OVERCOMING THE OBLIVION OF TECHNOLOGY IN PHYSICS EDUCATION[1]

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Abstract. Technology is generally viewed as 'applied science', that is to say, as something that comes 'after' science. This conception justifies the lack of attention paid to technology in science education, especially where physics education is concerned. In this chapter we question this simplistic view of the science-technology relationship, historically rooted in the unequal appreciation of intellectual and manual work, and we try to show how the absence of the technological dimension in science education contributes to a naïve and distorted view of science which deeply affects the necessary scientific and technological literacy of all citizens, as well as the preparation of the future scientists and technicians that our societies demand.

INTRODUCTION

When we ask university physics students 'what technology is', almost one hundred per cent of the answers make a reference to 'applied science'. This common view shows the lack of attention to technology in physics education and, actually, in science education in general. In fact, the most frequent references to technology included in science textbooks are limited to simple enumerations of *applications* of scientific knowledge (Solbes & Vilches 1997). On the other hand, most studies about the nature of science don't pay any attention to the science-technology relationship (Gil-Pérez et al. 2005).

Our intention is to show the need to overcome this simplistic conception of technology in order to favour more meaningful physics learning as well as better attitudes towards physics and physics learning. This is necessary, we insist, because many students regard science, and particularly physics, as an esoteric, abstract knowledge of little interest to them (Gil-Pérez and Vilches 2005). What is more, the idea of technology as applied science contributes to these distorted and impoverished views of science (Gil-Pérez et al. 2005).

TECHNOLOGY AS 'APPLIED SCIENCE': A SERIOUS MISCONCEPTION THAT REINFORCES DISTORTED AND IMPOVERISHED VIEWS OF SCIENCE

Questioning the simplistic view of technology as "applied science" should be quite easy: all we have to do is briefly reflect on its historical development to understand that technical activity has preceded the mere existence of science by thousands of years (Gardner 1994). This obliges us to disregard the notion of technology as a by-product of science (Maiztegui et al. 2002). Nevertheless, this simplistic conception continues to be generally accepted, even by science educators, because this reflection is absent.

But the most important thing to clarify is what citizens' scientific education and future scientists' preparation may lose as a result of undervaluing technology. This leads us to ask, as Cajas (1999) does, if there is anything in technology that is useful for citizens' scientific literacy that we science teachers are not taking into consideration. Several authors have

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pointed out, in connection with this, some characteristics of technology which, if ignored, impoverish science education (Gardner 1994; Cajas 1999; Maiztegui et al. 2002). We shall study here a particularly important consequence of the oblivion of the role of technology in the construction of scientific knowledge: *the reinforcement of serious distortions of the nature of science* responsible, to a great extent, for many students' and citizens' rejection.

A Decontextualised, Socially Neutral View of Science

We shall start with a misconception criticised by abundant literature **(**Fernández et al. 2002): the transmission of a socially neutral view of science which ignores, or treats very superficially, the complex relationship between Science, Technology and Society, STS or, better yet, STSE, adding the E for Environment to direct attention towards the serious problems of environmental degradation which affect the whole planet.

This superficial analysis implies, as we have already seen, the consideration of technology as a mere application of scientific knowledge, so *exalting science, more or less explicitly, as an absolute factor of progress.*

In contrast to this naïve view of science, there is *a growing tendency to blame science and technology for the environmental degradation in process on our planet*, with the destruction of the ozone layer, acid rain, etc. In our opinion this is also a serious misconception: it is true that scientists and technologists have a clear responsibility for, for instance, the production of substances which are destroying the ozone layer… but along with businessmen, economists, workers or politicians. Criticism and calls to responsibility should be extended to all of us, including the 'simple consumers' of dangerous products. Besides, we cannot ignore that many scientists study the problems humanity has to face nowadays, draw attention to the risks and look for solutions (Giddens 1999).

These simplistic attitudes of absolute exaltation or rejection of science are not founded at all and must be criticised. Nevertheless, *the most serious problem in science education comes from purely operative approaches* which completely ignore the social context (Stinner 1995), as if science were an activity carried out in ivory towers, at the margin of life's contingencies, by solitary geniuses who manage an abstract language of difficult access. This constitutes a second distortion of scientific activity that we must contemplate.

Science as an Individualistic and Elitist Activity

This individualistic and elitist conception is one of the distortions most frequently signalled in literature (Fernández et al. 2002), together with the closely related socially neutral view we have just studied. Scientific knowledge appears as the work of isolated 'great scientists', ignoring the role of co-operative work and of exchanges between different research teams. Particularly, it is implicitly suggested that results obtained by only one scientist or team may be enough to verify or falsify a hypothesis or even a theory.

