HOW SCIENCE CENTERS AND MUSEUMS CAN SERVE THE FORMAL LEARNING IN THE SCHOOLS

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1. Multiplicity of formal thinking

Physics is not a science like the other ones: it is a mathematicized or formalized knowledge which describes, interprets and foretells the phenomena of nature.

We know that there are many types of theories in physics. But often we forget that they do not use the same mathematics. Likewise, we often ignore that they don't have the same conceptual organization [1]. The classical mechanics uses the mathematics of infinitesimal analysis and it is structured on principles, but the classical thermodynamics makes use of a much simpler mathematics and it is organized on only one central problem: the impossibility of perpetual motion. The geometrical optics is organized on principles, but it does not use mathematical analysis: it only needs Euclidean geometry.

Notwithstanding this variety of forms in which the physical theories present themselves, when we talk about the formal thinking of physics, we often make a drastic reduction of them, we refer only to the model of classical mechanics: that is, to the infinitesimal analysis («in act» infinity) and to the hypothetical-deductive structure. It is not a mystery that physics has been dominated by the Newtonian paradigm.

A deeper historical knowledge could aid us to consider the multiplicity - developed during the time - of the physics-mathematics relationship and to recognize the plurality of «formal thinking» in physics.

Therefore it is useful to know that Galilei used a mathematics with only rational numbers and he faced the arguments in a discursive, not axiomatic way: it is sufficient to think of the *Dialogo*. His follower Cavalieri had already introduced into physics irrational numbers, with the *Theory of indivisibles*, that is also the first example of infinitesimal analysis [2]. This theory was not shared by Galilei probably because, placing among the rational numbers also the irrational ones, it implied mental operations that clashed against his constructive and experimental vision of the concepts. After a few decades, Newton founded infinitesimal analysis and he put it at the basis of his *Principia* with an organization of the physical concepts structured in a hypothetical-deductive way, precisely on «principles». The formal thinking of this new physics was decidedly different from Galilei's one. So Galilei was not Newton's forerunner, as the positivistic and linear vision of history wants, the same vision which inspires many text-books [3]. Afterwards, in spite of the great success of the choices made by Newton, not everyone accepted their validity. During the period of the French Revolution, for example, Lazare Carnot propounded a mechanics with completely antagonist choices. Sadi Carnot, with identical choices, founded the classical thermodynamics which, as we have referred to before, doesn't make an essential use of the mathematical analysis and it doesn't let itself be dominated by the differential equations. I could mention other, also more recent, examples, but here I would like to refer to Faraday, whose work in electromagnetism was realized with such an elementary mathematics that it almost appears without a formal thinking [4]. At the end of this historical reflection, someone could object that - for example - in the school courses we find no trace of the formal thinking of the mechanics of Lazare Carnot, although it is alternative to the Newtonian one. And he could conclude that in physics there has been a sort of Darwinian selection of the formal thinking that has given us the strongest. This is what Kuhn, a very famous science historiographer and philosopher, asserts. According to him, the formal structure of the mechanics is the historical product of the cognitive evolution [5], passed through successive linguistic stratifications, also contrasting, and that we have to take it as it is, because it is the best possible result given by the history of science.

2. Does the formal thinking of the mechanics represent all the physics?

But, let's ask ourselves, does the formal thinking of mechanics represent really all the physics? Yes, apparently. In fact it externally appears with a compactness and with a simplicity of enunciation which doesn't leave doubts. The only criticisms are the relativistic ones, which, however, don't discuss its validity inside the limit of the low speed. And yet, if we stop to consider the firmness of its internal logic, we discover that its concepts and its laws leave much to be desired [6]. The inertial principle is not demonstrable. The concept of force is circular with the second principle, which is exactly the principle which should give the predicting basis to the whole theory. In other terms: this important concept results to be a metaphysical one. The concept of mass, moreover, can be defined correctly by using only the experimental basis contained in the third principle. If it is not in the internal logic, therefore, where is the force of this theory?

