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Physics Teaching in the Search for Its Self

From Physics as a Discipline to Physics as a Discipline-Culture

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Abstract. The crisis in physics education necessitates searching for new relevant meanings of physics knowledge. This paper advocates regarding physics as the dialogue among discipline-cultures, rather than as a cluster of disciplines to be an appropriate subject of science education. In a discipline-culture one can distinguish elements of knowledge as belonging to either (1) central principles and paradigms – nucleus, (2) normal disciplinary area – body of knowledge or (3) rival knowledge of the subject – periphery. It appears that Physics cannot be represented as a simple dynamic wholeness, that is, cannot be arranged in a single tripartite (triadic) structure (this result presents a deconstruction), but incorporates several discipline-cultures. Bound together by family similarity, they maintain a conceptual discourse. Teaching physics as a culture is performed in polyphonic space of different worldviews; in other words, it is performed in a Kontrapunkt. Implications of the tripartite code are suggested with regard to representation of scientific revolutions, individual conceptual change, physics curricula and the typology of students learning science.

1. Introduction

> *Besides the future engineers are other less numerous pupils, destined in their turn to become teachers, and so they must go to the very root of the matter; a profound and exact knowledge of first principles is above all indispensable for them* (Poincaré 1903)

The epigraph serving as the starting point for the article represents the criticism by Poincare, a prominent scientist at the beginning of the twentieth century. It addressed the way science was (and still frequently is) taught. Poincare actually recognized that the student population in science classes includes pupils whose needs and interests vary. In particular, he claimed that:

- science instruction is commonly oriented towards students who will become engineers;
- a different type of teaching is necessary for those who aim to become science teachers;
- the scientific knowledge relevant to future teachers is different to that needed by future engineers, being of higher conceptual quality and more oriented to the fundamentals.

It is important to realize that the subject matter knowledge required for teacher training extends the expertise of many science practitioners. In fact, modern society empowers a group of professionals possessing a new *scientific* discourse related through multiple interdisciplinary texts with other scientific (also humanitarian) discourses – “science teaching”. The latter is still in a stage of maturation (Redish 1999) or, as expressed in the title of this work, “in searching for its self”. To be successful, science teaching, as an area of expertise, should realize the necessity for *conscious* self-reflection.

It is recognized among science educators that scientists, although they are frequently teachers themselves, often fail to consider science in an educational perspective (e.g., DeBoer 1991). Matthews reflected this perception in the play of words *Time for Science Education* (Matthews 2000) in the title of his recent book. We do not address Science in general (a poorly defined concept), but the stereotype of its representative image, held by university professors.[1] Kuhn termed this perception – “normal science” (after being himself a “normal” physicist at the beginning of his career).

This paper addresses only two aspects of science (physics) education, viz. “commonplace subject matter” and “commonplace learner” (Schwab 1964, pp. 4–47). Regarding the former, many physicists, as well as physics teachers, believe that all physics curricula should include certain topics and concepts, which are regarded as “proper knowledge” (as used by “normal” scientists). However, it was the reservation in brackets that prompted us to dispute the validity of this widely accepted assertion with regard to *education*. In this context we will consider the knowledge and *not* the texts or discourses that produce scientific knowledge. Indeed, the current situation in physics education is that original texts normally do not play any role in teaching; as it is well known, they are almost never included in the bibliographies of general physics courses. Leaving aside discussion regarding the necessity, or appropriateness, of using original texts for instruction, we will deal here with the *contents* that constitute instructional resources that should be (in our view) presented in physics instruction. We will consider their global organization, their nature and the way of teaching physics as a discipline-culture rather than just a discipline. Being expanded to “culture”, discipline possesses certain simple organization (structure), extremely useful for development of scientific curriculum. We should also mention that despite the close subject and terminology, “structure of the discipline” (e.g., Schwab 1964, 1978[2]) or using this concept by Bruner (1960) and Piaget (1968), the ideas of this study possess a different meaning due to their actual and possible relations to a wider area of knowledge (discipline-culture), the one including texts and discourses. The introduced here structure expresses, on the first place, just this difference, essential for the area of science curriculum.

Importantly, the concept of discipline-culture emerged in the process of evaluation of physics curriculum and seeking its improvement. That is we “contemplate” physics in the perspective of its teaching. This presents a special and especially effective way of “cultural reflection”. Observing the introductory physics course not as a part of professional training, but as an important sub-culture, we seek the way to integrate physics teaching into the education of Culture. Within this program, we perceived a natural and rather simple way to consider basic physical theories represented in their important features by a simple model, seemingly applicable also to other scientific as well as non-scientific domains. This model might help the physics teacher (and subsequently a student) to observe and attain a Gestalt of the whole great area of the knowledge affiliated to physics, as a culture. At the same time, we intended to remove the impenetrable wall established by the paradigm of "Two cultures" (Snow 1961).

Pursuing this goal, we are different from the attempts of philosophers of science[3] who usually try to represent science *as it is, and not as it is to be consumed (that is studied)*. Thus, for instance, the model suggested by us will be less inclusive than scientific programs of Lakatos (1970). We may mention a close similarity of our approach to that of Duhem (1906/1954), who in his celebrated work addressed the nature of science in a perspective of physics teaching. Our model promises to be convenient for education, at least because it is useful and can represent other "common places" of science education, by organizing them in a similar manner. (This makes common places compatible and producing a system.) At the same time the model we suggest is not trivial, possessing a high potential for the description of fine features of scientific discourse: a dialogue between different theories, their competition, crises of discourses, scientific revolutions etc.

The suggested representation of basic physical disciplines as "cultural wholeness" provides an opportunity to realize the limited validity of separation between physics and chemistry. Such separation could make sense only if each of these areas presented certain wholeness. We investigated this wholeness and performed deconstruction (Derrida 1976) of this subject.

Among the implications of the approach we suggested (1) a new representation of scientific revolution, (2) a new representation of conceptual change of the learner; (3) a new guiding principle in construction of physics curricula; and (4) a new characteristic of physics students, currently considered in a simple dichotomy of either able or unable to learn physics.

2. From a Discipline to a Culture

Physics disciplines (mechanics, electricity, etc.) belong to inclusive discursive areas structurally similar to cultures. One can arrive at such a perspective also through a critical consideration of the present instruction of physics.

2.1. HOW IS PHYSICS TAUGHT?

In schools and universities, physics is regularly taught as an engineering discipline

Even a brief review of contemporary textbooks used in universities, colleges and high schools shows that physics is taught as a compendium of factual knowledge delivered in a sequence of disciplines (mechanics, hydrodynamics, thermodynamics, electricity, and so on). The subject matter is presented in the form of rules, laws and principles, mathematically elaborated by formulas and equations, and illustrated with experiments and representative examples. Well-structured mathematical formalism is used to train the application of the theory to problems. It therefore should not surprise us that many physics educators consider the mastering of mathematics as an indisputable premise of physics education. In many universities the type of physics course is determined according to the mathematics used: "calculus", "algebra" and "conceptual" (without mathematics) (e.g., Hecht 1996a, b; Hewitt 1998). Furthermore, in most universities prospective physicists and engineers study in the same classes, and are instructed in the same manner. This is reflected in the titles of the textbooks (e.g., Giancoli 1988; Fishbane et al. 1993; Lerner 1996; Serway 1997; Tipler 1999).

2.2. DISCIPLINE AND CULTURE

Since physics discipline does not simply describe the world but interprets it, it is appropriate to present the former as some general wholeness – a discipline-culture. Most of introductory physics courses do not fit the contemporary conception of culture.

It is unlikely that the type of instruction described above will endow prospective physicists with its "spirit", values, nature and commitments. The appropriateness of these facets of knowledge for prospective educators is especially obvious. Many prominent physicists have indeed, expressed this view.[4] In order to discover how to educate people differently, one first has to clarify the nature of physics knowledge, establishing its organization and conceptual hierarchy.

Each of the fundamental sciences (such as physics, chemistry and biology) pretends to describe the whole world. In a sense, they create their own virtual worlds. They produce statements regarding the nature of reality, adopt some and reject others, which are regarded as non-disciplinary. This differentiation makes the discipline non-neutral, because it distinguishes between the statements that belong to it and those that do not. Some of those rejected do not, however, disappear; they establish the horizon of the discipline.

What distinguishes between disciplinary and non-disciplinary knowledge? In other words, what makes an aggregate of knowledge a discipline? That something should be related to all of its components. That something is the *structure* of the discourse (an arrangement of statements in a hierarchical and meaningfully related manner) that establishes a discipline – this is a point well argued by Joseph Schwab forty years ago (Schwab 1964).