In the same sense, science is quite frequently presented as a domain only accessible to especially gifted minorities, therefore conveying negative expectations to the majority of students, resulting in ethnic, social and sexual discrimination: science is presented as an eminently 'masculine' activity.

No special effort is made to make science meaningful and accessible; on the contrary, the meaning of scientific knowledge is hidden behind mathematical expressions, without previous qualitative approaches. Nor is the human nature of scientific activity shown: an activity where errors and confusion are inevitably part of the process… as happens with pupils' learning.

We sometimes find a contrary distortion which presents scientific activity as something pertaining to common sense, thereby forgetting that science begins by questioning the obvious (Bachelard 1938). Still, the dominant view is the one which regards science as an activity of isolated geniuses.

Lack of attention to technology contributes to this individualistic and elitist view. On the one hand, the complexity of scientific-technological work which demands the integration of several kinds of knowledge, impossibly mastered by a single person, is ignored; on the other hand, importance is not given to the contribution of technicians who play a vital role in scientific-technological development. The starting point of the Industrial Revolution, for example, was the steam engine invented by Newcomen, a blacksmith and smelter. As Bybee (2000) points out: ‘In reviewing contemporary scientific research, one cannot escape the reality that most advances in science are based on technology’. This questions the elitist vision of scientific-intellectual work being ranked above technical work.

The individualistic and elitist image of scientific activity is made evident in iconographies which usually depict a man in white in an isolated laboratory, completely surrounded by strange instruments. Thus, we come to a third distortion: the one which associates scientific work almost exclusively with work done in a laboratory, where the scientist observes and experiments in search of a happy ‘discovery’. Thereby, an empirical-inductive view of scientific activity is conveyed, which the oblivion of technology contributes to.

An Empiricist-Inductivist, Non-theoretical View of Science

The idea of experimentation as ‘the principal route to scientific knowledge’ is, probably, the distortion which has been most studied and which most frequently appears in literature (McComas 1998). It is a conception which enhances ‘neutral’ observation and experimentation, forgetting the important role played by theoretically founded hypotheses as a guide to research.

Several studies have shown the discrepancy between the view of science given by contemporary epistemology and certain teachers' conceptions, which lean heavily towards empiricism (Giordan 1978; Hodson 1985; Nussbaum 1989; Cleminson 1990; King 1991; Stinner 1992; Désautels et al. 1993; Lakin & Wellington 1994; Hewson, Kerby & Cook 1995; Thomaz et al. 1996; McComas 1998; …). These erroneous empiricist-inductivist views of science are frequently voiced by even scientists themselves, because they are not always explicitly conscious of their research strategies (Mosterín 1990).

We should point out that the view of scientific knowledge as a result of experimentation, overlaps with the notion of scientific ‘discovery’ presented by mass-media and other forms of popular culture (Lakin & Wellington 1994).

Although this distorted view of scientific activity is the most studied and criticised in literature, most science teachers continue to adhere to this conception. To understand why, we have to take into account that, in spite of the importance verbally given to observation and experimentation, science teaching, in general, is mainly a simple transmission of knowledge, without real experimental work (beyond some ‘kitchen recipes’). For this reason, experimentation is still seen, both by teachers and students, as an ‘awaited revolution’, as we have observed in interviews with teachers (Fernández et al., 2002).

This absence of experimental work in science classes is in part caused by teachers' lack of acquaintance with technology. Effectively, experimental work always requires the support of technology: for instance, to test the hypotheses which guide a research, we are obliged to conceive and construct experimental designs; and to speak of *designs* is to speak of technological work. It is true that, as Bunge (1976) points out, experimental designs are based on theoretical knowledge: the conception and construction, for instance, of an ammeter demands a sound knowledge of electrical current. But this construction also requires the solution of many practical problems in a complex process which has all the characteristics of technological work. It is not just a question of saying that *some* technological developments have been crucial to make possible *certain* scientific advancement (like, for example, the role played by lenses in astronomical research): *technology is always at the centre of scientific activity*; the expression experimental *design*, we insist, is perfectly illustrative of this.

Unfortunately, the laboratory practices in school science prevent students, even in higher education from getting acquainted with the design and implementation of adequate experiments to test hypotheses, because they typically use designs already elaborated following *kitchen recipes*. Thus, science teaching focused on simple knowledge transmission impedes the understanding of the role played by technology in scientific development and favours the permanence of empirical-inductive conceptions which emphasise inaccessible experimental work as a key element of the so-called 'Scientific Method'. This conveys two other serious distortions which we shall discuss next.

