is reinforced by school teaching in many subjects. Not even the mathematics children learn is well understood by their parents, and vice versa. Two consequences may be observed. First, children do not develop confidence in their material, social, and even cognitive environment. They simply wait what comes next. Of course, they have an enormous need for stability and confidence, and this may equally well be projected upon the heroes of comic strips as on scientists, and it is therefore difficult to convey a balanced view of science to them. Science is either seen to be the guarantee of stability, of what can be depended upon, or it is seen as changing and thus does not reward serious study.

Second, children, and subsequently adults, lack what may be called cultural continuity. Mathematics and physics have been school subjects contributing strongly to this cultural continuity. They made easy communication between generations possible, at least in these fields. The last two decades, roughly speaking, have seen many attempts at 'modernization', restructuring, or what else, of physics as a school subject. Of course, changes of this sort take place also in university teaching, and the whole curriculum reform has, in fact, begun there. It would be stupid to deny teachers attempts at modernization. But they should take into account the price to be paid. And I think it did not happen by mere chance that the interest in the historical approach to physics teaching has been revived during the sixties, the period of a lot of 'completely new' curricula. Whatever may have been the overt reasons for embracing history, there is a deeper meaning in it. It is an attempt to locate physics in a tradition.

It is, of course, a question of debate, whether you best prepare students for change by anchoring them in historical ground, or by cutting them free from all traditions, directing their view solely to the future. My own view is very definite: The future always is the future of some past. It is a continuation, just as our present is understandable only as the future of some past. A conservative historical approach to science teaching may prevent a proper preparation for change. But if 'tradition' is understood as continuation, the historical approach may prove to be the main way to prepare students for change conceptually.

5. I have made comments on some types of change, technological, scientific, political, individual/societal. It would be easy to react if we could unequivocally say what changes are to the better or to the worse. Unfortunately, this is seldom the case. If we could tell, we would be in possession of norms or criteria according to which we could judge. But it is obvious for every observer of the last decades that norms and criteria change and even drastically change, too.

In general, no change is possible without *some* element of stability. Especially no rational decision is possible, if 'anything goes'. Thus, there must be also *some* measure of confidence in the validity and stability of science. This applies also to the agent himself: He has to find some stability amidst change within himself, in his motives, his thinking, his emotions, in short, in his inner and outer environment. I may be allowed to remind you of Kant's analysis of knowledge and of moral actions: There is always some measure of identity, of an ego, which gives unity to the acts. If *all* is changing, there is nothing which changes. Thus we are faced here with the primary example of a balance problem. And it is not only a conceptual problem, but a problem everybody is concerned with in their personal life, and sometimes also in their professional life, as with the educationalist, and especially the physics teacher. They find themselves between forces dragging them in opposite directions. One side demands that they teach: physics knowledge is only tentative, liable to change every minute; physics is wholly a historical affair, arising and fading away with cultural traditions. The other side demands that they teach: physics knowledge is valid, dependable, stable, the best knowledge mankind has got so far; it has been overwhelmingly successful, in constructing bridges, airplanes, rockets, nuclear power plants, and so on; and there is not the slightest reason to surmise that things will change in this respect. Without any historical and philosophical background in their training, most physics teachers resolve this dialectical situation by stressing stability and validity. Even if we feel that this could be an antidote to the going anti-rationalism and anarchism *à la mode*, we are reasonably sure that also in physics major changes are ahead. Thus the antidote may well turn out to be a disappointment, for students as well as for teachers. We are now approaching physics more directly, moving in the centre of the theme, coming from a more general environment.

3. PHYSICS AS A MODEL

Having discussed fields of change generally, I shall try to show in this section, that physics can be looked upon as a model with respect to the dialectical relation between change and stability. I do not try to avoid some overlap with the foregoing sections and some repetition of statements. In fact, this seems to me necessary in order to stress important points. This character of a model may be seen in two respects: Physics as a model of problems, and physics as a model of solutions.

Physics as a Model of Problems

1. That physics is a model of revolutionary change scarceley needs mentioning. Since Thomas Kuhn's well-known book there is to be observed a widespread discussion of scientific revolutions. Now, the first book I read on this topic is Ernst Zimmer's *The Revolution in Physics* (in German: *Umsturz im Weltbild der Physik*, which is more precise). It first appeared in Germany 1934 with a foreword by Max Planck. It is still on my bookshelf. (An English translation first appeared in 1936). Of course, talks of revolutionary changes in science go far back into the past. In fact, physics itself has always been felt to be the result of a revolution of 'modes of thought', to use Kant's phrasing. And only since the first half of this century we have learned about continuity with scholastic modes of thought.

This aspect concerns the intellectual side, the modes of thought or frames of mind, corresponding to the 'physical world picture' (Müller 1974). It may suffice to mention a few elements of this substantive picture, in contradistinction to the methodological elements. One very important categorial change is the change from substance to process, discussed under various disguises by so different men as Whitehead, Toulmin, Prigogine and the physicist F. Bopp of Munich.[7] The mass points of classical mechanics may be looked upon as the final echo of Greek unchanging and indestructible being. The change from substance to process also changed the conception of identity. I only need to mention the Pauli Principle and nonclassical statistics here, in order to make clear that far-reaching conceptual changes are involved. Also in classical physics nobody would have dreamt of creation and annihilation operators and corresponding processes, combined with stochastic indeterminacy. All this is far away from the world picture of classical physics. I shall refrain from discussing the ramifications of modern physical world pictures as found within different schools of thought. Of course, many working physicists do not posses an overt categorial framework, or world picture. But most physicists, getting older, like to embed their physics within a wider context, which is, I think quite natural.

In recent discussions of quark theories a new paradigm change is seriously considered. It may be termed the end of the paradigm of atomism. V.F.Weisskopf (1980, p. 158) once discussed it in general terms: by smashing an object into fragments and synthesize it again from these fragments you come to know, under certain criteria which I will not discuss here, of what the object consists and what are the laws of coherence or forces. Now it may well be that this part-whole-scheme, which served so well during two centuries, does no longer function within the range of elementary particles. Some physicists speculate that the ultimate basis of physics will turn out to be gauge fields with certain symmetries, though nobody knows why nature should prefer these symmetries.[8] Be that as it may, my aim here simply is to point to fundamental changes in physics that have taken place already, and to possibilities of fundamental changes ahead. Such changes have always been judged to be beneficial in the end. But especially in this century we observe unsettled conflicts between different world pictures even in physics.

2. There are other changes no less important than the substantive changes indicated just now. We may call them changes in *methodological conceptions*.[9]

First, we observe changes in the way experiment and theory are seen to be connected. Of course, this also is no new process. From the Greek beginnings of science we notice opposing conceptions such as rationalism, deductivism, inductivism and similar conceptions. Different conceptions concerning the significance of theory are as old as Greek astronomy, which gave birth to the still living idea of a theory as a fiction whose sole function is to save the phenomena (Duhem 1969; Hanson 1973). Today, with the experience of quantum theory and quantum field theory in mind, there is in fact some trend in the Feyerabend direction of 'anything goes', though he as usual overstates the case. What many physicists believe in, and allege to practice, is free symbolic experimentation. There are no apriori limits to theory construction, it is in no way deduced or derived from experimental facts. Axioms or principles are changed at will and experimentally, and you see what happens. Of course, if you scrutinize examples, you will find that this methodological conception is more of a fiction than of a fact: The symbolic experimentation is always done with some experimental effects, anomalies and similar elements in mind.[10] But it seems to me true that since the turn of the century, after the quantum shock, physicists have decidely lowered their claims as to the significance of theories. In order to bypass vexing philosophical questions, they resort to a conception of theory as a symbolic or syntactic machine. This is in line with the overall technological, intrumentalist *Zeitgeist*. But we find many younger students, even future physicists, who are disappointed by getting merely equations as answers to their quest for understanding.

