DOI: 10.1478/AAPP.99S1A1

AAPP | Atti della Accademia Peloritana dei Pericolanti
Classe di Scienze Fisiche, Matematiche e Naturali
ISSN 1825-1242

Vol. 99, No. S1, A1 (2021)

TOWARDS A HISTORICAL APPROACH TO PHYSICS EDUCATION

ENRICO GIANNETTO *

ABSTRACT. Modern physics is a complex multiplicity of practices: theoretical, mathematical, experimental and simulation practices. Experimental and simulation practices are related to the pragmatic dimension of a physical theory. Mathematical practices are related to the syntactic dimension of a physical theory, but theoretical practices involve an often neglected semantic dimension. Physics and consequently teaching physics are usually reduced to the syntactic and pragmatic dimensions. Semantic dimension is linked to the conceptualization of the physical reality, to the conception of Nature. By neglecting the semantic dimension, physics is reduced to a pure mathematical game and to technological manipulations. Thus, the cultural aspect of science is lost and physics education is reduced to a mere technical training. This process of de-culturalization of science had its roots in the Enlightenment's turn in physics to free it from theology and metaphysics and had its completion in the post-second-world-war era. I believe we have to recover the cultural aspects of physics to understand it more deeply in its whole complexity. We have to recover all its relationships with other disciplines as philosophy, mathematics, psychology, sociology and other sciences, even theology, which are fundamental to constitute its semantic dimension. Historical approach to physics and physics education is the only way to recover this interdisciplinarity at the roots of the various physical conceptions of Nature. In this way, for example, we can understand that beyond mechanics there is a mechanist conception of Nature, beyond thermodynamics there is a thermodynamical conception of Nature, and beyond electromagnetism there is an electromagnetic conception of Nature. These different conceptions of Nature are not compatible and their historical fight has produced the relativistic, quantum and chaos revolutions in XX century physics. These different conceptions of Nature imply different existential self-understanding of the meaning of mankind in the universe and different ethical perspectives.

1. Modern Physics, Philosophy of Nature and Metaphysics

Modern and contemporary physics differs from other historical forms of physics (ancient physics, medieval physics, Renaissance physics) because, with William Gilbert, Thomas Harriot, Galileo Galilei and others, it is constituted as a form of philosophy of Nature not based on pure reason or on mere experience, but on an experimental practice with respect to which a theory is entirely a posteriori. It is therefore no longer a philosophy based on a theoretical contemplative *ethos*, a theoretical philosophy, but rather a philosophy based on an *ethos* of active research through experimental actions, a practical philosophy, an experimental philosophy, in which also the theory it is no longer a mere intellectual contemplation but is understood as a practice (Giannetto 2017).

The need for experimental physics was established between the XII-XIII and XIV centuries following the Franciscan criticism (especially by John Duns Scotus and William of Ockham) of Aristotelian physics: the possibility of founding physics on our limited experience and on our limited reason breaks down. If the world is not metaphysically presupposed as having a rational structure and if it is the creation of the inscrutable will of God, then it is not knowable rationally a priori: we cannot know if it is finite or infinite; we cannot know if there is a void or not, because other worlds or the void may exist beyond our experience; we cannot know if it has a mathematical structure or not. Experimental measures are necessary to understand if it is actually possible to establish *a posteriori* mathematical relationships that govern phenomena.

Nature is no longer a set of data of experience or intellectual vision: in the experiment not only there is an artificial re-production of natural phenomena or their simulation through mechanical phenomena, but rather there is a production of another Nature (think, for example, of the production of the void that we do not encounter on Earth; or, today, the production of subatomic particles or even antimatter) not accessible to experience due to the limits of human sensitivity and due to the microscopic dimensions of phenomena with respect to humanity or for the cosmic distances at which they occur (think, for example, of the four Medici satellites discovered by Galileo with the telescope) (Galilei 1968, 1992, 2001, 2009). Furthermore, Nature in the experiment manifests itself not directly to the human subject, but through instruments such as subject-objects that measure its properties independent of the subjective properties of a living being.