Science as a Rigid, Algorithmic and Infallible Process

This is a very well known distortion which presents the 'Scientific Method' as a sequence of steps to be mechanically followed, enhancing quantitative treatments, rigorous control, etc, and forgetting –or even rejecting– anything related to invention, creativity, or doubt.

This is a wide-spread view among science teachers, as we have confirmed using different designs (Fernández 2000). For example, in interviews held with teachers, a majority have referred to the 'Scientific Method' as a sequence of well defined steps in which *observations* and *rigorous experiments* play a central role which contributes to the *exactness* and *objectivity* of the results obtained. Such a view is particularly evident in the evaluation of science education: as Hodson (1992) points out, the obsessive preoccupation with avoiding ambiguity and assuring the reliability of the evaluation process distorts the nature of the scientific approach itself, essentially vague, uncertain, intuitive. This is particularly true when we refer to experimental work, where technology plays an essential role and, as we have already remembered, many unexpected problems appear which must be solved in order to obtain the correct functioning of the experimental designs. Evaluation should take into account this ambiguity instead of trying to eradicate it.

Some teachers, in rejecting this rigid and dogmatic view of science, may accept an extreme relativism, both methodological -'anything goes', there are no specific strategies in scientific work (Feyerabend 1975)- and conceptual: there is no objective reality which allows us to test the validity of scientific construction. 'The *only* basis for scientific knowledge is the consensus of the research community'. This is a relativism close to the theses of radical constructivism (Glasersfeld 1989) which has received serious criticism (Suchting 1992; Matthews 2000; Gil-Perez et al. 2002).

Nevertheless, the dominant conception is the simplistic algorithmic one, which, like the related empirical-inductive conception, is easily accepted in as much as scientific knowledge is presented in a finished form just to be accepted and learnt: effectively, in this way, neither students nor teachers have the possibility of putting into practice and realising the limitations of the so-called Scientific Method. For the same reason one falls easily into an aproblematic and ahistorical view of scientific activity which we shall comment on in the next section.

An A-historical and, therefore, Closed and Dogmatic View of Science

A teaching orientation based on the simple transmission of knowledge often results in ignoring the initial problems scientists intended to solve, neglecting the evolution of such knowledge, the difficulties encountered, the limitations of current scientific theories or new perspectives. In doing this, one forgets that, as Bachelard (1938) stated '*all knowledge is the answer to a question*'. The omission of the problem and of the process to construct an answer makes it difficult to perceive the rationality, relevance and interest of the knowledge constructed and its tentative character.

Let us emphasise the close relationship between the distortions we have considered thus far. For example, this dogmatic and ahistorical view reinforces simplistic ideas regarding science-technology relationships which present technology as a by-product of science. We should bear in mind that research is an answer to problems that are often linked to human needs and so to the search for adequate solutions to previous technological problems.

As a matter of fact, the absence of a technological dimension in science education impregnates the naïve and distorted views of science we are eliciting. This lack of attention to technology is historically rooted in the unequal appreciation of intellectual and manual work, and deeply affects the necessary scientific and technological literacy of all citizens.

But the distorted, impoverished view of science we are discussing here includes two other misconceptions which both fail to consider that one of the aims of science is the construction of coherent bodies of knowledge. We are referring to an 'exclusively analytic' view and to a 'linear, cumulative' view of scientific processes. Although they are not so directly related to the oblivion of technology, we shall briefly refer to them, because this ensemble of distortions form a relatively well integrated framework and they support each other. We need, for this reason, to analyse all of them, in order to question the ensemble and make possible a more adequate vision of scientific activity.

An Exclusively Analytical Approach

Why do we speak of an exclusively analytical view as a distortion? It is obvious that analyses and simplifications are initially necessary, but we should not forget the subsequent efforts to synthesise and construct increasingly larger bodies of scientific knowledge, or the treatment of problems which overlap different disciplines and can be integrated. It is the omission of these syntheses and integration processes which constitutes a distortion. This is the reason we speak of an *exclusively* analytical view.

Current science education is strongly affected by this omission of the integration process. We have verified (Fernández et al., 2002) that most of the teachers and textbooks do not enhance, for example, the integration achieved by the Newtonian synthesis of heaven and earth mechanics; an integration which had been rejected for more than a century with the damnation of Copernicus' and Galileo's work and the inclusion of their books in the '*Index Librorum Prohibitorum*'. The same happens with the presentation of biological evolution (still ignored by many teachers and opposed by some social groups) or organic synthesis (considered *impossible,* for ideological reasons, until the end of the XIX century).