This leads us to the second point, which is the growing complexity of physics as an accumulating science. There are different aspects, the one that I shall discuss may be termed: from double-layered to three (or more) – layered physics. The term 'double-layered science' is borrowed from St. Körner's discussion of categorial frameworks (Körner 1972). What he means is not new, namely that in physics – as in other sciences – there are two layers. First the fundamental layer using common language and referring to the common world of perception. It is true that even a description of an experimental effect is normally shot through and through with interpretation. But in classical physics the physicist can always resort to phenomena and descriptions which he shares with everybody, even with the man without any knowledge of physics. We all make use of this in elementary teaching. Second, upon this layer is constructed a lot of theories which in some way refer to this basic layer. I scarcely need to mention the well-known classical examples of these types of theories.

The development of experimentation and theory construction has led to a much more complicated situation. On one end we have highly abstract mathematical structures which cannot be interpreted in terms of commonly understandable entities. Everybody could for example easily understand what was meant by a particle in classical kinetic theory, but this is no longer the case with virtual photons. On the other end, the side of experimentation, we find a situation which is best described by J.Ziman speaking of accelerator experiments: 'The Gargatuan scale of such an instrument has two consequences for scientific epistemology. In the first place, the physical complexity of the apparatus . . . demands elaborate rationality of design . . . . The results of the experiment are irretrievably embedded in the design theory of the system and all its parts, whose correct working must be taken for granted as the controlled background of the observation. In the end, we cannot say wether the data are derived primarily from the 'external world' or from the theories they are supposed to be validating or falsifying' (Ziman 1978, p. 62). In other words: We do no longer know if we observe erratic properties of the instruments or independent phenomena of nature. This ambiguity has always haunted physics since the advent of quantum mechanics. Thus we are far away from the simple scheme of a double-layered science. It is no longer possible to integrate experiment into common sense, with theory referring to it.

3. What has been said means that in the most advanced parts of physics the bonds between 'reality', the world everybody is living in, and physics gets more and more loosened (Ziman 1978, p. 63). This is enhanced by one of the most influential changes in the philosophy of science, the elimination of the concept of truth, or of approximation to truth, by adopting what H. Putnam (1973) has called 'truth surrogates'. Instrumentalism and pragmatism, still the most influential methodological doctrines

with scientists, substitute fruitfulness, predictive power and so on for truth. All that matters is that a theory 'works'. I do not want to discuss this widespread opinion epistemologically.[11] I only try to point to the consequences for teaching physics: Many young people feel that it is not worthwhile to take the trouble of learning theories that are no more than machines for controlling events in nature, or in industry, but do not in any way fulfill their desire to understand. Of course, there will be a long debate about what understanding means (see, e.g., Teller 1982). Here I only wish to describe the ambiguity of this loosening of bonds with reality, which may be seen simply as trivialization: the lofty theories are dissolved into mere technical devices. The revolt against this reduction is quite unavoidable, in fact, we in the midst of it. To my mind, one reason why so many young people, and according to my experience also physicists, embrace political, quasi-religious panaceas, is to be found in the disappointment about science which seems to be dodging every path to truth.[12]

The educational upshot of this discussion is that we are confronted with another balance problem, closely related to the first one already mentioned. It is the balance between truth and mere technical functioning. On the one hand we feel relieved by being allowed to tell students that of course physics does not spell out eternal truths; on the other hand we are thereby in danger of losing many students by overstating our case, by trivializing physics as a mere technical device.

4. I should like to add some remarks about changes in the social and political dimension.

First, what Ziman called the Gargantuan nature of apparatus raises the serious problem of controlling applications. Formerly they could be felt as in reach of human foresight. Now we are beginning to doubt if it is possible to really control the application of physics, which opens such far-reaching possibilities as the destruction of mankind on this earth. A new dimension of responsibility has to be integrated into physics research and development again.

Second the bigness of science, especially of physics which is pioneering here as in other fields, has led to sociological problems of management. Getting the enormous amounts of money needed for modern physics instruments[13] requires adopting the techniques of modern advertising. The attitudes of physicists are subtly changed, traditional norms of scientific behaviour violated. Bigness is becoming a criterion of success. In order to get the money for a huge project you have to beat the competitors, to advertise that you are much better such that you need not even quote their publications. Of course, I am describing tendencies, and there are counter-tendencies. But the rise of physics from the level of manufacture to that of industry inevitably brings with it dangers of this kind. And it would be futile to hold to an idealized picture of physics. Physicists neither discover eternal truths nor do they follow eternal moral rules.

Third, another important development is connected with this growth of number and diversity: Younger physicists are in danger of losing track of the roots of their science. They are trained within highly specialized channels of information, and even the introductory courses tend to be much more abstract and rationalized than a generation ago.[14] It is my experience that future physics teachers do not learn much more about topics of school physics than they already learned at school. In fact, in discussing teaching problems they draw upon their school knowledge, not on what they have learned in their physics course. This may be an extreme case. But given the short time for learning in the university and the necessity of rationalizing the course content according to modern standards, there is danger that the traditional phenomena do not get the attention they deserve. They deserve it, because they are the spots where more abstract knowledge can be anchored to common knowledge. The hurried-up rationalization of modern physical treatments leads either to forgetting these phenomena alltogether, or using them as mere illustrations. It is here that for teaching physics on every level historical elements may be most valuable for widening the view beyond the narrow specialities of the day.

What we are talking about now is continuity. The dialectical relation *between newness and continuity* is the third important balance problem in education just as in physics and society. There are other sociological changes that could be discussed in this context, for example the diversification into special languages, which is only another expression of the diversity of research groups and interests. There are many analogies with developments in other fields of culture, art for instance. Everywhere we can observe a loss of common ground for symbolic meaning. This growing subjectivity is interrelated with the cult of creativeness, so beloved by many educationalists. Creativity in the sense of highly individualized and subjective expression and conceptualization, and of original construction, is certainly to be appreciated. But on the other hand, for your creative expression to be actual you need an audience. Creativeness in order to make sense needs the cultivation of the consensible and the common. This is one aspect of the aforementioned balance problem.

Physics as a Model of Solutions

1. That there is to be kept a balance between change and stability is a topic of physics itself. To search for laws means to search for constant elements, more or less abstract in character. It need not be 'things', it may be forms, or functions, that are constant within change. This search can be seen as the *raison d'être* of physics, and physicists have been very successful in finding them.

Turning to analysts writing about the development of physics we may note that the tendency to stress revolutionary changes can be balanced by a tendency to stress continuity. Thus while Kuhn and many followers seemed to describe a revolution as a sort of quantum jump without proper rationality, there are others that come to the conclusions that there is continuity in the themes and basic concepts. Strauss, for example, has discussed the major revolutions in physical theory such as those of Copernicus, Newton, Maxwell, Einstein's Special Theory, his General Theory, Quantum Mechanics and Quantum Field Theory, and he concludes, that 'the evolution of physical theory is a complicated dialectical process in which both innovation and conservation play equally important roles. Hence, to speak of a 'paradigm change' is both superficial and misleading: where the explications of that model are true (in the sense of a zeroth approximation) they are trivial, and where they are non-trivial they are wrong' (Strauss 1977, p. 46). It would be of no use to discuss the details of his arguments. What is important is to point to the fact that it is a matter of perspective if you see a revolution, or a modification embedded into an encompassing continuity. Also Holton (1975) has described certain overall themes recurring again and again in the development of physics.

Discontinuity has come up in another disguise, as a form of incommensurability.[15] The contention of Feyerabend that fundamental theory change makes for incommensurability of concepts and statements has been much debated. Many felt that it was an assault against the tradition of rationality which is the basis of Western Culture. And I think it was meant as such. Apart from epistemological and philosophical discussion, there has also been at least one detailed physical argument showing that so-called incommensurable theories such as Newtonian Mechanics and the Special Theory of Relativity have common ground enough such that rational decision between them is still possible (Angel 1980).

