Science-Technology Cross-Hybridization and its Role in the Crisis of the Scientific Method: An Historical Perspective

Assunta Bonanno, Michele Camarca and Peppino Sapia

Abstract Nowadays, in the science-related community, an urgent need has emerged to clarify a crisis of the methodological paradigm known as "Scientific Method". Such a crisis, arising from some recent striking experimental results achieved in experimental sciences, undermines the very foundations of knowledge, with potential serious consequences to the development of future technological applications. In this work, the crisis is analysed within an historical survey on the evolution of the Scientific Method. Furthermore, the role played by cross-hybridization between sciences and technological development is highlighted, throughout the last three centuries, as a possible factor in overcoming that crisis.

Keywords Scientific method · Science · Technology · Scientific knowledge · Scientific method crisis · Science-technology relation

1 Introduction

All those involved in physics, and more generally in experimental sciences, as well as people working in many applicative disciplines related to them, warn today of an urgent need to clarify a crisis of the methodological paradigm known as "Scientific Method" (SM), arising especially from some recent striking experimental results achieved in these sciences. Just to give some examples, we mention here experimental results related to quantum teleportation (Bouwmeester et al. 1997; Ma et al. 2012), a topic challenging common sense and the usual way SM is intended; or the experimental enterprise that lead to the discovery of the Higgs boson (Riordan et al.

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2012), a context in which the experimental “evidence” is far beyond the possibility of direct understanding and control of a single individual, or even a small group of experimenters. Conclusions can be drawn from these (and many more) results that undermine the very foundations of knowledge and create a state of permanent confusion, with potential serious consequences on the development of future technological applications. This conceptual framework finds, in recent decades, its philosophical correspondence in the fact that theories such as the so-called “weak thought”, or crypto-idealistic, gained ground, leading to a dangerous atmosphere of uncertainty and doubt (Vattimo and Rovatti 2012). In order to highlight the way in which the recent evolution of SM can affect the rate of development of technological implementation of scientific discoveries, it is necessary to define—in a contemporary perspective—what the SM is, and how it has been developed over time.

In the present work we accomplish this task, highlighting in particular the role played by cross-hybridization between sciences, on one side, and technological development, on the other side, throughout the last three centuries. We show by an historical analysis that (i) the achievement of cognitive goals and the formulation of more and more general principles, and (ii) the ability of this knowledge to change (via technological applications) the world and the same structures of thought, are cross-linked in a bi-directional causal way. This way of thinking has been challenged by many recent scientific discoveries.

2 An Overview on Scientific Method

Let us start speaking about the SM in an historical perspective, focusing on how it has been put together over the course of time, through achievement of the fundamental goals of knowledge and formulation of more general principles. The first period of development of scientific thought had its roots in ancient Greece, based its early stage on the experience and doctrines of older Ionian physicists (Britannica 2013), and reached its highest point in the period of the reorganization and consolidation of knowledge coinciding with the age of Aristotle (384 BC–322 BC). This is the context, in fact, in which the concept of “cause” (which constitutes one of the foundations of science) appears and consolidates. Moreover, it is still in ancient Greece that uninterrupted flow of thought going under the name of “realism” is manifested.

We will consider here only three stages in the development of the SM: (i) its birth with the physics of Aristotle (384 BC–322 BC), (ii) the change of perspective with Galileo Galilei (1564–1642) and Isaac Newton (1642–1727) and (iii) its crisis in modern physics (both in astrophysics and in microphysics) mainly due to phenomena which are no longer explainable in intuitive terms and which violate laws for a long time considered valid (at least within the solar system).

We will try to illustrate, first of all, that there actually was a sudden transition from one “unscientific” thought (which lasted almost 2000 years) to a “scientific” one (which was born and developed suddenly). Furthermore, we will show that the

Aristotelian doctrine of "Potency" and "Act" continued to possess unchanged liveliness and explanatory power throughout centuries. Even in the twentieth century, in fact, it will be invoked by Werner Heisenberg (1901–1976), one of the founders of modern physics, to explain the meaning and interpretation of one of the crucial points of quantum mechanics.