A linear, Cumulative View

The last relevant misconception we have detected consists of the consideration of the evolution of scientific knowledge as the result of a linear, cumulative progression (Izquierdo, Sanmartí & Espinet 1999; McComas 1998). This ignores periods of crisis and profound change (Kuhn 1970) and the fact that the development of scientific knowledge does not fit into any well-defined predictable pattern of evolution (Giere 1988; Estany 1990).

This misconception complements, in a certain sense, the rigid and algorithmic view we have already discussed, although they must be differentiated: while the later refers to how a particular research is organised and carried out, the cumulative view is a simplistic interpretation of the evolution of scientific bodies of knowledge, which is seen as a linear process. Science teaching reinforces this distortion by presenting theories in their current state, omitting the process of their construction, which includes occasional periods of confrontation between contrary theories or outbreaks of authentic ‘scientific revolutions’ (Kuhn 1970).

Summing Up: A Naïve Image of Science and technology

These are the seven major distortions we have elicited and seen referred to in science education literature. They do not constitute seven autonomous "deadly sins". On the contrary, they form a relatively well-integrated conceptual framework and they support each other. For example, an elitist view of science as an activity carried out by solitary “geniuses” in their "ivory towers" supports the empiricist notion of “discovery” and it fosters a socially decontextualised view of scientific work, with a complete oblivion of the role of Technology and of the science-technology-society relationships. This image is not only incorrect, but could easily convince most students that they are not capable of or interested in working in such a fashion.

Such interrelated misconceptions transmit a naïve and socially accepted image of science and technology which science education reinforces, sometimes explicitly, and most of the time implicitly, by omitting the discussion of such erroneous views (Gil-Pérez et al., 2005) and, above all, by not giving pupils the opportunity of *doing science*, this is to say, of “engaging in and developing expertise in scientific inquiry and problem solving” (Hodson, 1992).

We have studied the actual presence of these distortions in current science teaching by means of, among other procedures, analysis of textbooks, laboratory guides and assessment exercises; direct observation of classroom activities; questionnaires; interviews… (Fernández et al. 2002). This study has shown that the naïve image of science and technology expressed by the seven distortions we have mentioned is deeply rooted in current science teaching, centred almost exclusively in the transmission of conceptual knowledge. This occurs as well at the university level, with the result being that future teachers implicitly embrace this naïve image of science and technology and related ineffective teaching strategies based on the simple transmission of conceptual knowledge.

For this reason we have conceived a workshop which gives teachers the role of researchers who have to critically analyse the image of science and technology usually transmitted by science teaching. The participation in this oriented research makes it possible for teachers to begin to overcome their distorted views of the nature of science and technology and approach current epistemological views (Fernández et al. 2002). We complete the workshop synthesising these epistemological views as a way of reinforcing teachers' questioning of the distortions of the nature of science and technology. Because, in spite of some discrepancies in concrete aspects, and many nuances, the views of most contemporary philosophers of science show a basic consensus which presents an image of science radically opposed to the naïve view reflected by the seven distortions we have discussed in this section. We shall synthesise this basic consensus in the next section.

THE ESSENTIAL CHARACTERISTICS OF SCIENTIFIC ACTIVITY

The nature of scientific activity has given rise to many debates in which nuances and discrepancies are noted (Toulmin 1961; Popper 1968; Kuhn 1970; Bunge 1976; Lakatos 1970; Feyerabend 1975; Laudan 1984...). Sometimes, this creates certain confusion among teachers and researchers in science education and leads us to ask if there is any sense in talking about an adequate view of science and technology and if it is worthwhile to include the philosophy of science in programmes for teacher training (Martín, Kass and Brower 1990; Stinner 1992). Nevertheless, there are some essential aspects which deserve general consensus and must be enhanced, taking care that nuances and partial discrepancies don't obscure what the views of the different authors have in common. These are, then, some points of consensus which we should enhance:

1. First of all, we must refer to the general rejection of the idea of the "Scientific Method" as a sequence of perfectly defined rules to be applied mechanically and independently of the researched domain. "The expression (Scientific Method) is misleading because it may cause us to believe that there is a set of exhaustive and infallible recipes …" (Bunge 1976; McComas 1998).

2. In the second place, we must point out again a general rejection of what Piaget (1970) denominates "the myth of the sensorial origin of scientific knowledge", that is, the rejection of an empiricism that conceives knowledge as the result of inductive inference from "pure data". These data do not make sense in itself. It has to be interpreted according to a theoretical system. Thus, for example, when one uses an ammeter one does not observe the intensity of the current, but the movement of a needle (Bunge 1976).