Aristotle's physics was a physics based on experience and reason and it was dealt with Nature that gives herself to experience: in earthly experience one does not encounter vacuum and therefore this is excluded from Nature. The physics of experience thus contradicts the physics of the experiment. Thus we have the paradox of Tom Stoppard, presented in the pièce *Rosencrantz and Guidenstern are dead* (Stoppard 1967). It is said that Galileo established as the law of Nature that bodies, from the same height, fall with the same speed and arrive at the same time on the ground. Then the actors drop a lead ball and a feather together from the same height and these bodies do not reach the ground together and the lead ball falls faster. This is the physics of our experience in which the void does not appear and this is the situation studied by Aristotle: that of a world in which there are frictional forces that slow down motion according to the bodies and their forms and in which motion does not continue long after the cessation of the exercise of a force. Aristotle's considerations are not absolutely wrong, but refer to the world of experience with all its limits, specifically to motion in a material medium, while Galileo studies motion in a vacuum. Experiments show that Nature is wider than that accessible to our experience. And there is a corresponding didactic problem of modern physics; male and female students who have not been initiated into experimental practices have conceptions based only on a physics of experience (for this reason, many times, they associate themselves with the physics of Aristotle; obviously, it is not possible to identify the complex and elaborated physics of Aristotle with the naive and spontaneous conceptions of the male and female students).

Modern physics is therefore configured as a set of practices: an experimental practice, a mathematical symbolic practice that codified its measures, a theoretical discursive practice that interpreted these practices, and also a technical realization practice of instruments subordinated to the purposes of experimental knowledge. In the twentieth century, a logical symbolic practice (typical of mathematical logic) and a practice of computerized simulation and virtual reality were added. Physics is therefore divided into several dimensions: a logical-mathematical syntactic dimension, a theoretical semantic dimension, and a fundamental dimension of experimental and computer pragmatics.

Galileo had performed a de-functionalization of the tools and technical operations giving them a new "experimental" sense embodied in the understanding of Nature by actions as proofs, and had subordinated mathematical practice as a symbolization a posteriori of measurements of experimental physics. The experiments at the origin of modern physics, in fact, constituted nothing more than a mechanical model of physical phenomena by means of mechanical phenomena. Galileo was certainly aware that it was a model, which made it possible to transform abstract thought into an experimental action, on which to base a new gnoseology in order to be able to access physical reality. With Descartes and Newton, however, the model was transformed into reality, Nature reduced to a machine (including animals), mechanics was transformed from technical art into the fundamental ground of physics. The mechanical model, from a simple heuristic model, was transformed into ontology, replacing an actual physical theory and reducing it for technical application purposes: it became a real mechanistic conception of Nature which is still the most widespread today and constitutes the ideology of the dominion over Nature (no ethics is necessary in this way towards Nature and animals) [1].

Already with Descartes and then with Newton's reinterpretation of Cartesian work, mathematical practice mostly returned to being considered a priori with respect to physics and at the same time physics was increasingly subordinated to technical purposes, and science to technology. Descartes, subordinating science to technique, created a "technical meta-physics", which emerged as a mechanistic conception of Nature, in which Nature and all living beings, except human ones, were considered mere *res extensa*, devoid of *res cogitans*, as machines and so useful instruments for mankind.

On the other hand, Descartes and Newton established apriori general mathematical laws of Nature and physics presented itself as an axiomatic-deductive structure, identifying itself with (Descartes identified Nature with the mere *res extensa* of geometry), or modelling itself on geometry. This mathematics assumed a priori with respect to experimental physical practice was constituted as a "meta-physics", a "mathematical meta-physics" and this allowed Descartes and Newton to construct also a theological metaphysics. For Descartes the reduction of Nature to *res extensa* leads to a technical meta-physics which coincides with the mathematical meta-physics, and with a theological meta-physics in which Nature devoid of forces, inert and passive, is subject to the only divine power that is expressed in the laws of Nature. Newton introduced mathematical space and time, which are absolute, that is, they exist independently of material bodies and their relationships, as attributes of God (*sensorium Dei*), and of which physically measurable space and time are only an approximate image. He introduced also gravitation as instantaneous forces and as actions-at-a-distance not attributable to material bodies, but only to the ruling action over the world by God. These first metaphysical deviations of modern physics itself show however that

[1] Giannetto (2010, pp. 141–237)

physics also constitutes an image of Nature which is inscribed in its dimension of theoretical practice and in which the hierarchy between its practices determines a theory of physical knowledge, a gnoseology and an epistemology, and conceptual semantics develops an ontology and a possible metaphysics.