The meaning of the structure is provided by a group of unique elements that can be called the *center* (Derrida 1967/1978). Practitioners often uncritically identify some of these elements of knowledge to be the disciplinary knowledge itself. Such are the principles of symmetry, the requirement for in- and co-variance of physical laws and concepts, causality, etc. The center includes the ideas, which determine frames and angles of consideration, applied by the discipline explicitly or tacitly. Such are, for instance, the ideas of absolute space and time in Newtonian physics. We identify this unique and, in a sense, a priori unity as the *nucleus* of the discipline.

Regarding the criteria of belongingness to the *nucleus* we might mention that this apparently non-simple decision might be pragmatic. Indeed, our model is suggested, first of all for the goals of teaching. It is the simplest model which however succeeds in catching the important aspect of science, namely its being a culture. For example, keeping as a goal school teaching of physics, we could identify mechanics of 18th and 19th centuries with Newtonian mechanics, which is an obvious simplification. The theories by Hertz, Kirchhoff and Mach were all in critical opposition to the Newtonian theory. Even Galileo's mechanics did not coincide with Newtonian mechanics. To include these interesting and important[5] approaches one should upgrade the initially simple idea of nucleus. One might distinguish in it a core, shared by all mentioned theories, and segments that specify each from the theories. Thus, absolute time and space, rigid bodies (or point masses), would belong to the core, whereas Newton's first law could be located in a nuclear segment, also incorporating Mach's principle, etc.

To remain within a reasonable education format, one would refrain from introducing a different nucleus for each of the mentioned theories. Such a step might be unavoidable with regard to the theories essentially incompatible with the Newtonian one. Such were, for instance, the vortex theory of Descartes, Prigogine's theory including irreversibility, Vlasov's theory of statistical nature, etc. We, however, will preserve our discussion within a simple model, since it appears to be sufficiently beneficial for the considered goal.

For a given nucleus, all those scientific statements that are consistent with its statements constitute the *body* knowledge of the discipline, while the others (which genealogically, by subject or in other way) could be related to the nucleus, but conflict with it, belong to the horizon, or *periphery* of the structure. There is thus formed a super-disciplinary world which is consistent and ordered in itself, although conflicts with the point of view of other "super-disciplines". This leads us to state that:

> Any fundamental physical theory arranges all statements in a centralized structure, a sort of quasi-culture, with its own values, language, conceptions, norms, etc. This structure, like a cell, has a nucleus, body, and periphery.

Our perspective essentially extends the "living space" of physics, enabling us to examine and accumulate a variety of conceptions; it provides a tool for formulating in a simple way what constitutes physics. Within this perspective it becomes clear that the common method of instruction in physics focuses mainly, if not solely, on the body-knowledge. Many practitioners identify physics with its body-knowledge, displaying beliefs that philosophers regard as naïve (Bunge 1973, p. 4). Actually, Thomas Kuhn's notions of *normal* science and *normal* scientists (Kuhn 1956) represent this phenomenon.

Some prominent physicists, such as Niels Bohr and his colleagues, held another perspective. They considered the *nucleus* to be the most important subject for research activity in physics. In fact, considering science in its development the philosophy of science usually addresses the nuclear contents. Thus for Karl Popper it is the paradigm of a nucleus which presents a subject for permanent analysis, testing and refutation.

At all times in the history of science there have been enthusiasts (also prominent scientists), who developed marginal approaches with respect to the prevailing paradigm practiced by the majority of the scientific community. Thus David Bohm and his followers developed their own interpretation of the quantum theory (e.g., Bohm & Peat 1987, pp. 88–97), not accepted by the majority of practitioners who follow the Copenhagen paradigm.[6] Similarly, some of the works of Erwin Schrödinger and Louis de Broglie belonged to the marginal areas of then contemporary physics. Among philosophers of science, Paul Feyerabend ascribed great importance to the development of ideas belonging, in our terms, to the periphery area of physics disciplines (Feyerabend 1975).

The structure introduced by us might cause misinterpretation that we follow the structuralist framework of thought with regard to science. In fact, our model does not fit the structuralist dogma. Thus, the periphery zone of the organization, which incorporates texts representing "other" views, essentially destroys the order prescribed by structuralism. We do *not* argue for science as a systemized wholeness, which is formed and develops by virtue of some *intrinsic* laws. The development of a scientific theory, in our view, might be rather due to the dialogic interaction with the theories of the periphery, not only (and might be even less) by virtue of the dogma of the nucleus. Lacan could say that the development of science is performed against the background of the "beliefs" of the "other". Science cannot exist without the "other". Any scientific theory projects its beliefs on the other view and vise versa; this is a dialogic interaction, instead of juxtaposition or succession of two monologues. It may resemble an argument, debate between incompatible theories. In fact, being isolated, any of the competing pair would be unable for self-expression and production of the correspondent bulk of the normal knowledge. Moreover, such normal knowledge, which results from the competition, appears highly disordered (also at odds with structuralism), making it impossible to assume an ordered knowledge even as an initial state. This endless interaction between competitive and essentially different theories cannot be restricted to a mere external disturbance of one for the other, but it is just their incompatibility that presents a pledge for the permanent existence and development of science, incorporating both competitors. By analogy, our discipline-culture is in relation to structuralist view on science (Piaget, 1968) similarly to the relation between the dialogic theory of personality of Lacan (1973) and the anthropocentric theory of individual development of Piaget.

In our view, it is physics as a quasi-culture that should constitute a subject of education. Students will study physics within the horizon of the texts (knowledge) "observed" by physics, while realizing their status within the particular perspective. The new approach makes explicit those indispensable elements that determine physical knowledge but often remain implicit and deprived of attention they deserve. Studying physics begins to transform itself to a study of a culture. What makes us closer to *culture* is the presence of the "Other" (other knowledge). What allows us to talk about teaching *physics* as a Culture will be that we will present physics not only as Knowledge, but also as a space of statements (views, theories) of physicists, a discourse, and that is, as a Text.[7]

The results of the present day common focus on the "normal" area often disappoints physicists with regards to students' conceptual understanding.[8] We may proceed and say that the most probable product of teaching the "normal" knowledge is a "normal" physicist. If so, this type of teaching approach contributes to the crisis, and to the dissatisfaction of those numerous students who expect to acquire other kinds of knowledge, corresponding to different cultural interests.

2.3. THE STATUS OF THE LEARNER

Some science educators regard the learning process as similar to that of scientific research. We criticize this conception suggesting another status of learner. The new approach requires addressing cultural codes.

The idea that "a learner is similar to a researcher" is frequent in science education research (e.g., Driver 1983; (Curavita & Hallden 1994) Gopnik 1996). With regard to physics, it means that the student in the course of learning makes discoveries, which is similar to a physicist performing research (not to be confused with the permanent learning of scientist (Habermas 1981)). However, although the same term is applied when both the scientist and the learner construct knowledge, it has different meanings.

1. In any introductory course, a learner aims to familiarize him/herself with a whole area of knowledge established by the scientific community. In this activity a teacher guides either explicitly or implicitly, making his/her way as direct as possible, suppressing all kind of difficulties and uncertainties. A researcher, on the other hand, constructs the previously unknown, although based on the known.[9] This discovery essentially includes contingency. It is apparent that the most important scientific discoveries were adventures, not recipe applications.[10] An essential difference is the belonging of scientists to the scientific discourse, without which

discoveries are impossible. We can express the conceptual relationship between the learner and scientist as following:

$$\frac{\text{learner}}{\text{scientist}} = \frac{\text{study}}{\text{discovery}} = \frac{\text{linear}}{\text{broken}} = \frac{\text{determinicity}}{\text{contingency}} = \frac{\text{disciplinarity}}{\text{discursiveness}} \qquad (*)$$

To the same extent, to which it is impossible to reduce discursiveness to disciplinarily, contingency into determinicity, it is impossible to represent a scientific discovery by the learning activity. The study-discovery relationship is understood here as addressing the goals rather than processes. Our approach in this study was inspired by the last of the concept relationships (*).

2. The learner must acquaint him/herself with different theories, metaphysical conceptualizations, forms of presentation, and cultural styles. In a rather *short time* the student must familiarize themselves with at least four fundamental physical disciplines: (i) classical mechanics, (ii) electrodynamics and the special theory of relativity, (iii) thermodynamics, and (iv) quantum theory (Heisenberg 1958). In contrast, a researcher usually practices a specific method and focuses on a problem in a particular area.

3. School studies are short in time, and aim to foster a broad interest in knowledge accumulated over a long time. The learner *can* afford (and normally is expected) to construct a *superficial* knowledge of a range of topics, "to catch the ideas" of a variety of conceptions. Unlike the researcher, he/she *cannot* afford time and energy for a comprehensive exploration. Therefore, learning does not presume a discovery, although it represents the first step to it.