The sharp contrast between the Aristotelian philosophy and the Galilean one has produced on the former the layering of an incredible amount of negative criticisms, eventually ruling out its exclusion from the history of scientific thought. From the educational point of view, Aristotelian physics is nearly ignored today and it would almost seem that, not only scientific thought, but also the thought *tout court*, was born with the Copernican revolution. This negative judgment also results from the contribution of authors of primary importance, which led to the persuasion that the Greek civilization was only the "world of approximation". For example, Alexandre Koyré (1892–1964) argued that the Greeks had no real technology, no real physics in our sense (Koyré 1961). However, in spite of this current of thought (which eventually relegated the Aristotelian philosophy to the role of an unfruitful theory, far from any empirical aspect and having a decidedly metaphysical and speculative character), in spite of this we believe that Aristotelian physics has been a rigorous, flexible and sophisticated architecture of thought. In this regard, some illuminating reflections on the subject by Mary B. Hesse (1924–) comfort us. She recognizes that:

> Comparing the arguments by which Aristotle reaches his primary qualities with those by which the atomists reached theirs, it is remarkable that Aristotle relies on common experience of actual properties of bodies, however superficially he may interpret this, while the atomists on the other hand were influenced by the most sophisticated metaphysical speculations. This example and others like it make it somewhat ironical that in the seventeenth century it is atomism which is regarded as progressive and empirical, while the Aristotelian tradition carries the stigma of non-empirical speculation.[1]

We shall not debate here whether Aristotelianism had been a school of thought that gave course to practical applications, because surely they were poor or non-existent. However, we think that Aristotelianism is to be placed in a stream of thought having some degree of continuity with Galilean thought, and we believe that this fact should be properly emphasized. Continuity does not mean identity between the natural philosophies of the two paradigms, but rather the recognition that both have in common the spirit and the desire to be in front of nature with the aim of explaining phenomena, using terms and concepts sometimes similar. The main difference between the methods adopted, however, is to be found in the purposes that they were intended to achieve and in different social references.

Aristotelian physics has a profoundly observational character and looks for "causes" of phenomena (*cognitio certa per causas*), even if it runs out in purely qualitative descriptions. It establishes the rules for correct reasoning because the exercise of reason was then a practice widely appreciated by a gentry who abhorred any manual activity. The Galilean physics, on the contrary, looks for the "laws" of

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[1] Hesse (2005).

phenomena (*cognitio certa per leges*); it begins setting up a quantitative representation of phenomena, using mathematical tools and employing a new experimental method. Lucio Russo (1944–), in a fundamental book on the history of science (Russo 2004), shows that in ancient Greece, as well as in the late Hellenistic period, there were a large number of technical applications, and this leads him to believe that ancient societies had created and exploited technological knowledge. However, cited examples suggest that, in the long historical period under consideration, only isolated individuals (such as Archimedes, c. 287 BC–212 BC, just to give an example) were individually able to turn into practical applications the evidence hitherto accumulated in the various fields of knowledge (hydraulics, optics, etc.). Anyway, science needed to become a *social enterprise*, in order to produce true technological applications: and this was done only in the seventeenth century. Indeed, it is not a coincidence that in this period arose "academies", which, unlike "universities", were not expected to simply transmit "knowledge" but to strive to acquire it in an experimental and direct way. In addition, "academies" were required to make public their results so that they could be socially exploited and be useful to the community (Bernal 1971).