The surprising fact is that all these problems, have been known for some time [7]. Mach and Hertz's criticisms of the nineteenth century are well-known, to mention only the most famous [8]. Still more surprising is that physicists implicitly entrust to this mechanics the task of representing the formal thinking of the whole discipline. In fact we know that the students, from the secondary school to the University, pass through its conceptual structure when being initiated to physics. This strident contradiction is almost always put at the margin of pedagogic discussions. Specialists in education prefer to observe the mote of the misconceptions in the students' eyes, who - poor fellows! - bring with them the misunderstanding of the common language, rather than observe the beam in the physicists' eyes! It is astonishing to hear what Kuhn says on this problem. He maintains that the language which expresses the concepts of the mechanics and the laws of nature they would like to explain are related by a «indivisible mixture» [9] and that is a natural fact. Instead, according to me, this fact is not natural. It is here that we find the origin of the drama of thousands of students who are forced to pass through the narrow door of an unpleasant physical thinking. This drama, which induces a large part of the young people to give up the scientific studies, compels us to stop and reflect [10].

3. Formal and informal

But, in order to do this, we need to move out of the narrow circle of the physics specialists, who - as we have seen - haven't produced, in the course of the time, appreciable improvements to the quality of their thinking. Modern sensitivity asks us to widen our horizon and to consider this problem not only as scientific but also as pedagogical and, so, as civil [11]. Let's see, therefore, what formal thinking means in this larger cultural ambit. First of all let's start by asking ourselves what the adjective «formal» [12] means. It is a synonym of tidy, logical, sequential, but also of mathematical, expressed by symbols, and sometimes it is identified with «scholastic». Its opposite, «informal», instead denotes the episodic, the casual, the extemporary, the partial, the intuitive and the out-of-school. The adjective «formal» also assumes derogatory meanings like the ones of rigid, abstract and abstruse, and so the «formal thinking» is also the one difficult to understand, that is the educationally problematic one. Consequently, «informal» stands for easy, simple to grasp, educationally elementary, and sometimes even banal.

In the press and in the debates of cultural politics the binomial formal-informal is just what supplies the most frequent categories for the discussion about the learning of the sciences in general and of the physics in particular [13]. People even assert that the children who normally frequent planetariums and interactive museums are also the ones who better understand the importance of mathematics for the study of physics and of the other sciences in general, and so of the formal aspects of the scholastic subjects. People assert, moreover, that a common person gets half of his scientific culture through informal procedures. Even the new expression «informal science» has been coined to denote a science which is offered by out-of-school institutions, for example by the science centers and the scientific museums, structures which compete in a strong way with the school itself on the level of the educational efficiency [14]. This fact lead us to think that, actually, there exists an informal thinking which we must recognize. This kind of thinking could be imagined as a thinking which, being contrasting to the dominant one, has passed through history, out of the paradigms of the scientific community and which is still living in the wider human community. A thinking which evolved at the margin of the niche and of the slang of the specialists.

4. Does an informal thinking really exist?

This idea is much more than an hypothesis of work. Its consistence emerges very distinctly if we consider a pedagogic and scientific problem the United States are now facing. The National Science Foundation (NSF) has learnt that the American students' attainments in mathematics at the end of the high school studies result unsatisfactory. The data come from an international research on the mathematical skills of young people, divided according to their age, published by the National Center for Education Statistics [15]. Well then, it results that American young people, though they start with good results in mathematics at the primary school, in the course of the studies - starting from the teens - progressively they remain behind in the classification of excellence, in comparison with the ones of their same age in other countries. The NSF has charged with this problem all the educational agencies of the United States. Even *Dimensions* [16], the bimonthly of the ASTC (Association of Science-Technology Centers), which is primarily interested in informal teaching of sciences, has opened the debate on the argument, dedicating one issue to the mathematics which must be discovered in the science centers. The same attitude has been expressed by *The Exploratorium Magazine* [17], the quarterly of the famous science museum of San Francisco, entitling its last issue «Math Explorer» and underlining that this publication has been supported by a fund from the NSF.

Mathematics is that part of the science which is, by nature, typically formal. Then it is really remarkable that the task of contributing to the solution of the educational problem of the mathematics has been assigned to the community of those professionals of the so-called «informal science». Therefore people are looking for a mathematical thinking out of the tightly scholastic conceptions. Is this an implicit recognition that the interactivity and the "hands-on" are believable vehicles of education for mathematics? Traditional teachers say that the interactive scientific exhibits are only external hints for the essentially intellectual scientific education, does this prejudice fall? The answer is still open.

In the meantime, however, the prompt reactions of *Dimensions* and of the *Exploratorium Magazine* to the problem show how the «experimental» resources of the science centers are already capable of presenting interesting solutions. The exhibits, having been built to stress natural properties, educate to analyze singular problems of a physical nature in which converge, all together, the logical aspects, the geometrical ones and the ones of calculation, aspects which the progressive distribution in the school time doesn't render equally effective.