But to be quite specific here: To my mind the question is not whether besides changes also constancies can be found in physics. My point is that changes only make sense if seen within a wider context of continuity.[16] N.R. Hanson once remarked, and I fully agree, that there can be no completely novel explanation because it would be incomprehensible (Hanson 1961, p. 54). Similarly, there can be no complete conceptual change, no completely new theory.

2. Concerning the widening gap between physical theory and everyday life we may note astonishing recurrences. I restrict myself to two examples. First, Quantum Theory, or to be more precise one categorial frame behind the theory, has unknowingly revived the Aristotelian doctrine of the undecidedness of future contingents (Aristotle, *Hermeneutics* 18a19b) which has always been basically a common sense doctrine. It has also revived more refined conceptual schemes of the Aristotelian tradition such as the act-potency scheme and the conception of dispositional states (Heisenberg 1959; Strauss 1977; Müller 1974). Second, particle physics as seen by Ziman (1978, p. 156): 'Modern particle physics is delightfully anthropomorphic: look at the 'life story' of the 'strange particle' in a bubble-chamber photograph . . . . To understand the 'annihilation' and 'creation' of particles it is as necessary to have read fairy tales and murder mysteries as text-books of analytical mechanics'. It is the same author from whose

book I have already quoted skeptical remarks concerning modern high energy particle physics. The unity of opposites could scarcely be better exemplified.

There is a widespread tendency among physicists to take account of the relation between physics and everyday life, and to turn away from mere mathematical formalism back to types of theory which give understanding and insight.[17]

3. Concerning the question of truth we may also note countertendencies. As H. Putnam has remarked the physicist actually behaves in accordance with the truth concept; this can be seen because truth surrogates possess different formal properties compared with truth (Putnam 1973, p. 214f.). Quine (1960, p. 24f.), after discussing truth claims asks himself the skeptical question: 'Have we now so far lowered our sights as to settle for a relativistic doctrine of truth – rating the statements of each theory as true for that theory . . . ?' His answer deserves to be repeated for its precision and shortness: 'Not so . . . . Within our own evolving doctrine, we can judge truth as earnestly and absolutly as can be; subject to correction, but that goes without saying.'[18]

Physics itself has developed schemes that can be used as an analogue model for the solution of the relation between stability and change. I mean the global and the local aspects of the spacetime-manifold: *Locally* we can always treat it as Euclidian, and in fact we have to do so. But *globally* this is not possible. In that same manner we have to look upon our physics as locally true and invariant while it may change globally. We simply do not know if there is some law governing the structure of our evolving physics just as the structure of space-time. But it would be rash to allege that this is impossible. Put within von Neurath's well-known analogy with the mariner that has to rebuild his ship on the open sea, we may say: He may, by rebuilding plank by plank, arrive at a sort of ship we cannot foresee, but he will always rebuild a ship.

4. Now we have to come to a very important point: What is it that can be looked upon as invariant locally? There is a broad spectrum between hard experimental facts, doubtful experimental effects, doubtful theories and hard theories.

Concerning experimental facts one recalls what R.W. Pohl wrote in his *Elektrizitätslehre* (1947, p. 283): 'Theories come and go, experimental facts stand.' Now, today nobody would subscribe to that bold statement without qualification, especially concerning highly sophisticated experiments of industrialized physics. On the other hand there are hundreds of experimental effects which have a long standing. Whoever, for instances, doubts the validity of the inverse square law of gravitation, within certain limits – but 'that goes without saying' –, may raise his hand, 'paper doubt' (C.S. Peirce) is not allowed.[19]

To my mind Pohl's general direction is sound: Conceptual tools and theories tend to be more variable, more liable to change, than do experimental effects, once they are established and have become canonical.

Later theory may make for correcting overgeneralization, even correcting decimals, and these corrections may be important for theoretical reasons. But this does not detract from the fact that there is a field with impressive stability. Look, for instance, at the following introduction of electricity at the beginning of Maxwell's Treatise: 'Let a piece of glass and a piece of resin . . . be rubbed together . . . let them be separated. They will now attract each other. If a second piece of glass be rubbed with a second piece of resin, and if the pieces be then separated and suspended in the neighborhood of the former pieces of glass and resin, it may be observed –
1. That the two pieces of glass repel each other.
2. That each piece of glass attracts each piece of resin.
3. That the two pieces of resin repel each other.
These phenomena of attraction and repulsion are called Electrical phenomena, and the bodies which exhibit them are said to be electrified, or to be charged with electricity.'[20]

This may seem a very primitive piece of physics. But it *is* very stable, and with minor modifications it is the basis of teaching introductory electricity even today. It is also an admirable example of what Goethe (1963, p. 179f.) called, in a rather unknown paper titled 'Experience and Science', the production of a 'pure phenomenon'. At the same time it is an example of the common sense layer in the many-layered structure of physics. Everybody is able to understand and to identify the phenomena who has learned the common language. One needs no special physics knowledge, but some working acquaintance with materials such as glass and resin, just as you must have some acquaintance with bread and butter in order to live in the common world. We have every reason to look upon our ability for pattern recognition (Ziman 1978, chpt. 3.2) and even colour recognition (Rosch 1976), which lie at the basis of such phenomena, as a locally very stable basis of our physics.

Concerning theory we should, I think, agree with N.Koertge (1973, p. 177) who wrote in her essay 'Theory Change in Science' that 'there have been long periods of theoretical stability . . .' But, of course, nobody would deny that small and important changes did and do occur in theory construction in physics. In fact, the prime element of change in physics must be seen in the range of theory and conceptual schemes. For the only change in the set of estabilished effects is addition. What is substantially new comes from interpretation. For example a new effect is or is not compatible with current theory, and eventually new conceptual schemes arise from difficulties of interpretation, or at least conceptual revisions of estabilished theories are felt to be necessary. And these new conceptual elements also concern the old estabilished effects.

5. Concerning sociological and political changes we may note countertendencies, too.

First, discussions about social consequences get more and more part of the informal scientific discussions. More and more physicists make known their opinions and arguments concerning important social and political decisions, speaking from the background of their physics knowledge.[21] This *is* a very delicate development. It would be dangerous not to see the perils. But a discussion of this issue would lead us away from our main interest here. In fact, I would not dare to speak in this respect of physics as a model. We may discern a tendency to more rational decision making also in science, by widening the area of what has to be considered before making a decision referring to research, or investments, etc. An example is the Weinberg criteria for scientific choice. We are, however, in this respect far from a widely acknowledged process of self-organization within the scientific community.

Second, though physics as an institution has become that more numerous and diversified, it is still a good model of 'societal learning' (Botkin *et al.*, 1979). No solution in physics is just personal. It is accepted only by the consensus of the relevant scientific community. There exist very effective information channels such that this societal learning is a rather rapid process in most cases. I may add that in physics even the problem description and reformulation is a process of societal learning. It is quite obvious that a study of such learning processes requires the study of historical cases, though, perhaps, cases from recent history. And it is equally obvious that in order to learn something transferable to other fields by such studies, we have to set studies of this sort within the proper perspective. As far as I can see, there is no consensus at all concerning the possibility of transfer. One aspect we should not forget is a difference in urgency: in physics you can wait till a solution is worked out. In social and political issues you cannot. From this must result differences in the type of societal learning, which is an important topic for further discussion.

