THE DEVELOPMENT OF SCIENCE AND TECHNOLOGY RELATIONS IN ENGINEERING: FROM GALILEO GALILEI'S "TECHNOSCIENCE" TO NANOTECHNOSCIENCE[1]

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ABSTRACT: Galileo Galilei was one of those who created new science oriented to technical needs. He established the relation between scientific knowledge and the objects of practice. Galileo created more than a model of experimental activity; he demonstrated how to develop scientific knowledge so that it could be used for technical purposes. That is why "technoscience" is an appropriate name for Galileo´s new science. Contemporary technoscience makes natural-scientific experimentation constitutive for design, while research results are oriented equally on interpreting and predicting the course of natural processes, and on designing devices. It is impossible to separate research from development and engineering design. This new model of technoscience is visible in nanotechnoscience.
KEYWORDS: Galileo Galilei, modern science, technology, technoscience, nanotechnology.

Science-based engineering activity

The traditional guild-regulated crafts were gradually replaced by science-based engineering activity. Technology comes to a point from which its further advance is impossible without its saturation with

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1 This article is prepared for the project „From Galileo's technoscience to the nanotechnoscience (philosopical and methodological analysis)", Nr. 13-03-00190 of the Russian Foundation for Humanities (2013–2015).

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science. The need is felt everywhere for new technical theory, for codification of technical knowledge, for some general theoretical basis of that knowledge. Technology requires the application of science.

The first engineers of the Renaissance were at the same time artists and architects; consultant engineers specializing in fortification, artillery, and civil structures; alchemists and physicians; mathematicians; natural scientists; and inventors. Gradually, the engineer became a professional like teachers, doctors, lawyers and so on, although the social organization of engineering (it had already broken away from the craft guild structure) had not fully taken shape. Knowledge was then considered to be a real power and the engineer its holder. The Education of Artist-Engineer was in the Artist Workshop, in the Abaco schools and Academies. For example the *Accademia del disegno* in Florence was the Florentine Academy of the Art of Design, or *Accademia dell'Arte del Disegno* was the first official school of drawing in Europe and an Academy for Doing. The Academy became a model of the training of artists and engineers in Italy. Artists, engineers, and mathematicians were often equally experts in practical geometry, geodesy, perspective, technical drawing etc.[3].

Galileo was directly associated with engineers and technicians of the Renaissance. His scientific career had a "technical" beginning; Galileo studied in Florence, where his teacher was Ostilio Ricci, an engineer and architect belonging to the Tartaglia school. Taking from him an interest in technical practice and engineering problems, Galileo maintained close ties with engineers all his life. The social need for technical innovation in Italy of that time stimulated many people to try their hand in some way at inventing things. Galileo was also caught by this fever. For years he built scientific instruments and carried out tests in a workshop in his house in Padua. Padua was in the Republic of Venice, and Galileo maintained constant contacts with the Venetian arsenal.

Many medieval views and notions were assimilated during the Renaissance, but they took on a new meaning and conveyed a new emphasis; the comprehension of the divine plan began to be interpreted as the discovery of the laws of nature (acquisition of scientific knowledge), and technical activity in accordance with those laws was interpreted as a practical "engineering" action. As a result, the architect-cum-engineer and the technician-cum-inventor of that time considered nature, described in philosophy and science, to be

3 M. Valleriani, *Galileo Engineer*, Dordrecht, Heidelberg, L., N.Y., 2010, pp. 7–12.

the object of practical activity, and the latter was regarded as the art that followed the laws of nature. But in the Renaissance time the relation between art and nature was interpreted in three different ways. Aristotle himself introduced no contrapositions between the laws of mechanics and those of nature. The conception of nature dominating over *techne* was formulated, for example, by scholastic philosophers on the thirteen century. The third position, according to which art tends to dominate over nature, started emerging in codified from the second half of the sixteen century and was supposed and proclaimed mostly by educated engineers.

The engineer, like the Divine Creator, became a creator by creating reality. Georgio Vasari wrote: "The origin of the arts we are discussing was nature itself, and that the first image or model was the beautiful fabric of the world, and that the master who taught us was that divine light infused in us by special grace, which has made us not only superior to the animal creation but even, if one may say so, like God Himself"[4]. These artist-engineers "were engaged in great enterprises like changing the course of river" and received "the impression of being deployed against nature". "Galileo supports the idea, that... laws of nature and laws of mechanics belong to the same domain"[5]. He criticized the craftsmen's approach to technical activity that overlooked scientific knowledge and the laws in building machinery: "I have seen all engineers deceived, while they would apply their engines to works of their own nature impossible..." The main reason for those errors was that practical engineers who developed their inventions on false foundations deceived nature, failing to see its basic laws[6].

The rapid development of the states and trade promoted improvements in military technology, mainly fortification and artillery; the construction of water works and civil engineering structures; the manufacture of machines, including ingenious mechanisms and automatic devices for entertainment. The development of artillery and fortification was essential to the existence of the cities and republics in Italy; their independence often relied on the accuracy

4 Georgio Vasari, *Artists of the Renaissance. A Selection from Lives of the Artists*, (Translated by G. Bull), London, George Bull, 1978, p. 19.