This perception matches the vision of Bibler (1999, pp. 12–14) who sees human activity in three categories: Shared Labor (as in an industrial plant), Common Labor (as in the activity of a spread community of scientists), and Learning (as an individual activity within an educational institution). The unique feature of the latter is that it does not aim to produce any social commodity. Moreover, being only on the edge of productive activity, it is normal even to refrain from such in the course of learning. To guide the learner in this way is among the most important functions of the teacher.[11]

Learning appears as if lacking any sensed and concrete result. This is because the result of learning is not a "thing" but rather an ability to produce "things". Learning causes a change in the state of the learner that cannot be transferred to anybody else. This statement becomes especially obvious with regard to culture. What do we mean by learning the culture? In a way, we ask for the unknown in the conceptual proportion:

$$\frac{\text{learner}}{\text{cultural person}} = \frac{?}{\text{live\_in\_culture}}$$

Seemingly "to familiarize the culture" presents an appropriate choice and a goal for the teacher's guidance. It is through such a process that the cultural basis of knowledge is established. Culture is then conceived as a personality to be appreciated and explored, rather than a tool to be mastered. This view implies the dialogical nature of learning. This learning may significantly soften the common relationship "human – petrified material" currently prevailing in science education. The dialogue then is impossible, more exactly, trivial, since a discipline presents a mere dead piece, a remnant of a living body of science. On the other hand discipline-culture provides a whole spectrum of answers in a dialogue. It is as if discipline-culture is asking the learner "whose side are you taking?" – a question that will not leave indifferent many of the learners. The physics lesson will then encourage a different kind of thinking: a "cultural" one. What comprises such learning?

One can distinguish between two major approaches in the learning of a culture. The first involves learning "*from inside*", i.e., internalizing the subject while living within it. This way an individual learns about and explores the culture, to which he/she was born, the mother tongue, etc.[12] This, also, is the way in which professionals continue to acquire knowledge within their areas of expertise. Such learning involves the hermeneutic reading of texts and the continual acquisition of additional insights into their significance, additional layers of meaning. Obviously this type of learning a culture "from within" would be practically impossible in a school environment, if only because of time restraints.

By contrast, learning a culture "*from outside*", as an unfamiliar subject, presumes general views and identifying characterizing features. It implies the need to address the structure, and to acquire holistic information of the culture. This information is expressed in terms of "cultural codes", unknown to the stranger. Among such codes are triple and binary ones (the latter are also known as "binary oppositions"). In the following, we consider and elaborate the important triple code with regard to the simplest organization of a discipline-culture.

3. Construction

We outline the presentation of some discipline-cultures in terms of triadic code.

3.1. THE STRUCTURE OF THE DISCIPLINE-CULTURE

A discipline-culture has a structure resembling that of a biological cell.

We have already suggested that a discipline-culture can be structurally represented by an organization, which might resemble a biological cell,[13] that is made up of three domains (Figure 1):

I *nucleus* – defines the identity of the discipline-culture, includes its fundamental principles, paradigm and claims of meta-disciplinary nature;

II *body* – incorporates all normal disciplinary knowledge. This is established knowledge, each item of which is based on the principles contained in the nucleus;

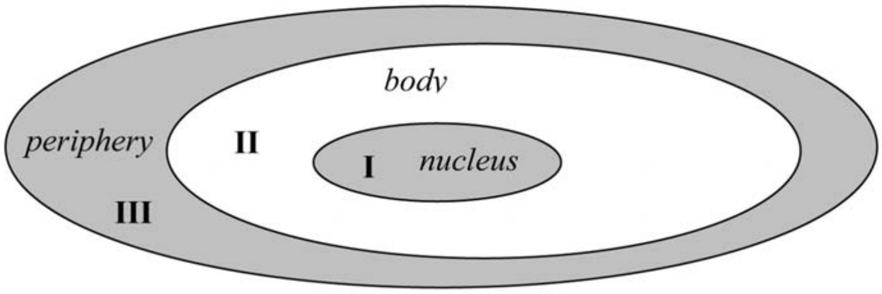

Figure 1. The cell structure of discipline-culture.

III *periphery* – contains the knowledge that conflicts with the principles of the particular nucleus. This knowledge presents a challenge for the fundamental claims of the nucleus and possibly a mechanism for its change and reconstruction.

The rest of knowledge, outside the periphery, is not within the horizon of the discipline-culture, as it does not address the subject matter or is identified as non-scientific in nature.

Such a rigid organization implies a mature culture defined as a culture-of-rules (Lotman & Uspensky 1978). Its nucleus includes the rules of self-reproduction, according to which new texts should be constructed. The opposite type of culture, according to Lothman and Uspensky, is the culture-of-text, which contains samples of texts, but not rules of text production. The cultures thus differ in their attitude to a newly introduced text. The culture-of-rules tests whether the new text conforms to the nucleus. If it does, it is included in the normal disciplinary knowledge. If not, it is assigned to the peripheral area (conflicting, but still scientific) or ignored (when identified as non-scientific). The culture-of-texts, on the other hand, is much less restrictive and therefore is more accumulative in nature. It might represent a new area of knowledge (such as science before the scientific revolution of the 17th century), or knowledge of the humanities (such as politics, art, literature, etc.).

Each basic discipline within physics (we have mentioned four) originates in a disciplinary culture which allows its representation in the mentioned triadic form. Each such culture considering itself at the center, often ignores or disparagingly refers to the theories of other cultures, assigning them to its periphery.

Even a brief review of standard physics textbooks reveals that fundamental claims, belonging to the nucleus receive little, if any, attention. As to peripheral knowledge, this is either ignored or presented as if it belonged to the norm (i.e., ignoring its conflict with the nucleus). Moreover, some textbooks present a view of harmony reigning between different physical disciplines. This belief can be expressed as a *principle of correspondence*. For example, relativistic physics gradually transforms into classical mechanics by going to the limit of low velocities,[14] quantum mechanics gradually transforms into macroscopic classical physics in the limit of big quantum numbers (or nullifying Plank constant),[15] reversible classical

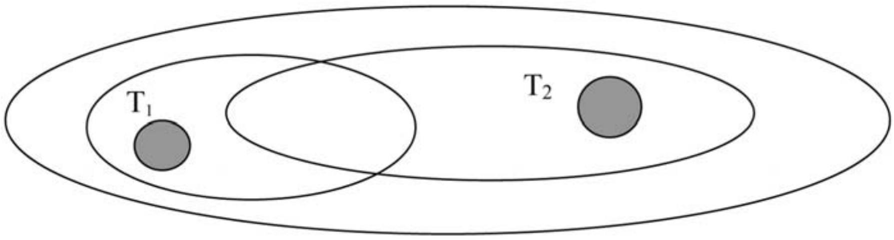

Figure 2. The relationship of two fundamental theories perceived as discipline-cultures. (Somewhat simplified case for the periphery is shown).

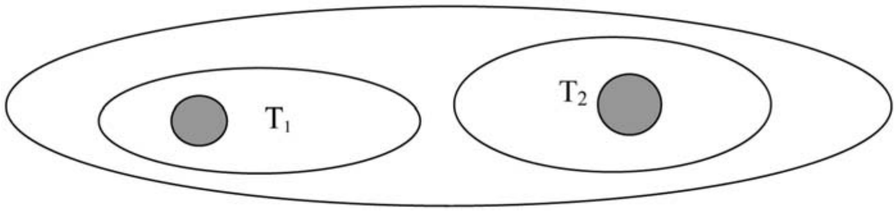

Figure 3. The relationship of two fundamental theories perceived as scientific discourses. (The simplest case is shown).

mechanics gradually transforms into irreversible thermodynamics[16] and so on. The fact that some physical results can be obtained by two fundamental theories (only in a certain area of parameters) might cause a belief that one theory is included in the other. Using the discipline-culture model introduced by us we can easily represent the relationship between the two theories: the body areas of two theories may overlay. However, the important thing is that the nuclei do not overlap. Peripheral zones can overlay. All together we arrive at the representation of Figure 2.

Considering physics as a whole (Section 4.2), we will return in greater details to the problem of the relationship between the physics disciplines. Meanwhile, however, we should emphasize that we consider here physics as *knowledge*. Were we seeking representation of physics as a *discourse*, we could obtain a diagram in which body areas would also be separated (Figure 3). Indeed even the statements that sound similarly might have a totally different meaning in different discourses. All together, the nucleus and the body of theory T_2 may belong to the periphery of T_1 and vice versa.

We see that the tripartite organization as a model of discipline-culture is able explicitly represent specific types of conceptual relationship between the different domains of physics.

3.2. CLASSICAL MECHANICS AS A DISCIPLINE-CULTURE

The arrangement of the cell-like structure implies substantial changes in the curriculum of the most traditional discipline of physics – Classical Mechanics.