Third, though problems of secrecy and the misuse of competition are notable, physics is still a model of international cooperation. This scarcely needs mentioning. It would be important to know more about the reasons that make cooperation in the field of science easy, and why this seems to be different in other areas. One point is the allegiance to a group with a common interest. But this is part of the problem, because interests are mostly defined by groups, and everybody belongs to many different groups, national, ethnic, religious, commercial, etc. groupings. This does lead to interest conflict, even in science. The only remedy I can see is stressing much more than usual that common interest makes for success in physics, and then pointing to common interests in other fields.

Having in mind the essential connection between interest and grouping, it would be futile to point to the interests of 'mankind' or some other too vast grouping. Thus what we should foster is the foundation of groups that cut across the frontiers of traditional allegiances, groups, however, that remain tangible. Examples of interests which are to be felt and accepted as common beyond traditional groupings are: preventing ecological deterioration, human deprivation, preventing arms races, to quote only a few. There are already beginnings in this direction.

Fourth, there is a very difficult last point I should like to discuss. In fact, it is another member of the family of balance problems. I mean the balance between the freedom of fundamental research following its purely internal dynamics, and the pressure for externally directed research. So far the position of physics has been that fundamental research accumulates a stock of knowledge which turns out to be useful in quite unexpected ways. Many cases could be cited giving evidence to this process. History teaches that often it is futile to directly attack a problem. A solution comes from an unsuspected corner. This is what problem solving psychology may teach us, too. There is an interesting commentary on this point in a recently discovered radio speech by M. Planck (Herneck 1976), in full agreement with what Whitehead (1949) has said long ago, 'Success in practice depends on theorists who, led by other motives of exploration, have been there before, and by some good chance have hit upon the relevant ideas.' (p. 107). I think that physics as an institution has solved this balance problem rather effectively by uniting fundamental and applied physics within one organism, although there may be some bias toward fundamental research which is to corrected: Still there is a widespread feeling of superiority of fundamental research which is mistaken. But it would be equally mistaken to set science the task of solving the urgent world problems by direct attack. It may well be that in these areas the solutions will come from quite unexpected corners, too. In fact, the corners may be well equipped already, only there must be some men that envision the relations. Setting more scientists on this task may indeed be a present need. We have to shift the traditional balance here.

4. PHYSICS TEACHING AND PREPARING FOR CHANGE

Moves for Preparation

In what way can we transport these positive aspects of physics into our physics teaching, thus helping prepare our students to cope with a changing world? Let us begin by asking, what are our possibilities generally. As far as I can see there are three types of 'moves' to be considered in this connection. It is not so much the moves themselves that make for the typology, but the overall stand against change generally that makes the difference.

First, we have those that think in terms of laws which regulate changes. They hope in the classical fashion known from physics that they are able to manage the initial conditions to their own favour. Roughly I find three moves under this type:

1. Try as far as possible to determine the nature of the change and the consequences it may lead to.
2. Try to pre-think and train specific and favourable reactions.
3. Try to find out as far as possible favourable opportunities and find conditions which will strengthen these against unfavourable ones.

We may call this type for the reasons indicated 'classical'. There is one idea which recommends it for educational and also political reasons: Fear is best controlled by removing uncertainty – if what is revealed is not too nasty in itself. These moves presuppose that certain types of change are highly probable, or even inevitable, and that you have to adjust within the possibilities open by the laws and your ability to select favourable conditions.

A second type is well known from political history. The overall reaction behind the moves is opposition to change in principle. Thus we have the conservative move:

4. Oppose change, even try to prevent it completely. A moderate variant would be:
5. Try to balance change by fostering opposing change; strengthen damping factors, and so on.

We come to the last and most difficult type which may be termed 'indeterministic'. Under this type there are two main cases. First, we may be convinced that changes are determined, but think it impossible to know the precise nature of the change. Second, we may believe that there is no well determined path of change ahead. In the first case you still have a choice between two subcases, first, to believing in the possibility of enumerating all possible changes, second, to hold this to be impossible. In the first subcase the proper move would be:

6. Try to enumerate all possible changes and construct alternative favourable reactions.

This is what chess-players sometimes try to do, and, with still less success, military planers.[22] It would be of no use to discuss every possibility covered by the second subcase. Thus I mention only the most interesting one: that we are convinced of determinate changes ahead, but are neither able to precisely know them nor to enumerate all possibilities. I think this is the situation as many see it now – what would be the appropriate move? I think the following move, roughly stated, should do:

7. Train for flexibility, strengthen and cultivate your fundamental resources.

This is what many enterprises do in awaiting uncertain changes in the market: They strengthen capital stock and will not invest in specialized equipment.

In the other case mentioned there also is a move similar to industrial politics:

8. Try to give development a new direction by offering a completely new construction, which means, try to shape the change by yourself.

Maybe I did not hit upon all possible moves, but I hope I have got the most relevant ones. It is also true that the gross typology of classical, conservative, and indeterministic moves is not a classification in the exact sense. There is considerable overlap and there are borderline cases. But this does not concern me now.[23] I should like to add only one more remark. In this computer age we may be inclined to think of the moves as worked out by a computer. We may also think in terms of probabilities and draw upon game theory. Now, game theory clearly is not applicable, because history is unique and there is no repetition such that you do not know what will be the case 'in the long run'. Concerning computers, the tendency to consider them able to work wonders may be one of the changes ahead that we have to face with some reserve. Apart from the common sense of reasonable men, the reign of computers would have led, for example, to atomic strikes many times, if I am not mistaken. There is some truth in the idea that our mental just as our moral furniture has not been adjusted by evolution to situations we are beginning to be confronted with. But still less is the computer. It is an admirable instrument. But all depends upon how we are putting it to use with our native wits.

Physics Teaching – the Proper Perspective

It is impossible to reproduce in this article all that has been said concerning the aims of physics teaching. I only want to indicate the proper perspective.

First, there is no doubt that modern men should learn modern physics. The reasons cover a wide range, from the necessity of orientation of the individual to the necessity of the society to foster interest enough such that the imminent problems can be handled in a controlled, scientific way and not by a modern sort of witchcraft. This last remark is quite essential not only for the common man but also for the future of physics itself. What I mean is physics, and not the individual physicist. There will and must be always people that are totally absorbed in their specialities. But there must be a growing number of physicists that also are interested in the wider social context of physics, that draw discussions of consequences into the scientific discussion itself. Physics as an institution must become conscious of the fact that it is not an affair of the ivory tower, but immensely influences the life of the whole population. Thus, physics teaching does not only possess an individual import, but also a societal one, and one for physics itself. And we even need to go one step further: Physics teaching has importance for the whole system of nature, of the life-fostering ecological interaction between the material world and man.

Science, especially physics, has to be seen as one of the most important mechanisms of the new level which evolution has taken on. The enormous speeding-up of part of the whole system, the man-made technological and scientific subsystem, has rendered too slow the old evolutionary forces of adaption. Either we succeed in making human learning a new agent in this fast moving evolutionary process, or we presumably will experience a reversion into more primitive forms of life. Physics, and science generally, is to be looked upon as one of the most efficient though very specialized ways of learning.

Second, this necessity of physics learning means that it should be solidly founded. This is another addition to the many balance-problems mentioned so far. On the one hand, we must demand a type of physics teaching and learning which takes account of the wider context of the whole social system including the society-nature interface; on the other hand we demand a solid foundation of physics learning, which, given the limited time available, inevitably means a very limited amount of course content, both horizontally and vertically.