The physical variables of the phenomena produced by the exhibits and the hands-on experiences are so numerous that they can constitute a real mine of mathematical ideas. What the two magazines propound is to proceed to the re-examination of these phenomena to make evident «where» the mathematics in the physics is. In this way we can trace the mathematical thinking inside physics, which is nothing but the formal - really effective - thinking of physics. This way is completely different from that indicated by the text-books, which are the teaching instruments still now preferred by the scientific community, and which bear the physics formal thinking almost exclusively by the algebra of the formulas.

5. The brain leads the hand, but the use of the hand shapes the brain

This «looking for» the mathematics in the interactive equipments also opens another path. The one which induces us to ask ourselves if this mathematics, different from the one learnt through pen and paper and from the abstract one, is also different in substance (it derives from different foundations). If it were so, a mathematical «quality» would be on the point of being introduced; it could be preferred because of the impact it has on those who learn.

The general problem is to establish if every physical process corresponds to a mathematical constructive algorithm and vice versa.
If this correspondence were demonstrated, the non-constructive algorithms - the ones of the mathematical analysis which are based on the infinity in act - would no longer be necessary. We would have a turning point after three hundred years of classical mechanics.
A starting point for this work is certainly the scientific datum that between the brain and the hand there is a bilateral dependence: the brain leads the hand, but the use of the hand shapes the brain. This means that the formal thinking of those who enter physics only through the descriptions and the formulas of the text-books is a type of thinking we must consider unbalanced and therefore incomplete. To complete it he would have to review the procedure using the "manual" dexterity (the effective realizability of the algorithm). Therefore the interactivity contained in the exhibits helps to build the physical thinking, also in a formal sense.
It is what my experience as a Fellow at Lemelson Center for the Study of Invention and Innovation of Smithsonian Institution of Washington has recently taught me.
But why through the exhibits and not directly through the physics laboratories? The professional equipment of laboratories is not educationally equivalent to the exhibits. The exhibits favour the necessary exploration of nature without creating, in those who makes the first steps in science, strong anxieties about the functioning of events which are very far from common life.

6. How science centers can serve the schools

The variety of the exhibits offered by the science centers and by the museums has a didactic fecundity more dense than an "ad hoc" experiment, supposing that this has really been proposed in the school lessons. Only one experiment, like only one exhibit, although it concentrates the attention of the spectator on a particular phenomenon, never exhausts the mathematical comprehension of the physical laws there are in it. Frank Oppenheimer, the founder of *The Exploratorium*, wanted collections of exhibits to represent a certain physical law, for example the harmonic motion or the waves. He was convinced that we build our scientific knowledge only when we catch what is shared by families of apparently different phenomena. Thirty years of success prove he was right. Therefore the «cornucopia» of different phenomena is another service to formal thinking that is offered us by science centers and by science museums. The school of the future can't give up this lesson [19].
Moreover, a collection of exhibits can supply what hasn't been understood sufficiently yet, that is the comparison of the theories. This exigency starts becoming more and more urgent once the phase of the astonishment and of the surprise given by the exhibits has been passed. Let's think about the concept of ray of light which is at the basis of the geometrical theory of light, and let's think about the interpretation of the images obtained by mirrors or by lenses through geometrical constructions. To understand this theory well what normally is done it is not sufficient: because it only gives one answer to the various questions. In fact we normally emphasize that the concept of ray explains the phenomena presented by the exhibits well and that the Euclidean geometry supplies mathematics to calculate distances and enlargements of the images. It would be more instructive, instead, to show how an alternative hypothesis to the one of the ray of light would function. On this subject, *The Exploratorium*, for years proposed the *Image Walk* [20], that is a walk among the exhibits having as a guiding principle another basic concept, the «spot of light». This walk forces the physicists to admit that a new fundamental idea, the one of an elementary cone of light (just to understand each other, the cone of the pinhole) can improve the quality of the explanation of the phenomena very well. With this new concept we can explain all the phenomena of the traditional optics, starting from the everyday experience of the circular form of the shadows produced by the leaves of a tree, difficult to be explained with the concept of ray of light. As this walk has been made famous by an artist, an outsider of physics, its language appears to the visitors like a curiosity. But not for *The Exploratorium* physicists [21], who have already confessed the embarrassing situation of having to prefer the ideas of the «walk» to the ones of the text-books on which they studied. If we analyse the differences between the two basic concepts, we note two different mathematical conceptions of

physics: one in which it is imagined that a beam of light can be assimilated to a straight line (a cone thinned several times through splits); the other, to a conical spot. The first is a very strong abstraction, the second is a less strong abstraction, more understandable because it represents the experience of the pinhole well. In conclusion, this example suggests how to utilize the exhibits to go into the depth of the theories. This would suggest moreover what they are made of and say what their models consist of. And also this can be re-proposed at school, obviously at a new school.