When Classical Mechanics is regarded within a *discipline-culture* conception, its *nucleus* contains Newtonian concepts of absolute space, absolute time and material points (or, later introduced, absolutely rigid bodies). The ideas of translational and directional symmetry, homogeneity and time-space independence all appear explicitly in the nucleus. We also find there the principle of inertia, the concept of inertial mass (persevering the state of homogenous motion), the concept of force (the faculty of interaction determined solely by the relative positions of the interacting bodies), and the symmetry of interaction.

It is on this basis that the body knowledge of classical mechanics is constructed, providing numerous applications of the fundamentals, explaining great variety of natural phenomena as well as technological devices. Thus, the body knowledge includes all rules and laws of ballistic motion, Kepler's laws of planetary motion, work-energy theorem, lever, screw, inclined plane and so on and so forth.

The *periphery* holds the items of knowledge at variance with the nucleus. Such are: relativistic deviations from Newton's account at high speeds, the Michelson–Morley experiment, the Mercury trajectory anomaly, the wave behavior of mass particles (electron diffraction, tunneling), interaction of charged particles (field mediation, vector interaction of electrical charges), thermodynamic irreversibility of a many body system, etc. These phenomena were explained in terms of the disciplines historically subsequent to Classical Mechanics such as the Theory of Relativity, the Quantum Theory, and Classical Electromagnetism. Although contradicting the nucleus, all they are within the vision of Classical Mechanics as a discipline-culture, and in this sense belong to it.

Moreover, the periphery of Classical Mechanics also includes alternative theories from the past that have been surpassed by Newtonian theory: the Aristotelian theory of motion, the impetus theory of Philoponus and Buridan, Descartes' theory of vortices, Prigogine's dynamic theory etc. Thus a characteristic of the marginal, peripheral domain in this discipline-culture is that it includes both historically precedent and subsequent, more advanced, physical knowledge. Classical Mechanics as a discipline-culture thus remembers its past (what was believed and why, how it was reconsidered and replaced) and it foresees its future defeat (pointing at the phenomena, which were difficult to explain and were accounted for by succeeding theories).

We argue that such organization is appropriate and necessary for a cultural perception of the discipline, even if seems at the first glance as complex or unnecessary for an introductory course. The holistic image of mechanics, its meaning, scope of validity and extent of reliability could emerge in the learner only from the acquaintance with the principal ideas and claims, and with the conditions, presumptions, and limitations of this knowledge. This kind of knowledge is not fostered by assessing students in manipulation with complex formalism (the body knowledge). The alternative approach is conceptually rich and less complex formally, which could make it comprehensive and wished by many of the students of the introductory physics course.[17]

3.3. LORENTZ MAGNETIC FORCE WITHIN THE DISCIPLINE-CULTURE

Presenting the Lorentz force in the general physics course as an element of normal knowledge is to ignore its inconsistency with Newtonian paradigm. The discipline-culture approach corrects this deficiency.

The Lorentz, or magnetic force ($\mathbf{F}_m = q[\mathbf{v} \times \mathbf{B})$ may serve a good example illustrating the discipline-culture approach. In general physics courses, magnetic force is usually presented after classical mechanics, in electromagnetism. Commonly, however, the instruction remains under the umbrella of *classical* physics, and does not address the fact that the Lorentz force does not fit the Newtonian paradigm of interaction (Galili & Kaplan 1997): particles in vacuum, interacting through *central* forces. Students' attention, when focused on the application of the formula in problem solving,[18] easily passes over the huge conceptual leap to the new framework of interaction (e.g., Galili 1995). Indeed, the Newtonian view excludes *field*, a concept essential to Lorentz force.[19]

Moreover, a totally awkward feature is the force dependence on the velocity of the charge as registered relative to a particular observer. The magnetic force is curiously different in magnitude to different inertial frames (and it totally disappears for the observer moving with the charge). Textbooks commonly ignore this point, as if perceiving a choice to teach relativistic theory (including the observer) or to remain within the classical physics (no observer-dependent forces). Their dilemma is that *consistency* seemingly prescribes that choosing the latter one should ignore the former, but on the other hand, the exclusion of Lorentz force would significantly reduce the "life-space" of the discipline.

Given this teaching policy, it is reasonable to assume that the learner refers Lorentz forces to the normal knowledge category established in mechanics, and this is a conceptual error. The approach of discipline-culture changes the situation, suggesting instead to use the Lorentz force *and* to explicitly mention its conflict with the Newtonian paradigm of interaction, defining its status as belonging to the periphery of classical mechanics. By using this perspective the learner is given a chance to discover the fundamental constraints of classical mechanics otherwise masked in the routine problem-solving activity. He/she "discovers" the concept of the *observer* as introducing a crisis into the classical mechanics, thus also making the nature of Newtonian mechanics distinct.

The peripheral status of Lorentz force in classical mechanics prepares the learner for the course of classical electromagnetism. Also in the form of discipline-culture, electromagnetism regards Lorentz force as an important element, constituting the paradigm of interaction valid in relativistic theory. As such it belongs to the nucleus, although it might be less fundamental than space-time relationship.

After taking both courses, introductory and advanced, the learner becomes aware of how the Lorentz force and other peripheral items in classical mechanics, the Aristotelian framework of forces and the medieval force-of-motion (impetus), represent a conceptual development of the force-interaction concept. This exemplifies what we mean by cultural teaching of physics: the recognition of the importance of each link in the conceptual evolution, in our case, the concept of force interaction.

3.4. ELECTRODYNAMICS AS A DISCIPLINE-CULTURE

Electrodynamics is a unique domain where the attribute "classical" implies "relativistic". The cell-structure of electrodynamics makes the absence of self-consistent Newtonian electrodynamics explicit.

In Classical Electrodynamics the nucleus contains the postulates of the Special Theory of Relativity, non-Euclidian space-time symmetry, the space-time relationship (metric), electrical charges, the concept of field (the mediator of interaction), and conceptual tools, such as Faraday's lines of force. The nucleus generates several fundamental laws: those of Gauss, Faraday, Ampere, Maxwell, Lorentz force. In the normal domain of the structure are all those applications of the nucleus, the contents usually taught in traditional courses of electrodynamics (e.g., Jackson 1962).

In the periphery of classical electrodynamics one finds the phenomena that classical electrodynamics fails to explain: the movement of atomic electrons without radiation, photoelectric phenomenon, the blackbody radiation, etc. All these challenged classical electrodynamics and caused it to be replaced by another discipline, quantum electrodynamics.

Also, the periphery of classical electrodynamics includes the medieval Alhazen theory of Light (as composed of rays), the theory of aether, and Ampere's, Weber's and Lorentz' theories from more recent times. As in the case of classical mechanics, the peripheral knowledge here presents a contrasting background to the fundamentals of the classical field picture, refining the meaning of the nucleus and promising its replacement. Such extended knowledge reveals to the students the fundamental features of the electrodynamics picture of the world, emphasizing its fundamental attributes. It is the appreciation of the specific discourse related to the electrodynamics (its nucleus and periphery) that encourages its holistic perception often missed when the instruction is focused on the body area of normal knowledge.

4. Deconstruction of Physics

Outside view and teaching of physics may imply an image of something whole. We challenge this conception by means of deconstruction.

4.1. NEW VISION

The new vision in humanities is of value for the interpretation of physics as a culture.

Observing physics may impose an image of physics as a unity. Expressions such as "philosophy of physics", "history of physics", "language of physics", "conceptual physics", "applied physics", "physics teaching" are so regular (titles of courses, books, disciplines, etc.) that they suggest an almost universal perception that the term "physics" signifies a subject having all-embracing fundamentals, well determined history, genealogy, etc. If this were so, it would be possible to represent physics in terms of the tripartite code as a *single* organized wholeness. We shall analyze this assumption, and argue against it.

In passing, it can be noted that a similar reconsideration of standards, creating non-classical vision occurred in humanities in the late sixties and early seventies of the last century. The new vision of cultural relationship between different interpretations and ideas regarding the same subject (variously dubbed post-structuralism, deconstruction, post-modernism, post-neoclassicism, etc.) heralded the post-structuralist era. For science education all these "critical approaches" could be of interest because of their addressing a cultural discourse: the post-structural analysis of text (by Barthes 1987), the deconstruction of binary oppositions in culture (by Derrida 1976), post-neoclassical synergetics (by Prigogine 1984), the semiotic discourse on culture (by Lothman 1978). The latter, for example, provides us with the claim: *each culture is encoded in at least two codes* – promising an interesting application to physics education (e.g., the nucleus of Newtonian mechanics is codified in mathematical and physical codes: mathematical space-time and physical inertia and force). For the present discussion, it is sufficient to refer to any critique of the structural claim as a "deconstruction". We shall illustrate such an approach in the perspective of physics education.

4.2. PHYSICS

Physics as a whole appears apt to be adequately represented as a sort of dialogue between discipline-cultures, which is in contrast to its common image as a single body of knowledge.