Third, this learning about nature, that is, science, is one of the most important factors that are going to promote changes, today and in the future. And personally I have no doubt that it will be urgently needed in order to cope with these changes in a rational way. But, considering the one-sidedness of scientific methodology with its isolating technique which leads to losing sight of holistic effects, we have to see the necessity of some corrections. This conclusion may be corroborated by referring to very interesting psychological experiments by Dörner (1979) showing that even rather intelligent students are unable to handle a lot of variables in an artificial game of 'reigning a town': many ruined the town. They did not learn to take into account the interaction terms between the different variables. And, in fact, also physicists prefer linear approaches in the first place. Thus there are many indications that ecological thinking in a very general sense has to be learned much more than usual so far. This means that we have to look into our physics teaching with a hope to find a solution for the problem of balancing the analytic, superpositional thinking which is trained in elementary physics courses,[24] and the intuitive way of thinking, which seems required by a complex situation. In fact, using intuitive methods in decision making may be the more rational choice, because treating some variables exactly and neglecting others may lead to more disastrous results than taking account of them all in a way which is not easily accessible to analytic reason. Of course, we will not give up claims to rationality of analytic proceedings, but we have to stress the fact that the more simpler procedures, the linear and superpositional ones, are approximations which in complex situations may lead to dangerous errors. While during the last 300 years or so common sense has been controlled by science, now we are becoming aware of the fact that in complicated situations also science has to be controlled by common sense. Of course, it should be well-informed and well-taught common sense.

All this may be summarized in saying that in physics teaching our aim cannot solely be to teach physics, I mean a well-founded, stable, applicable knowledge of phenomena, concepts, theories, methods of physics. By teaching physics we also have to teach a lot *about* physics,[25] in order to set the specialized knowledge into the proper perspective. This has been said many times. And we may ask why we did not succeed in finding efficient solutions. Those of us who have been in the teaching business for a long time have witnessed more than one generation of educationalists preaching pet solutions for all sorts of difficulties. What did we learn from this piece of experienced history if we do not ask for care in case a new cure like history of science is offered? In fact, it is not new, but it is being newly discovered,[26] though the perspective of innovative learning as described in *No Limits to Learning* (1979) is rather new. My reason to skeptically analyse these claims is not that I am against a historical orientation of physics courses. On the contrary. But this renders a critical assessment of the prospects only the more needed.

Now we are left with a lot of questions arising from forming a matrix by crossing the items in different lists: There is the list of types of change, the list of balance problems, including those of the aims and methods of physics teaching. (More dimensions could be added, for example, age-groups of students, ability groupings, regions of the world. For designing concrete measures, all these variables have to be taken account of.) Of course, it would be out of place to treat all the cells of this matrix here. I will try to confine myself to the most important ones, according to my own judgment.

First, concerning developments that can be foreseen with reasonable probability we should try classical moves. I may summarize these moves into: turn changes into opportunities. Of course, this means that we have to rely on local invariance of criteria for what is favourable. I may mention only a sample of such criteria: Freedom to develop one's own possibilities, autonomy, participation in decision making, etc.

Second, with strongly invariant principles in mind, we should try conservative moves with certain issues. One important example of such a principle is: oppose changes that lead to irreversible deterioration, for example, to the ruling of a few specialists over the many which form the rest of us.

Third, to my mind we are in an indeterministic situation concerning changes ahead at large, and thus we should proceed according to move (7): train for flexibility, cultivate your fundamental resources. What does this mean for physics teaching and the integration of the history of physics within physics courses? We are faced with the last chapter.

History of Physics and Physics Teaching

1. The history of physics can be used in different ways by physics teaching.

First, it can be used as an organizing principle of the curriculum by delineating the historical development of today's physics knowledge from the beginning.

Second, it can be used as an organizing principle by going back to the origins, beginning with recent physics.

Third, it may be used by studying paradigmatic cases such that systematic physics teaching is enriched by knowledge of the emergence of important conceptual schemes, ideas, experiments, tying them up with life histories, historical circumstances, etc.

Fourth, it may be used as an anecdotical enrichment, in order to relax students from the strain of hard work, or to offer opportunities for further historical studies, for motivational reasons, etc.

These may be not all possible uses, but I take it that the list covers the most important ones. I do not deal with these possibilities systematically. I only remark that the anecdotical approach does not seem sufficient for the aims discussed. For pragmatic reasons the enrichment of a systematic course with the study of paradigmatic case histories seems to me the possibility to be recommended.

We should not forget, however, to mention one important distinction between overall aims, which may cut accross these possibilities as listed above. For one we may wish to use the history of physics in order to introduce a philosophical element into our physics teaching, to get rich material for thinking *about* physics, to look at it from a distance, and seeing it in widely varying contexts. On the other hand you may use the history of physics to improve physics knowledge in the internal sense. That means, for example, to understand better the content of the laws of electrodynamics as understood today, or of quantum mechanics, etc., by integrating into your knowledge of what is valid today, how it came about, what were the motives of the discoverers, what were their conceptual tools, their frames of mind, and how and why all this changed into the present day form of knowledge.

I do not want to discuss these possibilities systematically, because to my mind the first aim, introducing philosophical points of view, is relevant here. I should like to give only one counterexample, admittedly an extreme one, which exemplifies why I am skeptical to the second aim: To really understand what a photon is you would have to get the path from the Maxwell field equations – or should we begin much earlier, with the Greeks? – to Planck's introduction of the quantum, to Einstein's cautious hints to a particle nature of light in his 1905 paper,[27] which has become much distorted by later pseudo-history in textbooks, on to the Bohr atom, the Compton effect and with many other following effects and theories arriving at quantum field theory. Most physicists would agree now that you cannot understand the photon outside the frame of quantum field theory.[28] This is a vast program, definitely out of place for the nonprofessional physics student. It is also true that one could learn all this and get not the slightest understanding of the nature of change, in physics, and in other fields. For that student may be studying all these developments with a frame of mind which may be characterized by the common 'now we know'-attitude. Thus it seems to me quite obvious that the decisive consideration for the inclusion of the history of physics into physics teaching is a philosophical frame of mind, a 'science observed' attitude which may be acquired best by historical studies.

2. Now we come back to the possibilities of preparing students for change as sketched above.

(i) The first possibility concerns developments that are subject to law and can be foreseen with reasonable probability. There are indeed such changes. They concern, for instance, energy and information (or entropy, if you like), applications of solid state physics in computers, robots, communication channels, and, of course, weaponry. The foremost duty of physics teaching in this respect will be to train students to discern the field of possibilities as a field of opportunities and to avoid the dangers. Obviously nobody has much of an idea how this can be done. I should like to provide some suggestions.

First, students have to acquire a solid basis of physics knowledge from which development starts and which sets limits to it. In some fields this is easy. For instance, concerning energy and information there are the first and the second law of thermodynamics and many other things of sound physics. It would be certainly favourable to combine these studies with history. For instance, with the second law we can easily see from a distance how it arose from thinking about possibilities of improving machines. But, to take another example, it is a matter of debate if it would be advisable to study the 19th century struggle to reduce thermodynamics to mechanics. This would be a study of many intricate details (cf. Brush 1976), which for the aim we are discussing would be justifiable only if we want to use it as a paradigm for the change of a world picture.[29] Another example could be nuclear physics with energy resources in mind. Similar remarks would apply.

Concerning the second point, the training for taking opportunities and avoiding the dangers, I do not know how to do this, nor did I find much enlightenment in the literature. One thing seems clear to me, the problem is much more complicated than my superpositional formulation seems to suggest: we have to take into account that exactly *by using* the opportunities we are fostering the dangers. There are not the dangers on the one side – and please avoid them, and the opportunities on the other – please move to this side and you are far from the dangers. It is not that easy. We could become aware of this by considering examples form quite recent history. For example, people by developing and using the atomic bomb thought of it as taking an opportunity to avoid grave dangers, even to create peace for our time, and a much longer time than the inventor of this phrase may have thought. Now we can see why this did not happen and that it has led us to one of the most dangerous situations in human history.

The example of nuclear physics as the basis for new types of energy supply, by fission and fusion power plants, tells a similar story. Physicists for example simply forgot – and this is scarcely a mere accident – seemingly trivial problems like the technology of materials, the technology of getting rid of active waste, and so on. Of course, if the need arises, clever physicists and technologists will solve the problem. They are doing a good job already. But it also can happen that immense damage results before the solution is working.