As we said, there was not a clean break between a "before" Galileo and an "after" him; there was not a non-scientific thought previous to Galileo and a sparkling scientific thought after him. Indeed, ancient Greece had already reached a high degree of formal mathematical perfection. Just think, to give some examples, of: Euclidean geometry, the development of conics theory by Apollonius (262 BC–190 BC), the work of Diophantus (c. fourth Century BC) on equations or the invention of the method of exhaustion by Eudoxus of Cnidus (408 BC–355 BC), later expanded and used by Archimedes to find the area of a circle. It is likely that the latter method, had it been properly studied, might have led to the birth of calculus with millennia of advance. Despite having developed such a sophisticated mathematics, however, the ancient world produced little progress in the *application*s of mathematics to physical phenomena, since it considered impossible that phenomena of the "sublunary world" could have aspects correlated with each other in a precise and quantitative way. The ancient world, in fact, had a predilection for the "proof" of phenomena over the "discovery" of them, and considered deductive logic superior to inductive logic, which was based on observation and experiment. Unavoidably, therefore, such a conception definitely hindered the development of technology, and consequently delayed the satisfaction of human needs. In this context, it makes sense to ask what the reasons were for the lack of scientific and technical production, so extensive and long lasting for civilizations such as the Greek, the Roman and later the medieval. Some historians of science believe that societies based on slavery (and the bondman was just a slave with a new name), had neither stimuli nor interest to promote the birth of scientific enterprise and technological progress. Such societies, indeed, found the workforce necessary to produce needed goods at practically zero cost in slavery. These researchers admit that there may have been other reasons, however they believe that what we have said above constitutes the basic reason of scientific poverty that lasted two millennia. In this regard, the following passage from Benjamin Farrington (1891–1974) is enlightening:

> The failure of ancient science was in the use that was made of it. It failed in its social function. Even when the acquisition of slaves became more and more difficult the ancients still did not turn to a systematic application of science to production. It is not claimed that such applications never occurred…. But the general truth remains that ancient society had set in a mould which precluded the possibility of an effective search for power other than the muscles of slaves. The dependence of society on the slave is everywhere reflected in the consciousness of the age.[2]

In the period from the mid-sixteenth century to the end of the seventeenth century (coinciding with the birth of commercial enterprises, industries, stock exchange, newspapers and academic reports) a great ferment of ideas appears together with an eagerness to communicate them by all means. Still relying on old institutions such as the monarchy, new ways of goods production and transportation have been growing and this reduced the strict division, until then existing, between the free man and the servants bound to the earth. For goods production, the nascent industry needed a new workforce and so a growing necessity for technical applications of science arises.

The spirit of the time in which Galileo worked (revitalizing the "practical" vocation of the Ionian physicists) was characterized by an underground ferment, by a complex network of subterranean currents of thought which finally resulted in the Enlightenment of the eighteenth century. Galileo, in addition to being an intellectual and a scientist, became an instrument maker, turned into a "vil meccanico" (ancient Italian for "mere technician"). The instruments that came into use in scientific practice were not neutral entities. In their construction, in fact, are already involved a number of ideas and assumptions about aspects of the phenomena that they are aimed to investigate. Moreover, they begin to represent—for the first time in the history of knowledge—a not-neutral channel through which information are acquired, or also a filter between the experimenter and the world under observation. Newly-invented scientific instruments amplified what otherwise could have not been perceived directly by senses and so allowed the measurement of important properties related to the study of phenomena. In this period there is the remarkable circumstance that technological tools, constructed from existing scientific knowledge, in turn led to the acquisition of new scientific knowledge. This is a first significant example of a kind of "feedback" of technology in science, which will become more and more relevant, as we shall see. In the light of this, we can certainly say that one of the peculiar characteristics of the development of Galilean science was constituted by the overcoming of the conception according to which intellectual and manual provisions would be opposite: on the contrary, they can coexist in the same individual. In other words, in that period:

> [...] has gained ground a new consideration of the manual work and of the cultural function of mechanical arts. Moreover, was established the idea of knowledge as a progressive construction, since it consists of a series of results that are placed, one after the other, to an always increasing level of complexity or perfection.[3]

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[2] Farrington (2000).

[3] Rossi (2001).

The main reason (though certainly not the only one) of the paradigm shift is to be found in the changed social conditions, which favored the release of new forces, and this gave rise to a new way of thinking and being. Nature was seen as an entity that needed to be questioned, forcing her to give answers, and no longer a mother who just needed to be contemplated.

3 From Aristotle to Modern Physics Through Galileo and Newton

In this section, we expose a quick overview of the evolution of SM from its origins to the crisis that arose in modern times, in particular with relativity and quantum physics. The analysis of specific aspects, here and there, provides an opportunity to highlight the claimed science-technology cross-hybridization. A more extensive analysis of this topic will be given in Sect. 4.