We have to insist upon the importance of conceptual paradigms, of theories, in the carrying out of scientific work (Bunge 1976), which is a complex process, not reducible to a defined model of scientific development (Estany 1990). This may include breaks and revolutionary changes (Kuhn, 1970) in the prevailing paradigms and the emergence of new ones. We also have to stress that scientific problems are initially "problematic situations": the problem is not given, it must be stated in a precise way, taking decisions to simplify the situation, clarify the aim, etc. And all of this is done starting from the available body of knowledge (Lakatos 1970).

3. Thirdly, we have to point out the role played by divergent thought and creative thinking, such as the *invention* of hypotheses and models or the design of experiments, neglected in the empiricist-inductivist approach. One does not reason in terms of certainties based on "facts", but in terms of hypotheses, i.e., "tentative answers" based on available knowledge, which must be tested as thoroughly as possible. This results in a complex process in which there are no universal normative principles for accepting or rejecting a hypothesis and the subsequent changes in the theoretical corpus (Giere 1988). Although experimental evidence obtained in defined and controlled conditions plays, undoubtedly, an important role in scientific research, we have to recognise that hypotheses play the central role: we do not arrive to scientific knowledge by applying an inductive procedure of inference to previously gathered data, but through the construction of hypotheses as tentative answers to be tested (Hempel 1966).

4. Another fundamental aspect is the search for coherence (Chalmers 1990). The fact of thinking tentatively, of working with hypotheses, introduces supplementary demands: we need to systematically doubt the results obtained and the processes followed to obtain them. This leads to continuous revisions and regulations, trying to obtain these results using different strategies and, very particularly, to testing their coherence with the whole body of knowledge.

It is necessary to warn against a possible experimentalist reductionism: experimental testing is not basis enough to accept or reject a hypothesis; we need to verify the existence, or not, of the global coherence of these results with the available body of knowledge.

In fact, one of the most important outcomes of science consists in linking apparently unconnected domains. In a world characterised by diversity and change, science looks to establish general laws and theories, applicable to the widest number and variety of phenomena. The atomic-molecular theory, the conservation and transformation laws (of mass, energy…), the electromagnetic synthesis… are good examples of this search for coherence and global validity which begins with the treatment of problems and situations initially quite concrete and narrow. Scientific development entails this search for generalisations applicable to real situations. And it is this coherence and applicability to the description of phenomena, in prediction-making, in the treatment of new situations, etc., which gives a growing validity –never certainty- to the concepts, laws and theories constructed.

We have to be aware, on the other hand, that an essential characteristic of the experimental approach is an explicit will to simplify and to rigorously control the studied situation. This introduces an artificiality which mustn't be ignored nor hidden: scientists *decide* to treat solvable problems, and this causes them to consciously put aside many of the characteristics of the studied situation, therefore moving away from reality: They also move away from reality by *imagining* models and *inventing* hypotheses. A scientific approach demands, as we see, artificial, partial and simplified treatments. But this approach shouldn't be seen as a reductionist and simplistic one: as analyses and simplifications are conscious, scientists are aware of the need for further syntheses and more profound treatments.

We must recognise that this strategy has made the unification of apparently unconnected fields possible, sometimes with strong ideological resistance, provoking persecution and damnation as in the well known examples of Heliocentrism and Evolutionism.

The history of scientific thought is a permanent confirmation of the validity of these treatments initially partial and limited… which lead to the growing construction of coherent bodies of knowledge and to the establishment of links between separate domains.