Computers and information processing technology, as far as it belongs to solid state physics, has a very short history, too. But having in mind the aim of preparing for change by training to taking the opportunities and avoiding the dangers, we should take account of a much longer history. It is certainly relevant from the time of Thomas Hobbes and Leibniz, with their idea of rational thinking as a sort of calculation, with the idea of coding, and of rules for invention. The dangers ahead can be summarized by the catchword 'enslavement': Enslavement of the many by the few in charge of the information channels, by using the enormous technical possibilities of manipulating information, etc. But there are more subtle dangers, for instance self-enslavement by seeing oneself merely as a minor and rather inefficient computer, as dependent on it in every way. What I advocate is historical and philosophical discussions which are enlightening and thus offer opportunities for more rational decisions, which means being aware of a wider range of contexts and consequences. Just as we are getting into dangers by using the opportunities, thus we may overcome the dangers by more knowingly using the opportunities.

It is true, to give a very concrete example, that clever people, knowing details of information processing, may gain information that is very personal, or secret, and they may make use of it for very narrowly egotistical objectives. But it is also true that people being aware of these dangers, though only in an in-principle-manner, are able to take political decisions which will in the long run limit or prevent these obnoxious possibilities. This example shows that the knowledge to be conveyed for general education has to be on a general level, not too detailed because details change rather rapidly, and that this knowledge has to be embedded into a wider context of social and humanistic values. Physics teaching done in a narrow spirit cannot do that, nor can it promote the equally important educational task to convey executive power: Students should not only *see* the technical possibilities in a wider context, they should be trained to *act* accordingly. Now, training to act in a certain manner is easy, if the act can be repeated many times. Set within a historical perspective action is not of this kind. And in that case knowledge of and acquaintance with historical examples may be the only means to prepare, if combined with the power of analogical thinking.

(ii) Now we may go on to the second type of preparation, mentioned above: conservative moves. As I said, we should take conservative moves whenever there is danger of irreversible deterioration. This enslavement of the majority of men by the minority in command of the technical machinery, information channels, nuclear weapons, means of genetic manipulation, or whatever, is a frightening list of examples, though by no means a complete one. Of course, it would be ridiculous to offer ready-made solutions to these distressing possibilities mankind is faced with. My question is: what can physics teaching, what can the inclusion of the history of physics – and in what way – do in order to prepare students to cope with these imminent changes for the worse? First of all, it seems to me obvious that physics teaching done in the wrong spirit may even support deterioration. I think of the experimental attitude some physicists recommend as a characteristics of physicists to be transferred to managing political issues, too. Fruitful as this experimental spirit may be in the laboratory, on a vast political and historical scale it may be disastrous: after an experiment you may not even have the chance to evaluate it, still less to draw consequences. Thus, the scale of changes ahead demands an unprecedented amount of foresight. Historical studies may be useful to bring home this message by demonstrating the difference of scale and scope of physics done in, say, the 18th century and the 20th century. Some may find, though, consolation with the idea that 18th century chemists for a period feared mankind could be extinguished by chemical experiments leading to a burning of the whole atmosphere.[30]

What can be adduced as a more positive contribution of physics teaching under this heading? I take it that an irreversible deterioration of the situation of mankind can be prevented only if more science, especially more physics, is learned, first, by the institutionalized physics, that is by research, and, second, by most people thus fostering the growth of the institution. But as indicated earlier there are many dangers of change for the worse ahead of physics itself. Physicists and a broad majority of people have to understand the dilemma. On the one side, physics has entered a new scale concerning power and consequences. Thus it has to be severely controlled, and its aims have to be set from external forces.[31] On the other side, physics would become useless and even harmful if it would betray its traditional standards of finding out and communicating what it has found out, without taking into account whom it may please, or whose interests are served. Physics as a servant of political and social forces would lose its quality of dependability.

Thus in physics teaching students should learn that physics is one of the most precious achievements of mankind, important for survival and cultural identity,[32] an achievement that has to be preserved. But they also have to learn that some changes are necessary. Physics as an institution has to integrate discussions about the consequences of research and development, it has to cultivate the channels of information with the general public and take serious discussions concerning the justification of its enterprise.[33] And by that I do not mean the erection of a public relation agency which sells physics like some industrial product. Physicists should come to acknowlege that there *are* problems with physics as an institution that concern not only physicists. There are many signs that developments of this sort are in progress.

Of course, the history of physics may be of help also in these conservative moves. It is, for instance, interesting to note that science in the modern sense arose with strong promises for the enhacement of public wealth and the improvement of men's conditions of living,[34] their independence from external authority, etc. A closer look at history may help to see physics of today as a continuation, thus aiding to identify and to strengthen characteristics which are to be conserved.

We may also discern as a conservative task of physics teaching balancing potentially unwelcome but inevitable developments. I mentioned this trend to loosening the bonds with everyday reality, this trend to part company with what is felt to be important by the majority of the non-physicists. In a way, this is a necessity of the dynamics of physics itself. Now, physics teaching can try to balance this trend not by teaching physics in the sense of speeding-up in a hopeless run behind the accelerating research front. It is by teaching to ask questions. This has been said many times. What I mean is asking questions to the physicists that drag them back to common ground with his fellow citizens. Of course, it is liberating to witness that a physicist cannot answer a question of a student off-hand, because it turns out to be too complex, or because he had never thought about the matter. But students, forming later on the educated public, must also be prepared to ask questions of a different sort, for example, why do you want to construct this super-accelerator? What do you expect from it? Why should taxpayers finance it? The specialist must not be allowed to draw back behind his specialized knowledge. There must arise pressures upon him to fill the gap. This may be troublesome but helpful for preventing the complete separation of a group of specialists from the rest of society. Modern science, physics included, arose as a movement aiming at liberating men from external authority, from arcane knowledge in favour of public knowledge. Whatever we can do we should do to prevent an inversion of this origin. Obviously this is a topic which may rightly be called historical, and deserves conservative moves. The following point has a similar background: To my mind it would also be very important to balance the trend to a mere instrumentalist conception of physics. One topic of discussion could be the notion of truth. Again and again arguments proceed by feigning a notion of truth which is an artefact of philosophers. I do not know a serious study of the notion of truth within the history of physics. But whatever may be the ideas of this or that physicist, today nobody would dream of purporting that the laws of physics are revelations and thus unassailable eternal truths. Truth should be, and this is a conservative move, seen much more as an earthly and human affair. It is a question of honesty, of standing behind what you say, of dependability. There may be no eternal truth attainable, but that does not mean waiving the obligation to act according to 'the best of our knowledge'. It would be very helpful to historically study the development of the truth concept in physics, especially the instrumentalist turn round the end of the 19th century. I could well think of the paradoxical move of invoking history in order to balance historical relativism and the current irrationalism.

(iii) I come to the third possibility which I have called indeterministic. It consists in training for flexibility and cultivating fundamental resources. It is rather obvious that the term 'fundamental resources' has a conservative implication, because it refers to a constant basis. Cultivating and strengthening it may be one of the most promising ways of preparing students for change. Now, apart from manpower resources which are not the topic of this discussions the most important ingredient of these fundamental resources is, first, knowledge, second, training in applying it. This is rather trivial. But concerning physics teaching we have to specify the sort of knowledge. First, it must be locally invariant knowledge. Second, it must be basic in the sense of being a source of new knowledge, enabling one to acquire more knowledge. Third, it must be applicable within and outside physics. This sounds like a very traditional physics curriculum. To my mind we should not shy from this consequence. There is no King's Road to physics, nor is there a King's Road to be prepared for change.