3.1 Aristotelian Physics

We said that Aristotelian physics is ultimately a qualitative physics. It observes phenomena in their wholeness and, limited to those occurring in the "sublunary sphere", renounces the possibility of developing a mathematical quantitative analysis of them. On the contrary, Aristotelian physics, instead, leaves this opportunity to the "extralunary world": the motion of stars and planets. The physics of Aristotle conceives of nature as a living body, as a whole: dissecting it would not have resulted in a greater understanding, but, on the contrary, would have meant to kill it. The overall vision of such a physics is therefore entirely holistic: it investigates the substantial unity of the cosmos and the order of the cosmos rests on a "telos" (from the Greek τέλος for "end", "purpose", or "goal"): the search for purpose is the fundamental premise of philosophical inquiry of Aristotle. However, the unity of the universe does not mean its uniformity: the cosmos is finite and is divided into a sub-lunar sphere (where bodies are changeable and alterable in quality and where generation and corruption operate as a part of Being) and an extra-lunar sphere (which is the realm of the eternal and unalterable). Planets (including the Sun) and stars moving around the Earth are formed by a solid crystalline, transparent, weightless and incorruptible substance: the cosmic ether or *quinta essentia*. These planets are embedded in the ethereal homocentric spheres, which rotate in a circular motion around the centre of the universe (which coincides with the centre of the Earth). The perfection of uniform circular motion, without beginning or end, will give rise to a kind of axiom and will become an element of continuity with either later Ptolemaic astronomy or with Galilean physics (and then with Keplerian astronomy). As regards the ultimate composition of the world, Aristotle believed that matter is infinitely divisible (as a process, he meant: an infinite in "potency" not in "act") and that the atomic theory of Leucippus (fifth Century BC) and Democritus (460 BC–370 BC) (who hypothesized an ultimate reality made up of indivisible atoms) is incorrect. In fact, atoms are objects lacking in quality, indivisible and unchangeable, and then, in the Aristotelian view, they are necessarily motionless. Atoms cannot move for two reasons: firstly because the movement would have resulted in a change in them, and secondly because atoms would have had to move in a vacuum, and this is not allowed in Aristotelian physics since this fact would have caused their motion with infinite speed. In the sub-lunar sphere, there are two kinds of local motion: *natural motion* or *violent motion*. Natural motions are those of bodies tending to reach their natural places, respectively, the centre of the Earth and the lunar sphere, and their trajectories are straight. Violent motions, instead, are those caused by an external motor agent. In the latter case motion is determined by contact between the agent and the body, and motion ceases as soon as the contact finishes (*cessante causa, cessat effectus*, in Latin, i.e., once the cause ceases, the effect ceases too). Without going into depth about this delicate subject, we will say that it constituted a lacerating contradiction. In fact, if a body, to move, needs something to move it (*omne quod movetur ab alio movetur*, in Latin, i.e., everything that moves is moved by something else), then you cannot understand what could be the cause of the motion after the body has detached from the motor agent. This view had a real weakness and provoked a multitude of criticism both inside and outside of Aristotelianism. Aristotle, in fact, was forced to define the medium in which the motion takes place as, simultaneously, a resistant and a boosting agent. Aware of this contradiction, he proposed as a solution the following mechanism (*antiperistasis*) to explain the motion of an object thrown into the air. The object in motion leaves behind a void that the surrounding air rushes in to fill, so impressing a boost to the object, which will continue to move forward in a straight line. However, due to the resistance of the medium, the so-generated propulsive thrust will gradually diminish and eventually the object will stop (*Nullum violentum potest esse perpetuum*, in Latin, i.e., no violent motion can be forever). This solution, albeit ingenious, was not convincing, because the medium played two opposite roles. An acceptable solution was proposed, some seventeenth centuries later, by Johannes Buridanus (Jean Buridan, 1295–1361), who introduced the concept of "impetus", a notion looking something like the modern concept of momentum. Before detaching, the thrust agent provides the bullet a quality (the *impetus*), which makes it move forward in a straight line. This quality is progressively consumed during the motion, becoming eventually zero. From now on the motion will cease to be a "violent motion" becoming a "natural motion" and the projectile will fall. Such a description is pictorially shown in Fig. 1 by a sixteenth century drawing depicting the Buridan theory of impetus (AB portion of trajectory), its progressive consumption (BC portion) and then the "natural" falling motion (CD portion). This aspect of Aristotelian physics can be a useful matter for reflection because it allows us to illustrate in an exemplary manner the concept of *common sense representation* of phenomena. This is of great interest because similar problems of representation are widely present in modern quantum physics. We mean here by "common sense" that kind of knowledge that comes from the popular dissemination of concepts and representations