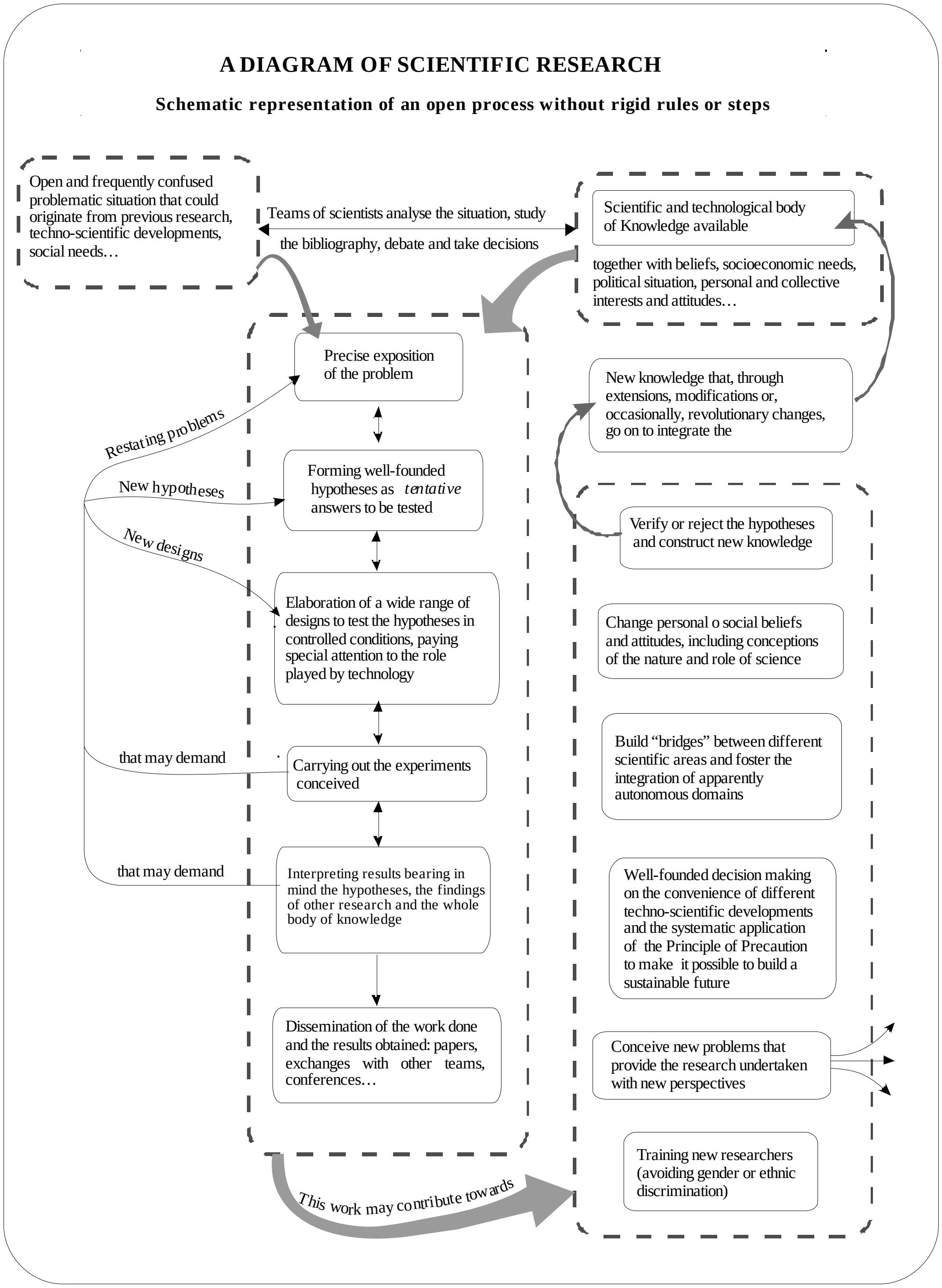
5. Finally, it is necessary to take into account the social nature of scientific work: current theories –which constitute the point of departure for the treatment of new problems- are due to the contributions of many researchers. Besides, research is increasingly promoted and controlled by institutions where the work of individuals is oriented by established lines of research, by team-work, by sponsors' interests… (McComas 1998).

In fact, the stereotype of completely autonomous research is invalid. The work of scientists, as in any other human activity, can't take place outside society and is affected, logically, by problems, interests and the circumstances of the historical moment. And at the same time, the work of scientists influences their physical and social environments.

To remember all this may seem superfluous; but the idea of science as an activity reserved for solitary geniuses, working apart from the world, is a stereotype which teaching, unfortunately, doesn't help to dispel, because it is almost exclusively centred on the transmission of conceptual knowledge.

These characteristics of science we have summarised may seem to draw a vague, nebulous image of scientific activity, far removed from the idea of a precise and infallible algorithm, but reveal science in a more authentic and complete light. We could say that the essence of scientific strategies –putting aside any idea of “method”- lies in overcoming a thought process based on dogmatic securities and common-sense evidence, in order to adopt a tentative, hypothetical reasoning. Reasoning which is both more creative (it is necessary to go beyond what seems obvious and imagine new possibilities) and more rigorous: it is necessary to construct well founded hypotheses, to test them carefully, to systematically doubt the results obtained and to look for global coherence.

These are current points of consensus about the nature of science which draw an image contrary to the distorted views we have elicited in the first part of this chapter. **Figure 1** synthesizes this consensus.