Above we have elaborated a vision of how a physics discipline can be presented as a discipline-culture possessing a triadic (cell) organization. This approach can be applied to each of the fundamental disciplines of physics. Heisenberg mentioned four such disciplines (Heisenberg, 1958) and added a special place for the General Theory of Relativity. Such new areas as fractals, non-linear physics and other interdisciplinary domains have currently been added to physics.

The belief that physics, as a whole, is a discipline (possibly the most fundamental one within natural science) is common. This belief is reflected in the highly popular perception of wholeness and certain organization, implying the existence of a center containing the "genus" of physics. Physicists believe in something common that identifies physics. If that something were knowledge we would expect that all physics knowledge (texts) could be codified in a single triadic arrangement. This belief, we submit, is mistaken because, as we have seen: (1) each discipline-culture creates such a structure and (2) different discipline-cultures may consider the *same* element in different meanings (thus providing it with different status in those organizations). This quality makes separate discipline-cultures conceptually incompatible. For example, if classical mechanics places Lorentz force in its periphery, in classical electrodynamics it becomes fundamental; if classical mechanics consider time and space independent, classical electrodynamics intertwine them.

Physics as a whole, therefore, does not allow codification into a single triadic structure. The relationship between all discipline-cultures comprising physics is complex and complementary in nature because they all represent different, and equally essential, aspects of nature. One may call them "Pictures of Nature", reflecting the cultural sense of their interpretations.

The existence of several complementary structures without a unified hierarchy challenges the main tenet of the structuralist dogma (unique nucleus, unique all-embracing structure) regarding physics, which loses its image of a formally rigid, unique construct. This physics might seem less "whole" or even less "scientific" to some people. However, at the same time, and by the very virtue of this lack of rigidity, domains of physical science could be seen as having the human feature of "family similarity" (to use Wittgenstein's terminology (1968, §§65–71)). For example, the conflicting pictures created by mechanics and thermodynamics are related (but not reconciled) by means of statistical physics, which incorporates elements of mechanics, as well as such from thermodynamics. Classical and relativistic mechanics could be related by weak relativistic approximation. Similarly quantum mechanics has a quasi-classical approximation in its arsenal. We thus observe a sort of relationship which resembles a family. In a simplest case, we may represent this situation by a structure in which several discipline-cultures have separate (incompatible) nuclei, but partially overlaying body areas of normal knowledge (bridging approximations) and the all-embracing periphery (Figure 4). This figure demonstrates the non-central nature of physics.

The fact that physics cannot be regarded as *a* discipline-culture causes extreme difficulty in attaining its traditionally sought Gestalt. Since the latter represents a

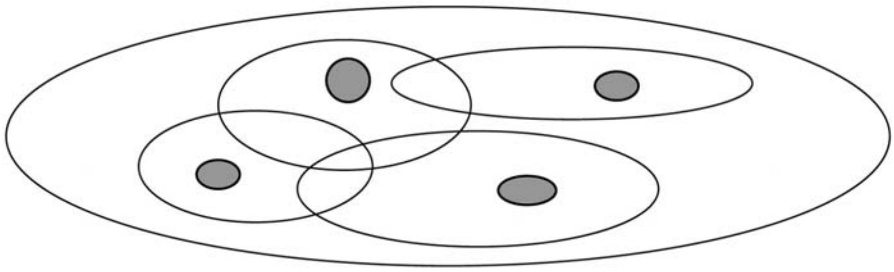

Figure 4. The relationship of four fundamental discipline-cultures comprising physics.

goal of many curricula, the question whether it is adequate is of great importance for physics education.

Prominent physicists often tried to present an inclusive, holistic picture of their subject. Examples are the courses of Hwolson (1923) and Ioss (1932) and, in more recent times, the unique course by Landau & Lifschitz (1962), as well as the famous course of Feynman (1964). A commonality of physics disciplines[20] should not mask the major conceptual incompatibility, especially clear in terms of their triadic structures, as shown above. The most extensive progress of physical knowledge in recent times apparently brought to the situation when a single holistic, all-encompassing framework of physics knowledge is impossible. Individuals claimed such knowledge (Helmholtz was the famous example) were rare already in the 19th century. Today the all-embracing physics worldview is often replaced by a mere psychological perception of such, that is, rather presents a myth. When a teacher proclaims a certain structure for *physics knowledge*, he/she usually addresses something specific (or uncritically uses structuralist rhetoric).

Triadic code (cell structure) is the simplest to describe the organization of some wholeness (binary codes miss the dynamics of the subject). Being applied, it imposes its simplicity on the real system, which in fact is richer, just by the virtue of its being real. This act assures necessity of deconstruction in the course of critical elaboration of the obtained understanding. The deconstruction reminds us of the real object revealing limited validity of the used model. In fact, it is an unavoidable nature of codes: while they reveal some aspects of reality, they inevitably overshadow others.

Physics, rather, seems to present a *dialogue* between different discipline-cultures. The discovery that what had been believed to be a single structure is, in fact, a dialogue of several structures presents a deconstruction.

Quantum mechanics may support further deconstruction with regard to a single discipline. The apologists of the Copenhagen interpretation (e.g., Landau & Lifshitz 1965) would put the statistical interpretation of the wave function in the nucleus, and the other interpretations ("hidden variables" (Bohm 1952; Jammer 1966), "ensemble" (Popper 1982), "many-worlds" (Everett 1957, 1973), "path-integrals" (Feynman 1948), etc.) in the peripheral area of the discipline-culture.[21] Reciprocally, any of the other interpretations would place the Copenhagen interpretation in its periphery.[22] One observes here many discipline-cultures of the same discipline and an intensive dialogue between them.[23] One can observe the reality of the dialogue between discipline-cultures of physics in such field as astrophysics, which actively applies and mixes the models and formalism of classical and relativistic mechanics, thermodynamics and quantum electrodynamics, and so on.

Furthermore, the dialogue in physics is not necessarily interdisciplinary. It could be within one discipline during the period of scientific revolution. Bohr's atomic theory incorporated elements of both new and old theories. In a sense, the ability to maintain such a dialogue is a privilege of the great masters in science. Such were Bohr and Einstein, who molded the new physics. Their dialogue established basic features of the new paradigms, in which new ideas were interwoven with the old ones until they began undistinguished. This is the true nature of a dialogue, which fuses the two initially separate ingredients.

This perception leads to an appreciation of the necessity for a new approach to the teaching of physics. Instead of presenting it as a hierarchically ordered unique dogma (even as merely a temporary goal), we should show that it presents an open discourse. Instead of teaching isolated disciplines, we should teach a Kontrapunkt of discipline-cultures.

5. Applying Triadic Model to the Topics Relevant to Physics Teaching

5.1. SCIENTIFIC REVOLUTIONS

Scientific revolution can be interpreted as a metamorphose of a discipline-culture.

The tripartite model of discipline-culture is apt to represent the changes in this knowledge organization. In fact, the fundamental changes in science are known under the name of "scientific" and/or "conceptual" revolutions. Their dynamics always attracted much effort to understand their nature and dynamics (Kuhn 1956). On the surface, each revolution is accompanied with a certain "semiotic revolution" – new concepts, new meanings of the old ones. These reflect more fundamental paradigmatic changes. In terms of disciplines, one used to present evolutionary, cumulative changes, antecedent theories attending this process, as if a spontaneous "puzzle-solving activity". It is always difficult to trace and explain the meaning of the particular conceptual shifts. The traditional approach often presents a chronological chain of events, replaced one another (Foucault 1972). Within a discipline-culture perspective, however, a revolution appears as a cooperative (synergetic) effect, involving a radical reorganization.

As was described, when a discipline-culture encounters ideas or empirical results which appear strange and controversial because they are in disagreement with the nucleus, it not only rejects them, but places them in its periphery, as incompatible of the central paradigm. These elements remain in the periphery until the breaking shift occurs and the "movement" of knowledge contents to and from the nucleus (across the domain borders of the discipline-culture) starts. A continual movement of knowledge elements (texts) from the nucleus to the periphery and simultaneous opposite movement of other elements (texts) manifests signals of revolution (Tinyanov 1977).

The cultural approach shows that a scientific revolution involves not only the emergence of new constructs, theories (as it often seems to the learner), but also a *rearrangement* of the whole system of knowledge contents. The conflicting elements are not "destroyed" or abandoned (as often presented), but rearranged in accordance with the new discipline-culture. The picture of relocation of texts, revision of their status promotes an integrated view of physics and its history, as opposed to the all-too-common depiction of naïve progress, a record of discoveries, as miracles and acts of liberation from the previous blindness or stupidity, which is far from the true account.