Today, indeed, physics and physics teaching are dominated by a form of reductionism, neglecting concepts and meanings. The semantic dimension is reduced to a mere pragmatic dimension, theoretical physics is reduced to mere mathematical physics, and so physics is reduced to a pure mathematical game and to technical manipulations. This perspective involves also a reductionist view of the process of theory changing and of the evolution of physics. When, for example, we say that in a certain mathematical limit general relativity is reduced to Newton's gravitational theory, we neglect that the first is a field theory and the second is an action-at-a-distance theory. That is, in this case we consider only the syntactic-mathematical dimension of physics in which a physical theory is reduced to a mathematical model: new equations reduce to old equations in a particular mathematical limit. In this way, we consider the old theory as a derivate of the new theory in a certain limit in a completely anachronistic frame implying even a mathematical continuity of the historical temporal process of change (Cerreta and Drago 2016). This is what involves neglecting the semantic dimension of physics. This is the way we have a loss of meaning and of our understanding of physical reality. Semantic dimension is related to scientific thinking and to a *conception of Nature*. This conception of Nature constitutes the cultural content of a physical theory. The loss of meanings and of the conceptions of Nature is a process of de-culturalization of physics. The historical roots of this process have to be found at Enlightenment's turn in physics to free it from theology and metaphysics: D'Alembert (Le Rond d'Alembert 1743), in his *Traité de dynamique* published on 1743 reduced physics to a mere mathematical structure without meaning. Only in this way D'Alembert was able to unify Newton's mechanics based on the concept of a force external to the body in motion and Leibniz's dynamics based on the concept of conserved energy as internal to the body in motion, and indeed so he destroyed Newton's theology of force and Leibniz's theology of energy. The price to be payed to de-theologize physics was too high: the elimination of any meaning and of any concept from physics. Thus we can no more understand what kind of conceptualization generated a physical theory, we can no more understand the meaning of mathematical formulas. This process of de-culturalization of physics was indeed completed only in post-second-world-war era of physics.

Only a historical approach to physics and physics education can allow us to recover meanings and concepts of physics. History shows the complexity of physical meanings and concepts, their trans-disciplinary or inter-disciplinary roots: myth, theology, philosophy, psychology, sociology, biology, anthropology and other sciences are involved.

For example, action-at-a-distance was related to myth and to magic. Newton followed Henry More (Taschini and Giannetto 2019) to deduce the impossibility to take count of the fall of a body to the ground in mechanical terms. More introduced the Spirit of Nature as the Platonic Soul-of-the World to explain a curvilinear trajectory, because Descartes had stated the tendency of a body to continue in a rectilinear uniform motion as the first law of his mechanics. More considered the process of attraction to the ground as a sort of a Platonic *eros*. Space and time existed also without matter as properties of the Spirit of Nature. Newton was a Christian who rejected Platonic concepts and so transformed More's explanation in this way: absolute space and time were considered as *sensorium Dei*, that is properties of God and eliminated the Spirit of Nature. Gravitational absolute force was identified as the same power of God, His dominion over the world, ad not as an action of a Spirit of Nature. Indeed, we can conceptually understand Newton's gravitation theory if and only if we know this historical process of transformations of conceptions of Nature from Descartes' mechanical conception to a Platonic one by More, and from the Platonic to Newton's Christian reformed theological one. Newton transformed More's Platonic *eros* of attraction into an *ethos* of a complete submission of the world (and of mankind) to the supreme power of God: this is the deep meaning of Newton's law of gravitation (Giannetto 2019). Newton's gravitation law had not only a certainty by experimental induction or as mere rational or mathematical law, but as a theological certainty.

2. Physical Theories as Conceptions of Nature

As is well known, the late 19th century saw physics broaden its focus from mechanics only, to thermodynamics and electrodynamics as well. This new situation implied the problem of determining the very foundations of physics, and the correlated issue of hierarchical relations among these different physical disciplines (McCormmach and Jungnickel 1986; Giannetto 2005).