When we present such a summary to the teachers' teams implicated in a research about distorted views of science, they easily point out how this summary overcomes each one of the studied distortions. This reinforces, of course, the clarification efforts made to approach current epistemological views and achieve a better appreciation of the nature of science and technology. But, what *practical* interest may this have? As we have pointed out in the introduction to this chapter, this clarification aims towards a better orientation of science education. We shall discuss this essential question in the next section.

TO OVERCOME A DISTORTED AND IMPOVERISHED IMAGE OF SCIENCE: SOME IMPLICATIONS FOR SCIENCE TEACHING

The seven major distortions we have elicited do not constitute, as we have already emphasized, seven autonomous ‘deadly sins’. On the contrary, they form a relatively well-integrated conceptual framework and they support each other, transmitting an impoverished view of science, *and technology*, which generates negative attitudes in many students and makes meaningful learning more difficult. This is the reason why Guilbert and Meloche (1993) have stated, ‘A better understanding by science teachers in training of how science knowledge is constructed is not just a theoretical debate but a highly practical one’. In fact, the clarification of the possible distortions of the nature of science and technology makes possible the movement away from the typical reductionism of the activities included in science teaching and the incorporation of aspects which give a more adequate view of science as an open and creative activity. An activity centred in a *contextualized approach* (Klassen 2003) of *problematic situations* (Gil-Pérez et al. 2002) –or, in other words, *Large context problems* (Stinner 1995)- relevant to the construction of knowledge and/or the attainment of technological innovations, capable of satisfying human needs.

This strategy aims basically to involve pupils, with the aid and orientation of the teacher, in an open and creative work, inspired in that of scientists and technicians, thus including essential aspects currently ignored in science education, such as the following (Gil et al. 2002 & 2005):

The discussion of the possible interest and worthiness of studying the situations proposed, taking into account the STSE implications, in order to make this study meaningful and prevent students from becoming immersed in the treatment of a situation without having had the opportunity to form a first motivating idea about it. In this way pupils, as members of the scientific community, will have the occasion to practice decision making about undertaking (or not) a certain research or innovation (Aikenhead 1985).

The qualitative study of the situations, taking decisions -with the help of the necessary bibliographic researches- to define and delimit concrete problems. If we want pupils to really understand what they are doing, it is essential to begin with qualitative and meaningful approaches… as scientists themselves do.

The invention of concepts and forming of hypotheses as tentative answers, founded in pupils' previous knowledge and personal conceptions, which will help to focus the problems to be studied and orientate their treatment.

The elaboration and implementation of possible strategies for solving the problems, including, where appropriate, experimental designs to check hypotheses. It is necessary to highlight the interest of these designs and the implementation of experiments which demand (*and aid to develop*) a multiplicity of knowledge and skills, including technological work to solve the practical difficulties usually posed by designs.

The analysis and communication of the results, comparing them with those obtained by other pupils' teams and the scientific community. This can produce cognitive conflicts between different conceptions and demand auto and inter regulation, this is to say, the formation of new hypotheses and the reorientation of the research. At the same time this can be the occasion to approach the evolution, sometimes dramatic, experimented by the knowledge accepted by the scientific community. It is particularly important to enhance communication as an essential aspect of the collective dimension of scientific and technological work. This means that students must get acquainted with reading and writing scientific reports as well as with oral discussions.

The recapitulation of the work done, connecting the new constructions with the body of knowledge already possessed and paying attention to establishing bridges between different scientific domains, which occasionally may generate authentic scientific revolutions.

The contemplation of possible perspectives, such as the conception of new problems, the realisation and improvement of technological products, which can contribute to the reinforcement of pupils' interest.

All this allows the application of the new knowledge in a variety of situations to deepen and consolidate, putting special emphasis on the STSE relationships which frame scientific development and, even more, human development, without forgetting the serious situation of planetary emergency (Gil-Pérez et al. 2003), as international institutions demand of educators of any area (United Nations 1992).

We would like to highlight that *the orientations above do not constitute an algorithm* that tries to guide the pupils' activity step by step, but rather they must be taken as general indications which draw attention to essential aspects concerning the construction of scientific knowledge not sufficiently taken into account in science education. We are referring both to procedural and to axiological aspects such as STSE relationships (Solbes & Vilches 1997), decision-making (Aikenhead 1985), communication (Sutton 1998), etc., in order to create a climate of collective research undertaken by students' teams, acting as *novice researchers*, with the teacher's assistance. In this way, pupils participate in the (re)construction of knowledge and learn more meaningfully (Hodson 1993; Gil-Pérez et al. 2002; Gil-Pérez et al. 2005).