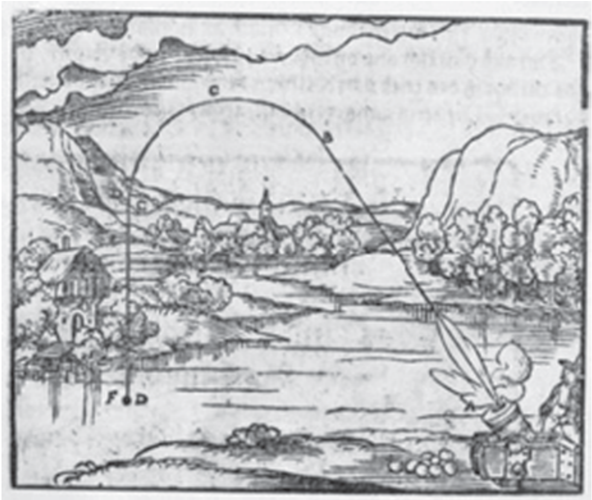

Fig. 1 A sixteenth century drawing by Walther H Ryff (1582) depicting the Buridan theory of *impetus*. (http://www.yorku.ca/lbianchi/nats1800/lecture16a.html)

and which constitutes the opinions, judgments, beliefs and anything else of ordinary people even on specialized topics that go beyond those of daily life. Without writing a treatise on the subject, we note that several authors refer to this concept, considering the theme also worthy of experimentation in physics education (Halloun and Hestenes 1985; Whitaker 1983).

3.2 Galilean-Newtonian Physics

The SM resting on Galilean "sensate esperienze" (i.e. "experiences made through senses"), sometimes considered revolutionary, is only one of the two instruments that Galileo used. The other conceptual tool was the mathematical method (what Galileo called "necessary demonstrations") which was used to formulate hypotheses and express scientific explanations, deducing the consequences that the assumptions implied. In this way, given the state of a mechanical system, one could predict not only its evolution in time, but also new aspects of the phenomena that could then be controlled experimentally, thereby closing a circular chain that, in this way, was always in progress. The failure in verifying predicted values or effects resulting from the hypothesis called for a revision, a settlement or a complete rejection of the hypothesis, and then for the re-formulation of new hypotheses. In Galilean physics, the aspects of phenomena were isolated in a manner appropriate to the possibility of describing them in quantitative and mathematical terms. This physics, moreover, began using the word "experiment" in the modern meaning of the term: man was no longer a passive subject who only watches the phenomenal aspects which nature consents to show him; on the contrary, he interrogates nature, setting the conditions in the belief that nature can adequately respond.

Let us consider, for example, the problem of falling bodies. Galileo realized that, for bodies in free fall, it was not possible to perform reasonable measurements due to their excessive speed. He noted, however, that making them move along an inclined plane could be a flexible way by which to slow down bodies to a desired speed. He conceived then a process that progressively eliminates the roughness of the parchment lining the groove in which he ran the bronze balls. Using pumice to make the parchment more and more smooth, Galileo performed space-time measurements in each state of smoothness. Measuring travelled space posed no particular problems, because the procedure for this was already well known from geometry; many problems, instead, arose from measuring time intervals (note that he could certainly not evaluate them with an hourglass!). Galileo built then a tool that would allow him to execute sufficiently precise time measurements: the *water clock*. He realized that, if you let water gush out of a small hole drilled in the wall of a large container, the amount of water gushing out in a given time interval should be proportional to the time elapsed. In this way, it was possible to make the quantitative comparison (i.e., the "measurement") of time intervals. Notice that, for his purposes, the mathematics of ratios was sufficient, and therefore he did not consider important to measure the absolute elapsed time, but only relations between time intervals (or the amount of water gushed out, collected in a bowl and then weighed). Of course, this "stopwatch" had provided proper relationships only in the case that the flow of water was uniform: Galileo had not proved this, but he sensed it, believed it, and then went on as if this had been proved. This was an approach to the knowledge of the physical world very different from any other previous experience, although it was a mode of proceeding that in many ways resembles the aforementioned "world of approximation", the uncertain, the unproved.[4] Indeed, this is the paradigmatic way forward of physics. The experiment contains errors, unexpected features, some incorrect or not fully tested assumptions, but it is still carried out until you can decide if the results are or not consistent with the assumptions you have made. Yet, you will have the courage to apply mathematics to this mass of inaccurate data. There will be time later to go back to correct, to give account of assumptions made, to repeat the experiments by making the experimental apparatus less uncertain. In this regard, it is remarkable to note that, when successively the mechanics was strictly founded in its principles, the Galilean intuition on the proportionality relationship between the amount of water and the time interval was confirmed true with a high degree of accuracy, depending on the ratio between the hole area and the area of the large container. However, Galileo had stated this already dozens of years before!