The progress presented as a metamorphose of discipline-culture elucidates the true relationship between the introductory and advanced courses in the university curricula (e.g., electromagnetism, within the introductory course, and Maxwell–Lorentz' electrodynamics, as an advanced course). As already mentioned, introductory courses usually ignore the nature of the Lorentz force. Within the discipline-culture approach, the scientific revolution of the theory of relativity presents a "movement" of Lorentz force and others elements into the nucleus, relating the introductory course to electrodynamics. Physics ceases to appear as a cluster of disconnected and isolated courses ignoring or even contradicting each other.

It should be noted that our model does not conflict with either Kuhn's (1956), or Lakatos' (1970) interpretation of scientific revolution, but refines them by an explicit scenario of the process. The efficacy of the discipline-culture approach is due to the articulated peripheral knowledge zone. The latter appear neither in Kuhn's nor, explicitly, in Lakatos' models. Our model easily adopts such features as protective belts (our normal zone), scientific research program, hard core, and paradigms (parts of the nucleus in our triadic model), thus exposing the fine structure and functioning of science.

5.2. CONCEPTUAL CHANGE

The tripartite organization can assist understanding of individual conceptual change with regard to scientific knowledge. Conceptual change obtains a new theoretical framework.

The tripartite model of discipline-culture can assist in interpreting the learning process. The rationale of this approach is in the attempt to conceive human cognition as organized in a manner similar to that of the culture, in which the learner is immersed (Vygotsky 1994). Consider for example learning the topic of motion in mechanics. As many researchers report (e.g., Whitaker 1983; Halloun & Hesteness 1985; Galili & Bar 1992; Galili 1995), the spontaneous ideas of the learner regarding motion are often close to those of Aristotle, who asserted: "motion implies force". Force is considered to be the cause of movement, and movement is considered to be a process of transition between two states, rather than continuous sequence of states replacing each other. The similarity between the initial knowledge of the learner and the views of Aristotle suggests to the physics instructor to imitate the scientific revolution of the 17th century, in order to bring the learner to the adoption of the Newtonian conception of motion – a strong conceptual change (Carey 1985).[24]

Similar to the account for a scientific revolution, the learning process can be regarded as involving a change in the contents of the nucleus, this time of the individual knowledge. The conceptual change necessarily involves the peripheral domain. Initially, it is the periphery that adopts the new ideas in the course of learning. Gradually, the tension arises between the new ideas (periphery) and the pre-instructional conceptions ("schemes of knowledge", Galili & Hazan 2000) located in the nucleus. Eventually, and following dissatisfaction with the old knowledge, as opposed to the intelligibility, plausibility and fruitfulness of the new knowledge (Posner et al. 1982; Strike & Posner 1992), this tension (termed "cognitive conflict" in psychology (e.g., Nussbaum & Novick 1982; Dreyfus et al. 1990; Limon 2001), and "difference of potential", in physics terms) reaches breaking point – and conceptual change starts.[25] At this stage of breaking, the body area of normal knowledge cannot protect and isolate the nucleus any more, and the knowledge "flows" into and out from the nucleus. The latter is reconstructed and its old content finds itself in the periphery, "waiting" for the opportunity to challenge the nucleus again (Galili & Bar 1992).

This scenario might imply that the process of conceptual change requires activities beyond solving standard problems using memorized algorithms. The teaching that aims to induce conceptual change begins by supplying new contents and fortifying the peripheral knowledge. The increase of tension with the nucleus could be encouraged through focusing on the new concepts, comparing them with those initially held, and emphasizing their incompatible nature – this is basically the constructivist strategy. Obviously, the more developed the peripheral knowledge and the less developed the normal knowledge, the easier it is to bring about conceptual change in the learner. Therefore it is easier to teach the novice and young (possessing a thin normal domain), than to "re-educate" the experienced and adult (those with a well-developed normal domain).

The importance of meta-cognition in the process of conceptual change, the self appreciation of the learning process has been discussed in educational research (e.g., White & Gunstone 1989; Hewson & Thorley 1989). The triadic model interprets this aspect as following. If the deficiency of the individual knowledge is not self-recognized, the new knowledge element might be mistakenly placed in the *normal* area (not in the *periphery*). Then, instead of promoting conceptual change, the new knowledge may even obstruct the conceptual change. Referring again to the Lorentz force, suppose it was considered to be a normal element. The tension with the nucleus would remain low, impeding the conceptual change regarding relativistic conceptions.

5.3. PHYSICS CURRICULUM

Discipline-culture approach suggests physics curriculum to attain the features of science itself, to be hierarchical and discursive.

Explaining the failure of many students to learn physics, researchers point to the difficulty of facing a great number of facts, procedures, rules and theories without the guidance regarding their relative importance and validity status. Learners often develop their own organization of knowledge (diSessa 1993; Minstrell 1992; Galili & Hazan 2000) and its spontaneous hierarchy.[26] This might be interpreted as the unsatisfactory nucleus of students' knowledge organization. Seemingly, the common emphasis of training in normal knowledge (problem solving) does not affect the nucleus. Moreover, students often become disenchanted and lose interest in the subject, divorced from the grand scientific picture – the worldview dimension of knowledge.

A discipline-culture based curriculum emphasizes the connection between the elements of the normal knowledge with the nucleus, as well as with the periphery. The former represents the metaphysics of the discipline and the latter challenges the presented "order of things". Together both aspects stabilize every piece of the normal knowledge within the general hierarchy. This approach makes the normal disciplinary knowledge more intelligible and plausible, increasing the chances for successful assimilation by using such a curriculum.

A discipline-culture based curriculum incorporates carefully chosen elements of the history and philosophy of science, as the contents of the nucleus and periphery. This knowledge becomes inherent in the subject matter, instead of being relegated to the sidelines as "non-scientific", or merely a "cultural debt".[27] This curriculum regards the discarded theories not as historical curiosities, but as alternative interpretations, contrasting the meaning of the adopted models and principles, and therefore fostering adequate understanding (Schecker & Niedderer 1996). Thus, by contrast (and paradoxically for many), learning about the Aristotelian paradigm of force-motion relationship fortifies understanding of its Newtonian counterpart, the Cartesian interpretation of weight helps students to understand Newtonian gravitation, the idea of the absolute space-time reveals the meaning of the relativistic conception, the geocentric world system facilitates understanding of the heliocentric model, and so on and so forth. Historical models remain relevant. The concept of field revived contact interaction. Light photons revived the particle theory of light. The new theory of vacuum revived the idea of aether. By facilitating dialogue of ideas the new curriculum provides wider scope and multiple perspective of knowledge, encouraging students to precede physics enterprise as a living project.

5.4. TYPOLOGY OF LEARNERS

The assumption that students might be attracted to the different areas of a discipline-culture leads to the correspondent typology of the students according to their cognitive preferences.

One often hears children (people) being characterized by statements such as "science was not for him ..." or "she was born a scientist ...". Such descriptions employ, usually intuitively, the "two cultures" concept of Snow (1961), which sees a clash between science (as based on mathematics[28]) and the humanities (as free of formal rigor). This thesis reflects the view that there are two types of people (two "breeds"), those who are naturally "good in physics", and those who are not. This view presents a well-entrenched commonplace. Many students regarded as "non-scientists" by their teachers and/or parents do not consider physics even as an option for general education and terminate their physics education in intermediate school.[29]

We believe that the binary vision of aptness for science is too rough and suggest recognition that individuals might have cognitive preferences reflecting personal inclinations to different components of discipline-cultures. One could interpret Snow's notion of "science" as assigned not to the "body knowledge" ("normal science"). The great paradigms of physics (nuclei) and their rivals (periphery knowledge) are missed in a simple approach. The ideology is reserved to humanities, identified with intuition, freedom of style, fantasy and imagination. They are interesting because they are controversial, and they break norms.

Within the tripartite vision of discipline-culture one can suggest another approach to account for the variety of attitudes to science.[30] This approach assumes that different aspects of physics as a culture will be of interest to different types of students. On this basis one may anticipate three types of learners.[31]

Learners of the *first* type ("philosophers") show an interest in the ideas and principles of their subject, they like to philosophize. They like generally ordered knowledge and might lose interest, and have difficulties in learning particular applications (problem solving), if not related to general principles, organized procedures, etc. They seek a holistic vision of science, gravitating to nucleus in discipline-cultures.

Students of the *second* type ("practitioners") prefer to apply the knowledge provided by the instructor in the form of well-defined procedures. They enjoy their studies, especially when the goals are concrete. They like to solve "fair" problems, which may vary in the ways of application of known rules, but not require invention of new ones. These students gravitate to the normal area, body knowledge of discipline-cultures.