The inclusion of activities such as those mentioned above is an example of the positive influence that the clarification of the nature of science may have. But not everybody agrees on how convenient this reorientation of science education is when we are discussing the preparation of future scientists.

SCIENTIFIC LITERACY FOR ALL AGAINST SCIENTIST TRAINING?

A decontextualised, socially neutral presentation of scientific concepts, laws and theories, and the rest of distortions we have discussed, is usually justified by teachers and curriculum designers in terms of the demands of preparing students for work as future scientists and technologists. It is commonly argued that preparing specialists in physics requires an approach that focuses on the concepts, principles and laws of this discipline. Science education for responsible citizenship (with its emphasis on STSE issues and the development of critical awareness) is seen as an alternative form of education *for non-specialists*, but it is argued that society needs scientists and technicians. Is there really so much opposition?

It is our contention that the critical awareness we seek for non-specialists is just as important, and possibly more so, for future scientists. We are also of the opinion that a science education focused exclusively on the conceptual dimension is equally negative for the education of future scientists and technicians. As we have already pointed out, this orientation transmits a distorted and impoverished view of science that not only diminishes the interest of young people in scientific careers (Matthews 1991; Solbes & Vilches 1997) but also negatively affects conceptual learning. Together with Hodson (1992), we contend that "students develop their conceptual understanding and learn more about scientific inquiry by engaging in scientific inquiry, provided that there is sufficient opportunity for and support of reflection" (p. 551). If we are to achieve a meaningful understanding of concepts and theories, we must reorganize science learning into an activity that integrates conceptual, procedural and axiological dimensions (Duschl & Gitomer 1991). This paves the way for a more creative, open and socially contextualized view of science, in accordance with the real tentative nature of techno-scientific activities, in which critical awareness and questioning of what seems "natural" and "obvious" plays an essential role.

The pursuit of scientific literacy should not be seen as a 'deviation' or 'reduction' to make science accessible to the population as a whole, but as a reorientation of teaching also useful for future scientists; useful to modify the current socially accepted but distorted view of science and to fight the anti-science movements; useful to facilitate a meaningful conceptual learning. In other words, we reject the notion that the usual conceptual reductionism constitutes an obstacle to citizens' literacy *but* a requisite for the preparation of future scientists and technicians. In our view, it is an obstacle *for both*. Both demand *immersion in a techno-scientific culture*. Both need to overcome the oblivion of technology.

CONCLUSION: PROMOTING THE DECADE OF EDUCATION FOR A SUSTAINABLE FUTURE: AN ETHICAL COMMITMENT

Last but not least, there is yet another important reason to overcome conceptual reductionism in physics education: the United Nations General Assembly, given the serious and urgent problems humanity has to face nowadays, has adopted a resolution establishing a *Decade of Education for Sustainable Development* (2005-2014). This constitutes a new urgent call to educators *of all levels and areas* to contribute to citizens' awareness and understanding of the situation of planetary emergency (Bybee 1991) in order to enable them to participate in well-founded decision-making.

The World Conference on Science Education for the 21st Century (Budapest Declaration 1999) and the *National Science Education Standards* (National Research Council 1996) are good examples of the importance experts and international institutions such as UNESCO place on citizens' literacy for decision-making about socio-techno-scientific issues. In the opinion of many authors (Fourez 1994; Bybee 1997; DeBoer 2000; Gil-Pérez & Vilches 2005), the preparation of citizens to participate in decision-making justifies scientific *and technological* literacy as a basic component of citizens' education and, above all, of scientists' training.

We are at the beginning of a decade that will be decisive in one sense or another: sadly decisive if we continue anchored in our routines and we do not take conscience of the need to revert a degradation process that is constantly sending us unequivocal signals in form of global heating, unnatural catastrophes, loss of biological and cultural diversity, millions of deaths by inanition and wars -consequence of suicidal short-sighted interests and fundamentalisms-, dramatic migrations… and a long etcetera; happily decisive if we are capable of generating a universal trend for a sustainable future that has to begin right now.

This is the aim that we can and must incorporate into science education, teaching and research, conscious of the difficulties, but determined to contribute, as educators, scientists and citizens, to build up the conditions of a sustainable future. And even though research in science education has shown that the state of the world and education for sustainability are absent in most curricula (Gil-Pérez et al. 2003), in fact there are many opportunities to introduce them in physics education. For instance, studying energy constitutes an excellent opportunity to deal with the world's situation and to contribute to a better understanding of the problems and possible action to be taken in the light of the current situation of planetary emergency (Furió et al. 2005).

This is for us a very important ethical commitment.

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