The evolution of the late seventeenth century, and then throughout the entire eighteenth century, did not change the overall picture of SM that had started with Galileo. Its subsequent development was both experimental and theoretical. The

[4] Koyré (1961) thinks that the "world of approximation" is that of the Aristotelian philosophy, but on a closer inspection, we find that this is not true. Galilean physics does not reject the "world of approximation", but instead uses it, because it receives suggestions for a glimpse of the "world of precision".

paradigm shift about the nature of motion came with Newton, whose working was characterised, on one side, by the achievement of an exemplary clarity in the enunciation of principles of the new physics of motion, and, on the other side, by alchemical studies of which we will not talk here. He established that bodies in rectilinear and uniform motion do not need any cause to do this, while causes (efficient, in the Aristotelian sense) are required to change the state of motion of bodies, and these causes are called *forces*. He stated that any force acting on a body, causes a variation in the amount of motion (the product of mass by velocity), and also affirmed that pairs of bodies mutually exchange interactions equal in intensity, in contrary to and directed along the line joining them. Starting then from Johannes Kepler's (1571–1630) laws, Newton clearly stated the universal gravitation law, which unified the laws of physics of the earth with those of the heavens, so overcoming the Aristotelian distinction between the "sublunary sphere" and the "extralunary world". Newton stated, moreover, that there was no need for any animism, or for ad hoc assumptions ("*hypoteses non fingo*"). In order to accomplish this enormous task of systematization he had the need to introduce absolute space and time to describe the motion. In the Newtonian picture, these two concepts represent the frame, we could say the passive "container", of physical phenomena (Jammer 2007, 2012).

In the eighteenth century and the first half of the nineteenth century, areas such as analytical mechanics and mathematical physics born and developed that deduced all the consequences contained in the Newtonian and Galilean postulates and at the same time applied SM to the study of physical phenomena in many different fields of mechanics, from statics to hydraulics, to atmospheric phenomena. Other areas not yet included within mechanical phenomena (such as optics, thermal phenomena, electricity and magnetism) began to seek their experimental and theoretical systematization. The success of SM, between the beginning of the eighteenth century and much of the nineteenth century, led to the unification of different phenomenal fields seemingly unrelated to each other. In this period, under the impulse of manufacturing industries, ironworks and the nascent railways, the theory of heat (thermodynamics) and electromagnetism found a fertile ground for development. The need arose for a solid theory of thermal machine's efficiency so as to take the most out of them, consuming the minimum amount of coal needed to produce a given mechanical energy. In this context, it is not surprising that the formulation of the second principle of thermodynamics (which deals with the efficiency of thermal machines) saw the light before the first principle, even before a clear definition about the nature of heat had been achieved! The method is always the same: if you go steadfastly ahead, successively someone will systematize the results. In the mid-nineteenth century, Joule showed that mechanical work and heat were both forms of the same physical quantity, energy, convertible into one another (although not symmetrically) and this laid the foundation for the formulation of a new principle of conservation of energy including heat.

Electrical and magnetic phenomena throughout the seventeenth and eighteenth centuries had been known only in their static form and therefore had appeared as different phenomena that did not influence each other. However, already in the early nineteenth century, Hans Christian Ørsted (1777–1851) showed that dynamic

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