ScienzaViva, the no-profit Association I am here representing, is committed to demonstrating that these efforts are really possible, realizing the «Interactive Science» Project, a program recently funded by the Italian Ministry of Scientific and Technological Research.

References

[1] A. Drago, "Storia delle teorie fisiche secondo le loro due scelte fondamentali: la matematica e l'organizzazione della teoria" in S. D'Agostino, S. Petruccioli (eds.): Atti del V Congr. Naz. St. Fisica, Accademia dei XL, Roma (1984), 365-373.

[2] A. Drago, "La nascita del principio d'inerzia in Cavalieri e Torricelli secondo la matematica elementare di Weyl" in P. Tucci (Ed), Atti del XVII Congresso Nazionale di Storia della Fisica e dell'Astronomia, Como, (1997).

[3] P. Cerreta, "Il confronto tra le storiografie di Kuhn e di Koyré", in AA.VV., Alexandre Koyré. L'avventura intellettuale, a cura di Carlo Vinti, Edizioni Scientifiche Italiane, Napoli, (1994), 653.

[4] T.K. Simpson: Faraday's Mathematics.On Getting Along without Euclid, Faraday Conference: Lecture, St John's College, Annapolis, March 30, (2001).

[5] T.S. Kuhn: Dogma contro Critica, Raffaello Cortina Editore, (2000), 116.

[6] P. Cerreta, A. Drago: "L'ideologia nella didattica della fisica: i principi della dinamica, suggerimenti per il loro insegnamento", in A. Drago (ed.), Fisica, Didattica, Società, CLU, Napoli, (1975), 82-98;

S. Sgrignoli,: "Insegnare la fisica senza partire dalla dinamica" in Epsilon, Paravia, Anno I, n°3, (1988), 34-38.

[7] L. Eisenbud: 'On the Classical laws of Motion', Am. J. Phys. 26, 144, (1958), R. Weinstock: 'Law's of Classical Motion: What's F? What's m? What's a?', Am. J. Phys. 698, (1961).

[8] E. Mach: La Meccanica nel suo sviluppo storico-critico, Boringhieri, 1977; H. Hertz: Principles of Mechanichs, The Macmillan Company, New York, (1899) .

[9] T.S. Kuhn, Dogma contro Critica, op.cit, 116.

[10] S. Tobias: "Math anxiety and physcis: Some toughts on learning 'difficult' subjects", Physics Today, June (1985).

[11] G. Delacote, "Putting Science in the Hands of the Public" in Science, Vol 280, 26 June (1998), 2055-56.

[12] P. Cerreta: Apprendimento formale e apprendimento informale delle scienze, Quipo Web X@X, Edizioni Project, (1999), 27-33.

[13] Inverness Research Associates: An Invisible Infrastructure. Institutions of Informal Science Education, Association of Science Technology Centers, Washington, (1996).

[14] R. J. Semper: "Science Museums as environments for learning", Physics Today, November (1990), 50-56.

[15] NCES 1999 - The Third International Mathematics and Science Study (TIMSS), Overview and Key Findings Across Grade Levels, NCES 2001- Highlights from the Third International Mathematics and Science Study- Reapeat (TMSS-R), Office of Educational Research and Improvement, US Dep. Of Education.

[16] Dimensions, Bimonthly News Journal of the Association of Science-Technology Centers, March/April (2001).

[17] The Exploratorium Magazine, The Exploratorium, San Francisco, Vol 25 n°1, (Spring 2001).

[18] F.R. Wilson, The Hand. How its use shapes the brain, language, and human culture, Pantheon Books, Random House Inc., New York, (1998).

[19] P. Dohetry, D. Rathjen, Exploratorium Teacher Institute, Gli Esperimenti dell'Exploratorium, a cura di P. Cerreta, Zanichelli, (1997).

[20] Bob Miller's Image Walk, Exploratorium Quarterly, The Exploratorium, San Francisco, Winter, Vol 11, Issue 4, (1987).

[21] Ibidem, p. 27.