There were at least four different «fighting» conceptions of Nature. The so-called *Energetic* conception of Nature, which looked at energy as the fundamental unifying concept of physics and had its most important proponents in Georg Helm (1851-1923) and Wilhelm Ostwald (1853-1932).

The *Thermodynamic* conception of Nature, which held energy, entropy and system as its fundamental concepts and looked at thermodynamics as the real foundation block of physics. Its major exponents were Pierre Duhem (1861-1916) and Max Planck (1858-1947).

The *Mechanical* conception of Nature, which was the most conservative in searching for a mechanical reduction of other physical disciplines and of all physical concepts in terms of mass, space and time through models of material point and action at-a-distance forces. Hermann von Helmholtz (1821-1894), Heinrich Hertz (1857-1894) and Ludwig Boltzmann (1844-1906) were the most representative proponents of this perspective.

The *Electromagnetic* conception of Nature, which was based on the concepts of field, energy and charge and looked at the theory of electromagnetism as the foundation of other physical disciplines. Among the physicists who gave the most relevant contributions to this perspective are Hendrik Antoon Lorentz (1853-1928), Joseph Larmor (1857-1942), Wilhelm Wien (1864-1928), Max Abraham (1875-1922) and Henry Poincaré (1854-1912). The electromagnetic conception of Nature has deep roots in the history of mankind and has certainly been developed by the elaboration of the Brunian-Leibnizian physics tradition. On the one side, it has developed within German physics or *Naturphilosophie*, while on the other, mainly within English physics.

William Gilbert (1540-1603) and then Johannes Kepler (1571-1630) himself saw magnetism as the force ruling the order of our cosmos, of our Copernican world, and Athanasius Kircher (1602-1680) developed a theology of magnetism and of the magnetic Divine Universal Love (Giannetto 2007).

Indeed, at the end of the process by which Newtonian gravitation was reduced from an active divine force to a passive property of inertial matter and Newton's theology of gravitation was given up in favor of a mechanistic conception of Nature, electricity came back as the path to a new, vitalistic conception of Nature. Electricity was seen as an active force and possibly the origin of animated life, that is an active vital force, Leibniz's inner *vis viva*, as well as the very *psyché* within things - a sort of electric unconscious - or the *Anima Mundi* itself. Many theologians and physicists, such as Prokop Divisch (1698-1765), Friedrich Cristoph Œtinger (1702-1782), Johan Ludwig Fricker (1729-1766), and Gottlieb Friedrich Rösler (1740-1790), developed a genuine theology and psychology of electricity. The controversy on animal electricity between Luigi Galvani (1737-1798) and Alessandro Volta (1745-1827), which lasted through the end of the 18th century to the beginning of the 19th, was a turning point; Volta's perspective won out, and his unveiling in 1800 of the first "electric machine", the battery, marked the victory of the mechanistic view, reducing life to a series of mechanisms to which even electricity could be assimilated. It was the Romantic physicist Johan Wilhelm Ritter (1776-1810) who turned Volta's interpretation upside down, stating that because there was no specific animal electricity, the presence of electricity made the entirety of Nature a living and animated being. Electric fluid was the *psyché* of everything. Romanticism continued to develop these ideas and Franz Anton Mesmer (1734-1815) described animal magnetism, magnetic fluid as universal soul, *psyché* as a magnetic nervous fluid, and psychic unwellness as a magnetic disease which could be healed by magnetic hypnotism.

Maxwell's theory of electromagnetism demonstrated that physical reality was not only inertial, passive matter, but also a dynamic, active electromagnetic field, not reducible to a mechanical model of matter. Furthermore, Maxwell's equations have vacuum solutions, that is in absence of charged matter: an electromagnetic field exists even when there is no matter. Thus, the possibility of a new non-dualistic view of physical reality was considered: if matter cannot exist without an electromagnetic field and an electromagnetic field can exist without matter, then the electromagnetic field could be the only physical reality, from which all matter is derived [2].

The electromagnetic conception of Nature is generally thought to have been superseded by the developments of 20th century physics. However, deeper historical inquiry shows that this conception is at the root of both relativistic and quantum transformations of physics.