But this is only half the truth, and this is why the history of physics comes in. Of course, as I said earlier, we have to make efforts to find didactic approaches to details in physics. Students, for instance, do not understand electromagnetic induction – well, find better approaches to teaching it, approaches better adapted to their preconceptions, to their expectations, to possible uses, etc. You may also strengthen understanding by discussing how the phenomenon first emerged, how it was conceptualized, how understanding of it changed during development. All this may be of help, especially if you are able to indicate to students that many of the misunderstandings they suffer from have been respectable conceptions in the past. All these advantages are well-known. I only want to add a cautionary note: You may apply this historic-genetic principle of teaching in excess, and then your students will have to learn a double amount of information or more, and I take it that there is somewhere a reversal point. But this is not my topic, only a side-remark. What does concern me here is the fact that of course by conveying the sort of knowledge sketched you do not explicitly prepare for change. We have forgotten the other half of the move, train for flexibility. Conveying a store of canonical knowledge, special methods included, may make for immobility, for false expectations as to change. Also change may refer to physics in a narrow sense, instead to transfer to other fields.

How can this flexibility and transference be acquired on the basis of a stock of stable knowledge? How can this stock contribute to versatility? In a way it can be done by studying history under this aspect. Physicists in the past had to face changes that came as a surprise to them, and we may learn how they reacted, how they could have improved upon their reaction. By this we do not only prepare by analogical reasoning. We simply generate a set, a definite way to look at our knowledge as a capital awaiting investment. We do not know how this model of physics, this physics as a model, makes transference to other fields possible. Of course, we may hope for it.

Let me finish with discussing an example, the photo-electric effect which is well-documented (cf. Stuewer 1979). First, look upon the traditional text-book treatment. The result of the refined measurements are described, and then the photon is parachuted as the explanation. Second, note the fact, that the effect itself requires very stable knowledge of the functioning of the apparatus. For instance, you have to know what a potential difference is, how potential drop and kinetic energy are connected, where Fermi levels come in for a finer analysis of the effect, etc. Third, note that in the text-book version the student learns nothing of the process of establishing the effect as a fact. You learn such things in one of two ways, either by taking part in actual research, or by studying historical documents. For most students the second possibility is the only feasable one. By studying documents, not in isolation that is, but of a whole story, he learns physics from the point of view of research, of applying knowledge and methods, of resolving controversy, in short: the student has an opportunity to learn how on the basis of stable knowledge new knowledge arises and some old knowledge dissolves.

For a fourth point concerning flexibility we should have a closer look at the interpretation after the effect has been established. To my mind this parachuting of the photon as the sole possibility of an interpretation may be judged to be sound if your aim is to convey accepted knowledge rapidly, though there are some problems in that case, too. To give rapid information is in itself very respectable. But as seen in my perspective it would be stupid. Let students strain their wits to think of other solutions by using all they know and combining it anew. For instance, could the effect be explained as a resonance effect? In a way flexibility can be trained by such studies, and students could eventually acquire a mental set, or outlook, not to be absolutely certain even with established knowledge. The history of physics, especially of modern physics, is rich with examples which show established facts and theories crumble into mere inaccuracies. Also we should not forget to acquaint our students with the fact that many highly accomplished physicists blundered in the course of development.[35] To make this known may have a doubly beneficial effect on the student: he may lose an exaggerated confidence in authority, and be encouraged to think for himself.

There is a last point to be discussed: The example does not indicate in what way this set, as I termed it referring to a psychological theory, can transfer to other fields. The mental set to be acquired concerning physics may be summarized into the following points: Know your basic resources without being absolutely certain; be flexible with interpretations; try to think for yourself; do not believe that the well-known authority does already know all the correct answers and can never make an error; expect changes, in this spirit of a well-distributed skepticism. It seems clear to me that an outlook of this kind may be a good preparation for coping with change, even with crises, also in other fields. But I can see no answer to the question how in fact this set has transferred or will transfer to other fields. We lack systematic studies of the way the culture of physics, and I do not mean physics knowledge, has influenced the behaviour of men in other fields, in social relations, in political affairs, in cases of personal crisis, etc. I think this could be a very interesting field for the history of physics, though it is far away from what historians of physics normally do. And in fact, this may be a disappointing impression from my paper: educational value does not come from the details of the historical development of physics, but from the history of its context. This is as it should be: value arises from the richness of interrelations.

NOTES

1. Cf. for example the book Braun & MacDonald (1978). Of special interest is the last chapter: Reflection on an electronic age, with the concluding remarks which echoes what was said respecting nearly all technological innovations: 'The flexibility of electronics is such that it can be used in almost any task. The critical choices concern the adaption of technology to our needs. We have irrevocably entered the electronic age and it is up to us to make it a good age in which to live'. (p. 200)
2. That the precision of mechanical devices such as clocks have played an important part in the development of scientific thinking has been pointed out by some authors. Concerning the clock as a model even in psychology cf. McReynolds (1980); the role of clocks in social life is stressed by Heidelberger & Thiessen (1981), p. 117; for a summary of relevant literature see Sachsse (1978), chpt. 6.
3. These are some aspects of the term 'physics'. Normally it is understood as a combination of knowledge and method. The institutional aspect for example is mostly forgotten. These and similar aspects can and have been used for differential evaluation of history in science teaching, see for example Russell (1981). But learning is such complex an issue that it would be rash to build upon so small an evidence. All we know from empirical educational research is that there may be critical variables.
4. See Forman (1971) and critical comments by Meyenn (1982). The influence of physics upon society is obvious, also upon general modes of thought: it would be difficult to entangle which 'caused' what. For an interesting position maintaining the priority of 'ideas' (called 'icons' in the paper for reasons explained there) over society's material forces, see Harre (1975).
5. This trend has been noted since the 1920s. In a recent Italian study by Portinari (1983) these forces are nicely analysed as 'ragrupamenti infrastatali'.
6. One of the first of those who noted these fundamental changes was M. Horkheimer et al. in their family studies (Studien 1936).
7. See Whitehead (1955, 1941); Toulmin (1974); Bopp (o.J.); Prigogine (1979).
8. I refer to a lecture of H. Schopper, director general of CERN, in Frankfurt, 18.5.1983.
9. There are hundreds of books on scientific methodology. An excellent synoptical discussion of types of methodological conceptions, from a didactic point of view, is to be found in Bevilacqua (1983), sections 1.3 and 1.4.
10. One well-known example is Planck's invention of the quantum of action. It was a technical invention in search for a physical interpretation. But, of course, it had a very definite background of experimental facts. Another instructive example is Mielnick (1976). It nicely exemplifies the axiomatic experimentations, upon the background of quite real experimental problems.
11. A very succint statement of the dialectical character of theory and practice is to be found in Whitehead (1948): 'In practice . . . the sole problem is, 'Does it Work?' But the aim of practice can only be defined by the use of theory; so the question 'Does it Work?' is a reference to theory. Also the importance of theory resides in its reference to practice.' (p. 80). Analogously it can be argued that by stating that a theory 'works' you are referring to truth, as an idea, not, of course as an infallible statement.
12. I only give a very recent example of a statement relevant to this issue. Schmidt-Tiedemann said in his Presidential Address at the 1983 Meeting of the Deutsche Physikalische Gesellschaft (my translation): 'It (physics, W.J.) is an instrument, but does not give

direction. Thus physics excludes itself by an act of methodological self-restraint from one ot the most important discussions of the present time. The numerous signs of crisis urgently require direction' (p. 169). When discussing a possible contribution of physics, he explicitly excludes 'physics knowledge', because (!) 'a moral world formula' is out of reach from methodological reasons.'