Finally, students of the *third* type ("critics") are inclined to criticize the presented knowledge, and resist theories authoritatively presented. They are creative and like controversy, they suggest their own ideas and explanations, sometimes paradoxical and inconsistent, which challenge the dogma. These students might appear as weak, stubborn, illogical and inconsistent. Facing rigid and indisputable subject matter and teaching, they feel bored and might be disruptive. Their success in class may vary. These students gravitate to the peripheral knowledge of discipline-cultures.

This typology of learners leads to the need for different instruction, different emphases and, indeed, a different curriculum for each type. Thus the courses focusing on "normal science" are unlikely to appeal to students of the first and third categories, even when the mathematical contents of such courses are reduced. The approaches that try to attract students to physics by merely writing in words the mathematical formulas ("physics for poets"), or by step-by-step detailed explanations, appear somewhat naïve. "Physics for humanities" requires mainly different contents (nucleus-periphery focused) beyond the simplified formalism. The cultural contents of physics may trigger the interest of many presently identified as not apt to physics, bringing into physics classes the students often lost within the common educational practice.

6. Concluding Remarks

We started by quoting Poincare regarding the special knowledge required by prospective physics teachers, and we arrived at the special organization of physics knowledge for much wider spectrum of consumers of physics in high school, college and university. We described this new perception in terms of a *discipline-culture*. Its tripartite organization of knowledge elements is applicable to each discipline in physics, while physics as a whole emerges as a dialogue of a several disciplines possessing family resemblance (epistemological similarity). Such physics presents a cultural subject and, as such, should be taught in a Kontrapunkt.

The approach of triadic code appeared to be beneficial in representing *scientific revolution* (a change of social knowledge) and students' *conceptual change* (a change of individual knowledge). The correspondent change of *physics curriculum* could be related to the new *typology of learners*, both facilitating the design of leaning materials in accord to the perception of physics as a culture, as well as of individual cognitive preferences.

This view could upgrade physics instruction; humanize its contents, introduce new values in physics education, whereas preserving of strict disciplinary course focused on the normal science, even if fortified by new pedagogy and equipment, means to keep many students outside of physics class. We believe it is a cultural change that may serve as a fulcrum to rescue physics education from its present crisis, and attract students who currently prefer humanities. People will study physics not only for professional purposes, but as a cultural resource, a means for understanding of the world.

Notes

[1] We apologize for introducing a stereotype. We believe, however, that it will not be difficult to understand our true intention.

[2] In this important work Schwab (1978) emphasized the special importance of "structure of the disciplines" for constructing science curriculum: "***How** we teach will determine **what** our students learn. If a **structure** of teaching and learning is alien to the **structure** of what we propose to teach, the outcome will inevitably be a corruption of that content. And we will know that it is*."

[3] One may illustrate the pursue to reveal the nature of science, "what science is", as a subject of study, by reference to such philosophers of science as Koyré, Toulmin, Popper, Lakatos, Kuhn, Feyerabend.

[4] E.g., Werner Heisenberg (1977), the speech given by at the alumni meeting in Berlin gymnasium.

[5] Thus, these approaches played an important role in the genesis of the theory of relativity.

[6] A special double issue of the *Science & Education* is devoted to a discussion of interpretation of Quantum theory. The discussion started by Bunge (2003).

[7] We know that the suggested expansion from the traditional contents of scientific discipline presents only the first step from discipline to culture, as a humanitarian category. However, even this first step already enriches discipline making it *more* cultural. For this reason we already adopted for the model the word *culture*, as indicating our intention and future studies.

[8] Mazur (1997) described his discovery of conceptual lag in his students of Harvard, successful in regular requirements. The extent of the failure caused an essential change in his teaching.

[9] We do not address here the need to learn texts of colleagues, fellows, scientists regarding the same subject.

[10] There is a striking difference between scientific discovery, always associated by scientists with the greatest possible luck, a miracle, and the discovery, as it is often presented in the classroom, a result of a rigid procedure, clear rules and methods (Baconian perception of the 17th century).

[11] We draw the attention of educators to this statement. It should be regarded as a criticism of the currently popular trend of introducing research projects, especially those time and effort consuming, already into the school classroom.

[12] Vygotsky draws attention to the essential difference in nature between the learning of one's mother tongue and the learning of a foreign language Vigotsky (1994).

[13] We should emphasize that "cell analogy" is used only as convenient image, a similar structure. Our model does not expand or rely on any functional resemblance.

[14] This is not true: the theory of electromagnetism is totally relativistic regardless velocity magnitude.

[15] This is not true: great many quantum effects exist at normal temperatures and cannot be obtain by classical theory in any limit procedure.

[16] This is not true: there is no gradual transition between irreversible and reversible physics.

[17] Although not coinciding with our approach, the course by Rogers (1960) may provide a certain perception of direction of the suggested change.

[18] The pedagogical effort at this point is often focused on mastering manipulation with vector product, a new feature of the formalism.

[19] Lorentz force was originally explained in terms of the electromagnetic ether, later replaced by the electromagnetic field in vacuum.

[20] One should not be confused with other *non-ontological* aspects, which unite physics in one science. Such are the inductive-deductive method, empirical epistemology, common concepts, the approach of modeling and mathematical account, etc.

[21] Sacharov (1990) wrote about his meeting with J. A. Wheeler, who told him about his rich collection of interpretations of quantum theory, and to which Sacharov added the interpretation of "Indirect Measurements" by L. I. Mandelstam, suggested in 1939. This interest was seemingly transferred to Feynman and Everett, both students of Wheeler.
[22] Since alternative interpretations are multiple, so is the deconstruction of one discipline-culture of the Quantum theory.
[23] For a representative example of such a dialogue regarding Quantum theory see 'Quantum Theory, Philosophy and Education', a special issue of *Science and Education* **12**(5–6), 2003.
[24] Similarity of onto- and phylogeny created in many educators the perception of recapitulation.
[25] The authoritative persuasion (intelligibility and plausibility of the new knowledge), dissatisfaction with the old knowledge, as well as fruitfulness, feasibility, parsimony, symmetry, and the beauty of the new theory apparently play different roles in the two contexts.
[26] For example, Bagno & Eylon (1997) reported that high school students consider Ohm's law as a more important than Maxwell equations, in accord with the fact that the former occupies much more attention in school curriculum.
[27] This, although on the surface positive attitude to the history and philosophy of science, often means practical rejection of such materials (Galili & Hazan 2001).
[28] This view can be traced to the positivist philosophy of Comte who stated the maturity of the scientific brunch solely when it essentially utilized mathematics.
[29] This is currently a situation in many countries, e.g., Israel, USA, UK and Germany, where a great majority of students turn their back to physics classes. Thus, in Israel, from about 150 000 high school students per year, only about 9000 take physics (an elective subject).
[30] We discuss the typology of students' preferences and not their taxonomy. The idea of hierarchy in this context is foreign to the modern cultural approach.
[31] These theoretical considerations suggest a correspondent empirical study.

References

Bagno, E. & Eylon, B.: 1997, 'From Problem Solving to a Knowledge Structure: An Example from the Domain of Electromagnetism', *American Journal of Physics* **65**, 726–732.

Barthes, R.: 1987, *S/Z*, Hill and Wang, New York.

Bibler, V.: 1999, *Shkola Dialoga Kultur*, Aleph, Kemerovo, Russia, pp. 12–14.

Bohm, D. & Peat, D.: 1987, *Science, Order and Creativity*, Bantam, New York, pp. 88–97.

Bohm, D.: 1952, 'A Suggested Interpretation of the Quantum Theory in Terms of "Hidden" Variables, I, II', *Physical Review* **85**, 166–179, 180–193.

Bruner, J.S.: 1960, *The Process of Education*, Harvard University Press, Cambridge, MA.

Bunge, M.: 1973, *Philosophy of Physics*, Reidel, Dordrecht.

Bunge, M.: 2003, 'Twenty-Five Centuries of Quantum Physics: From Pythagoras to Us, and from Subjectivism to Realism', *Science and Education* **12**(5–6), 445–466.

Carey, S.: 1985, *Conceptual Change in Childhood*, MIT Press, Cambridge, MA.

Caravita, S. & Hallden, O.: 1994, 'Re-Framing the Problem of Conceptual Change', *Learning and Instruction* **4**, 89–111.

DeBoer, G.E.: 1991, *A History of Ideas in Science Education*, Teachers College, Columbia University, New York.

Derrida, J.: 1976, *Of Grammatology*, John Hopkins University Press, Baltimore.

Derrida, J.: 1967/1978, 'Structure, Sign, and Play in the Discourse of the Human Sciences', in *Writing and Difference*, University of Chicago Press, Chicago.

Derrida, J.: 1976, *Of Grammatology*, John Hopkins University Press, Baltimore.

diSessa, A.: 1993, 'Toward an Epistemology of Physics', *Cognition and Instruction* **10**, 105–225.