Concerning relativity, the 1900, 1902, 1904 and (5 June) 1905 papers written by Poincaré (Poincaré 1898, 1900, 1902, 1904, 1905) show how special relativity dynamics derived from, and was a first realization of, the electromagnetic conception of nature. Einstein's (30 June) 1905 paper was only an incomplete semi-mechanistic version of this new dynamics (Einstein 1905). This historical recognition is also fundamental in order to understand the initial reception of special relativistic dynamics in all countries, particularly Italy (Enriques 1906; Giannetto 1995).

A first complete presentation of this new dynamics appeared in the July 1905 paper written by Poincaré and published in 1906 (Poincaré 1906). In this paper, the new dynamics are presented as invariant by the Lorentz-Poincaré transformation group, derived by Maxwell's theory of electromagnetism and also containing a theory of gravitation (absent in the paper

[2] Giannetto (2010, pp. 293–320)

of Einstein (1905)). The starting point was the electromagnetic self-induction phenomenon, related to the so-called radiation reaction. When a charged particle is subjected to the action of an electromagnetic field, it accelerates and irradiates. This radiation modifies the field and the new field modifies the acceleration of the particle, which again irradiates and so on. The electromagnetic field is thus dependent on the time derivatives of position, up to infinite. This also entails a contribution to the field force proportional to the acceleration, the coefficient of which involves an electromagnetic mass, that is an electromagnetic contribution to particle inertia. We can write:

$$\mathbf{F}_{e.m.} = m\mathbf{a}$$

$$\mathbf{F}_{e.m.} = \mathbf{F} + k\mathbf{a} + k'\frac{d\mathbf{a}}{dt} + \ldots$$

$$\mathbf{F} + k\mathbf{a} + k'\frac{d\mathbf{a}}{dt} + \cdots = m\mathbf{a}$$

$$\mathbf{F} + k'\frac{d\mathbf{a}}{dt} + \cdots = m\mathbf{a} - k\mathbf{a} = (m-k)\mathbf{a}$$

$$m_{e.m.} = -k, \qquad m = 0$$

Einstein's relativity takes the new mechanics without the electromagnetic conception of matter (Einstein 1905; Giannetto 2006, 2009). This shows how important the conceptions of Nature embodied in physical theories are to understand the evolution of physics. Also quantum physics was created by the interaction of thermodynamical and electromagnetic conceptions of Nature. Planck applied the second law of thermodynamics to electromagnetism and made a statistical thermodynamics of the radiation field.

Larmor and Poincaré considered h as related to the the quantum angular momentum whereas electrons were rotating electromagnetic fields (Giannetto 2008):

$$h = m_{e.m.}\frac{c^2}{\nu} = m_{e.m.}c\lambda$$

3. Conclusions

Different conceptions of Nature are not compatible. We can no more teach mechanics, thermodynamics and electromagnetism as cumulative knowledge. We have to understand and to teach physics and its evolution as a fight among different conceptions of Nature. Different physical theories involve different conceptions of Nature. This conceptual dimension of physical theories constitutes their cultural content. Only a historical approach to physics and to physics teaching can give back to us this cultural dimension of physics, can give back to us the meaning of revolutions in physics. Physics is an effective (experimental and mathematical) philosophy of Nature. Physics implies a gnoseology of experimental actions: no pure reason can understand Nature. Relativity and quantum physics operated a revolution in our understanding of physical reality. Quantum-relativistic physics gives us a new ontology of an indeterministic field becoming and a new gnoseology: truth becomes a probabilistic concept and there is need of a new quantum logic, a new way of thinking

(Giannetto 1989, 1990, 1991a,b, 2018). Indeterministic Nature does no more constitute a problem to understand ourselves as free living beings, our place within the cosmos.

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* Università di Bergamo
Dipartimento di Lettere, Filosofia, Comunicazione
Via Pignolo 123, 24129 Bergamo, Italy

Email: enrico.giannetto@unibg.it

Paper contributed to the international workshop entitled “New Horizons in Teaching Science”, which was held in Messina, Italy (18–19 november 2018), under the patronage of the *Accademia Peloritana dei Pericolanti*

Manuscript received 05 July 2020; published online 30 September 2021