13. See Rescher's 1978 book. In a recent publication you could read that the planned 20 TeV accelerator may cost about $2 \cdot 10^9$ dollar!
14. For example, Ridley (1976) writes in the preface of his small but valuable book, referring to the physics student: 'Occupied as he is with hacking his way through the thickets of thermodynamics, electromagnetisms, quantum mechanics and the rest, he may be forgiven for losing all sense of direction and wishing he could rise above the forest to get this bearings.' See also Teller (1982) for some enlightening remarks.
15. Different concepts of incommensurability have been used, and there is lack of a more rigorous definition, but see Körner (1973), p. 127.
16. Thus I agree with Kaufmann's saying: 'What makes the study of history fascinating is among other things, the perception of discontinuity in the context of continuity' (Quoted from Koertge (1973), p. 167). I should like to suggest a further step: You cannot see discontinuity without being immersed into continuity in the sense of Peirce, as 'unbrokeness'.
17. For example, Brian Josephson is quoted by Gliedman (1982) as saying 'As a scientist, I'm interested only in seeking fundamental new insights.' (p. 89). See also Teller (1982).
18. In Quine (1964) he seems to be much more radical, writing: 'Physical objects are . . . irreducibly posits comparable, epistemologically, to the gods of Homer. . . . Both sorts of entities enter our conception only as cultural posits. The myth of physical objects is epistemologically superior to most in that it has proved more efficacious than other myths . . . ' (p. 44). This need not be construed as in contradiction to what he said in *Word and Object*: Since everything, Quine himself included – or should I write 'Quine'? – is a cultural posit and a myth, because the thought is not the object, we have no reason to bother about this epistemological similarity. The question is: Does science purport, if only tentatively – which, as Quine rightly says, goes without saying – that its objects exist? Of course, everybody is free to unequivocally state what science is, tentatively, stating to be the case. As far as I can see, nobody was able to do that without quantifying over 'mythical' objects of this or that kind, thus giving evidence of his endowing them with existence. Quine nicely exemplifies that not even clever men are safe from pitfalls: he worked out a whole theory to the effect that there are no facts, upon the alleged fact that our only contact with the external world are 'surface-irritations', or 'nerve-hits' (1960, p. 23). But, obviously, nerve-hits are no better off than stones, bridges, electrons, sense-data: they are all myths, 'epistemologically'. And so are births, deaths, earthquakes, wars! So, all there is in this much debated denial of 'facts' is the rather trivial assertion that you can never know a single statement to be true with absolute certainty. But then, asserting that, you have to have some idea of truth, else what is your assertion?
19. A similar remark can be found with Shapere (1980): '. . . the possibility of doubt is no reason for doubt,' (p. 82).
20. Quoted from Achinstein (1968), p. 108.
21. There are many examples. I mention the resolutions of the joint Councils of ICSU, APS, DPG concerning disarmament, especially of nuclear weaponry: IUPAP *News Bulletin* **83**, April 1, 1983, *Europhysics News* **13**, 1982, 12, Nr.7. I also mention a lecture of I. Rabi with GSI, 'Physics at Mid-Century', saying in discussing the responsibility of physicists for the consequences of nuclear bombs: '. . . talk to the public from knowledge, from imagination, from human sympathy, from human pride and responsibility.' (cf. report in *Physik. Blätter* **39**, 1983, p. 189).
22. The following statement captures the substance of the problem: 'The trouble is that the unmeasured, or unmeasurable, aspects of a problem may be vastly more important than those which have been, or can be, measured'(A.R. Ross, quoted from Goldberg (1970), p. 127).

23. Move (4) is a good example of a borderline case: it could equally well be classified as a classical move. Yet there is the decisive difference of the underlying spirit, of the frame of mind. A similar case is move (8).
24. Of course, there are opportunities even in the elementary courses to train thinking in complex situations, for example in electrical circuitry, etc. But to my experience the isolating technique is much more prominent as far as the impact on the cognitive habits of the student is concerned. In advanced subjects, modern physics is, in fact, decidedly non-linear.
25. This has always been the position of the classic in German didactic literature, M. Wagenschein; cf. his *Die Pädagogische Dimension der Physik*.
26. For German speaking countries I should like to mention E. Mach, Dannemann and some decades later, Toeplitz. But it would be futile to document the details here. For France we could point to Duhem; see also Brush & King (1972).
27. He did not say, treating light as a sort of gas is the only way to explain the effect. For a historical analysis see: Pais (1982), Sec. 19c and e. In a well respected German text-book (Grehn *et al.*, 1981) one reads (my translation), 'Thus it can be seen that the photo-electric effect taken as an interaction between light and matter cannot be explained within a wave picture of light. However, Einstein's conception of 1905 explains the photo-electric effect: According to Einstein light consists ... of quanta of energy.' (p. 132). Now, what Einstein in his 1905 paper said was much more cautious, repeatedly stating 'as if': 'as if light were to consist of energy quanta of this kind', 'as if it consists of mutually independent energy....' To take another example, Halliday & Resnick state, 'energy travels in concentrated bundles called photons' (p. 1182), while it is difficult to discover the concept of travelling in Einstein's paper. They go on stating (p. 1183), 'Millikan, whose experiments verified Einstein's ideas in every detail, spoke of Einstein's 'bold not to say reckless, hypothesis''. If Pais quotes the documents correctly, which I would not dream of doubting, Millikan wrote in 1916, 'Despite ... the apparently complete success of the Einstein equation, the physical theory of which it was designed ... is found so untenable that Einstein himself, I believe, no longer holds to it.' (Pais, p. 380). Why Millikan is said to have verified Einstein's ideas in every detail is difficult to comprehend: he just verified the Einstein equation. In PSSC Physics the photon concept is explained and then added, 'He, (Einstein, W.J.) invented the whole picture on the basis of far less evidence' (p. 621). In the face of the 1905 paper, especially its first half which has nothing to do with the photo-electric effect, these comments are rather misleading for the learner. No word about the fact that Einstein till the end of his life was puzzled by what these energy quanta of light might mean.
28. See, for instance, Strnad (1984); Simonsohn (1980); Cohen-Tannoudji (1983).
29. That far-reaching changes are involved in this whole process has been described more than once; see for examples Elkana (1974); Brush (1982).
30. Having done extensive reading for four decades, I am sorry that I have forgotten where I did read this particular piece of information.
31. This issue has been discussed at length in Germany under the heading 'Finalisierung'. See Eberlein & Dietrich (1983); also Böhme, van den Daele & Krohn (1974).
32. It is quite interesting to observe another example of a dialectical relation here, that between identity and diversity. Obviously physics can be absorbed within a cultural tradition which is quite different from that of the Western World, as for instance with China. And in that respect there is a considerable 'universalism' in physics. On the other hand, there is also the possiblity of 'mediating' between a foreign culture and ours by thinking about physics: Since quatum theory, more educated peaple than ever got an idea of what the Tao could be; cf. Needham (1979). That means, we better understand differences and diversity by seeing them from the background of identity. Problems relating to cultural identity are also discussed in Botkin, Elmandjra & Malitza (1978).
33. A very deep-going discussion of the problem of legitimacy of science in the present situation is to be found in van den Daele & Krohn (1982). Just as Ellul (1964), they diagnose 'the dominance of means over ends' (p. 425), and hold that science is going to

develop into a sort of technology (p. 427), thus 'you have more and more to take into account the possiblity that the consequences of science are ascribed to science itself.' (l.c., my translation).

34. See for instance, Mathias (1977) (English original 1972), also Clark (1970).
35. I should like to quote one recent source only, Kemmer (1983). In his address after receiving the Max Planck medal you find side-remarks like the following: '. . . Proca . . . - erroneously tried . . .', '. . . Wentzel assumed . . . . But he made a mistake. He did not like the isospin symbolism and got a bit muddled.' '. . . Yukawa, Sakata, and Taketani . . . too late it was understood that they made an essential mistake.' (p. 172f., my translation).

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