Dreyfus, A., Jungwirth, E. & Eliovitch, R.: 1990, 'Applying the 'Cognitive Conflict' Strategy for Conceptual Change – Some Implications, and Problems', *Science Education* **74**(5), 555–569.

Driver, R.: 1983, *The Pupil as Scientist?*, Open University Press, Milton Keynes.

Duhem, P.: 1906/1954, *The Aim and Structure of Physical Theory*, Princeton University Press, Princeton, NJ.

Everett, H.: 1957, '"Relative State" Formulation of Quantum Mechanics', *Reviews of Modern Physics* **29**, 452–464.

Everett, H.: 1973, *The Theory of the Universal Wave Function, The Many Worlds Interpretation of Quantum Mechanics*, Princeton University Press, Princeton, NJ.

Feyerabend, P.: 1975, *Against the Method*, Verso, London.

Feynman, R.P.: 1948, 'Space-Time Approach to Non-Relativistic Quantum Mechanics', *Review of Modern Physics* **20**, 367–387.

Feynman, R., Leighton, B. & Sands, M.: 1964, *Feynman Lectures on Physics*, 3 volumes, Addison-Wesley, Reading, MA.

Fishbane, P.A., Gasiorowicz, S. & Thornton, S.T.: 1993, *Physics for Scientists and Engineers*, Prentice Hall, Englewood Cliffs, NJ.

Foucault, M.: 1972, *The Archaeology of Knowledge*, Tavistock, London.

Galili, I. & Bar, V.: 1992, 'Motion Implies Force. Where to Expect Vestiges of the Misconception?' *International Journal of Science Education* **14**(1), 63–81.

Galili, I.: 1995, 'Mechanics Background for Students' Misconceptions in Electro-Magnetism', *International Journal of Science Education* **17**(3), 371–387.

Galili, I. & Kaplan, D.: 1997, 'Changing Approach in Teaching Electromagnetism in a Conceptually Oriented Introductory Physics Course', *American Journal of Physics* **65**(7), 657–668.

Galili, I. & Hazan, A.: 2000, 'Learners' Knowledge in Optics: Interpretation, Structure, and Analysis', *International Journal of Science Education* **22**(1), 57–88.

Galili, I. & Hazan, A.: 2001, 'Experts' Views on Using History and Philosophy of Science in the Practice of Physics Instruction', *Science & Education* **10**(4), 345–367.

Giancoli, D.C.: 1988, *Physics for Scientists and Engineers*, Prentice Hall, Englewood Cliffs, NJ

Gopnik, A.: 1996, 'The Scientist as Child', *Philosophy of Science* **63**, 485–514.

Habermas, J.: 1981, *Theorie des Komunikativen Handelus*, Frankfurt a.Main, Germany.

Halloun, I. & Hesteness, D.: 1985, 'Common Sense Concepts about Motion', *American Journal of Physics* **53**, 1056–1065.

Hecht, E.: 1996a, *Physics (Calculus)*, Brooks/Cole, Pacific Grove, CA.

Hecht, E.: 1996b, *Physics (Algebra)*, Brooks/Cole, Pacific Grove, CA.

Heisenberg, W.: 1958, *Physics and Philosophy*, Harper, New York.

Heisenberg, W.: 1977, *Schritte uber Grenzen*, Reden und Aufsatze, Munchen.

Hewitt, P.: 1998, *Conceptual Physics*, Addison-Wesley, Reading, MA.

Hewson, P.W. & Thorley, N.R.: 1989, 'The Conditions of Conceptual Change in the Classroom', *International Journal of Science Education* **11**, 541–553.

Hwolson, O.: 1923, *Course of Physics*, 5 volumes, Grschebin Verlag, Berlin.

Ioss, G.: 1932, *Course of Theoretical Physics*, 2 volumes, Verlag, Berlin.

Jackson, J.D.: 1962, *Classical Electrodynamics*, Willey, New York.

Jammer, M.: 1966, *The Conceptual Development of Quantum Mechanics*, McGraw-Hill, New York.

Kuhn, T.: 1956, *The Structure of Scientific Revolution*, University of Chicago Press, Chicago.

Lacan, J.: 1973, 'Les quatre concepts fondamentaux de la psychanalyse', *Le Seminaire de Jacques Lacan*, Vol. 11, Seuil, Paris.

Lakatos, I.: 1970, 'Falsification and the Methodology of Scientific Research Programs', in Lakatos, I. and Musgrave, A. (eds.), *Criticism and the Growth of Knowledge*, Cambridge University Press, London.

Landau, L. & Lifshits, E.: 1962, *The Course in Theoretical Physics*, 9 volumes, Pergamon Press, the Netherlands.

Landau, L.D. & Lifshitz, E. M.: 1965, *Quantum Mechanics, Nonrelativistic Theory*, Pergamon Press, Oxford.

Lerner, L.S.: 1996, *Physics for Scientists and Engineers* Jones & Bartlett, Sudbury, MA.

Limon, M.: 2001, 'On the Cognitive Conflict as Instructional Strategy for Conceptual Change: A Critical Appraisal', *Learning and Instruction* **11**, 357–380.

Lotman, Yu. & Uspensky, B.A.: 1978, 'On the Semiotic Mechanism of Culture', *New Literary History* **9**, 211–232.

Matthews, M.: 2000, *Time for Science Education*, Kluwer, Dordrecht.

Mazur, E.: 1997, *Peer Instruction*, Wiley, Boston.

Minstrell, J.: 1992, 'Facets of Students' Knowledge and Relevant Instruction', in Duit, R., Goldberg, F. & Niedderer, H. (eds.), *Research in Physics Learning: Theoretical Issues and Empirical Studies*, IPN, Kiel, pp. 110–128.

Nussbaum, J. & Novick, S.: 1982, 'Alternative Frameworks, Conceptual Conflict and Accommodation: Toward a Principled Teaching Strategy', *Instructional Science* **11**, 183–200.

Piaget, J.: 1968, *Le structuralisme*, Presses Universitaires de France, Paris.

Poincare, H.: 1903, *Science and Method*, Dover, New York.

Popper, K.R.: 1982, *Quantum Theory and the Schism in Physics*, Hyman, London.

Posner, G., Strike, K., Hewson, P. & Gertzog, W.: 1982, 'Accommodation of a Scientific Concept: Towards a Theory of Conceptual Change', *Science Education* **66**, 211–227.

Prigogine, I. & Stengers, I.: 1984, *Order out of Chaos. Man's New Dialogue with Nature*, Heinemann, London.

Redish, J.: 1999, 'Milliken Award Lecture (1998): Building a Science of Teaching Physics', *The American Journal of Physics* **67**, 562–573.

Rogers, E.: 1960, *Physics for Inquiring Mind*, Princeton University Press, Princeton, NJ.

Sacharov, A.D.: 1990, *Memoirs, Part II*, Chechov, New York.

Schecker, H. & Niedderer, H.: 1996, 'Contrastive Teaching: A Strategy to Promote Qualitative Conceptual Understanding of Science', in Treagust, D., Duit, R., Fraser, B. (eds.), *Improving Teaching and Learning in Science and Mathematics*, Teacher College Press New York, pp. 141–151.

Schwab, J.: 1964, *Problems, Topics, and Issues*, in Clam, S. (ed.), *Education and the Structure of Knowledge*, Rand McNally, Chicago.

Schwab, J.J.: 1978, 'Education and the Structure of the Disciplines', in Westbury, I. & Wilkof, N.J. (eds.), *Science, Curriculum, and Liberal Education*, Rand McNally, Chicago.

Serway, R.A.: 1997, *Physics for Scientists and Engineers*, Saunders, London.

Snow, C.P.: 1961, *Two Cultures and the Scientific Revolution*, Cambridge University Press, New York.

Strike, K.A. & Posner, G.J.: 1992, 'A Revisionist Theory of Conceptual Change', in Duschl, R. & Hamilton, R. (eds.), *Philosophy of Science, Cognitive Science, and Educational Theory and Practice*, State University of New York, Albany, New York, pp. 147–176.

Tinyanov, Yu.: 1977, 'Lieraturni Fact', in Tinyanov, Yu. (ed.), *Poetica, Istoria Literaturi, Kino*, Nauka, Moskow.

Tipler, P.A.: 1999, *Physics for Scientists and Engineers*, Freeman, New York.

Vygotsky, L.: 1994, *Thought and Language*, MIT Press, Cambridge, MA.

Whitaker, R.J.: 1983, 'Aristotle Is Not Dead: Student Understanding of Trajectory Motion', *American Journal of Physics* **51**(4), 352–357.

White, R.T. & Gunstone, R.F.: 1989, 'Metalearning and Conceptual Change', *International Journal of Science Education* **11**, 577–586.

Wittgenstein, L.: 1968, *Philosophical Investigations*, McMillan, New York.