5 M. Valleriani, *Galileo Engineer*, Dordrecht, Heidelberg, L., N.Y., 2010, pp. 200–203.

6 A.C. Cromie, "Philosophical Presuppositions and Shifting Interpretations of Galileo", in: *Theory Change, Ancient Axiomatics and Galileo's Methodology*. Proceedings of the 1978 Pisa Conference of the History and Philosophy of Science, Vol. 1, Dordrecht, D. Heidel Publ. Comp., 1981, p. 277.

and range of their cannons and the strength of their fortifications. Therefore, engineering consultants were in demand everywhere and were valued by kings, dukes, and citizens.

But traditional artisan skills were no longer enough. That is why the first engineers and inventors turned to mathematics and mechanics, where they got knowledge and borrowed calculation methods. When that knowledge was insufficient, they tried to obtain new knowledge on their own, often becoming very productive scientists. The example of an ordinary Florentine engineer Cecca (Francesco d'Angelo, 1447–1488), one of the numerous engineers practicing at the time shows how highly that knowledge was valued. Cecca came from the guild of carpenters, who made wooden models for architects of buildings, scaffolds, and hoisting machinery. He was appointed municipal engineer and paid a salary by the city of Florence. He was killed accompanying the Florentine army in battle in 1488 "while attempting to measure certain heights from difficult point" and "having put his head over the wall for purpose of dropping a plumb-line". The enemy "dreaded the genius of that master more than all the power of the army"[7]. Cecca was not so much an outstanding engineer, as a typical figure of that time, when engineers lacked a proper (from the modern standpoint) scientific education. They had come from the world of handicraft, but they were all reaching out for science, feeling that it was indispensable to their technical activities. It can be said that they were already adopting a scientific outlook (although they still applied science on a limited scale in practice) discarding the mythological view of the world of the medieval craftsman.

In the 15th–17th centuries the attitude towards innovations radically changed. The mark of the Master took on a personal significance, and he became a free creative individual. The social status of the Master and his treatment by society also changed.

The engineers of the Renaissance did not canonize unattainable standards nor did they belong to a narrow circle of masters of a guild: rather, they tried to improve current technologies, to leave a personal imprint and make them public property, to associate the names of inventors with inventions so that they would bring fame to those people. That was not anything extraordinary in the Renaissance culture, something one created by an individual scientist in order to

7 Giorgio Vasari, *Lives of the most eminent painters, sculptors, and architects* (1550), Volume 2, London, Bell & Daldy, York Street, Covent Garden, 1871, p. 186

demonstrate the omnipotence of science, as it was with Archimedes. Ingenious machines like those developed by Archimedes were now built, by many people everywhere. They not merely amazed people, they became necessary, and their designers were paid by numerous customers and users.

In his letter offering his services to Lodovico Sforza, the Duke of Milan, the young Leonardo da Vinci first did enumerate his abilities as a military engineer and only then his achievements as a sculptor and artist. During his lifetime Leonardo managed to realize some of his promises, although many others could not have been realized in his times. His notes contain detailed descriptions and drawings, which, of course, are not addressed to anyone in particular, but which indicate a way to embody them in specific structures and devices. Some "draft projects" were based on careful studies of nature. An invention or even a painting was, for Leonardo da Vinci, not merely a product of imagination, a semi-artistic inspiration, or a blind adherence to craft traditions; it resulted from a careful study of nature and its laws. He wrote: "Those, who are not in love with principle or knowledge are like the sailor who goes into a ship without a rudder or compass and who never can be certain whether lie is going. Practice must always be founded on sound theory"[8].

Unrealized designs are no less important than those realized. "It now seems that both the traditional sharp contrast between the great inventor and his colleagues and the more recent attempts to continue Leonardo´s engineering activity within the limits of practice, procedures and projects already fully developed by contemporary engineers and those of previous generations must be rejected as inadequate. ... Leonardo was original also in his drawings which, even in their incompleteness, are correctly interpreted as the conceptual equivalent of the 'model'. ... In this field Leonardo boasts a supremacy which is unrivalled and which places him at the very beginning of modern scientific illustration. Never before had anyone managed to demonstrate a complex technical design so effectively in a drawing"[9]. Galileo goes in the same way to drawing of the machines. But unlike Leonardo, Galileo reduced such drawings to the geometrical models. For example, he used the inclined plane as the universal explanatory model for all machines. Galileo investigated in his *Mechanics* a nature of screw by means of the ideal model of the inclined plane as *triangle*.

8 W.B. Parsons, *Engineers and Engineering in the Renaissance*, Baltimore, The Williams & Wilkings Comp., 1939, pp. 36, 37.

9 Leonardo, *Art and Science*, Florence, Guinti Editore, 2005, pp. 131, 132.

Galileo's New Science as Technoscience

With the aid of geometry, Galileo could teach the military engineers to use the mathematical instruments. The Galileo´s military compass was a mathematical instrument for the art of war. "In the workshop, Galileo achieved a quite systematic production of military and surveying compasses of different kinds. ... In fact, the instruments produced and sold in Galileo's household were only useful together with the knowledge of how to operate them. The transmission of this knowledge was, therefore, another essential activity, going on in Galileo's household and intimately related to the workshop. Private lessons were Galileo's way of transmitting this knowledge. ... it was perfectly normal that a student destined for a military career took private lessons on Fortifications. Accordingly, fortifications and military Architecture formed a part of the *shared knowledge* of many Engineers and Architects. ... Entries regarding private lessons are, as a rule, labelled according to their topic. These topics are: Geodesy, Mechanics, the Sphere, Perspective, Euclid, Arithmetic, Fortifications, and Use of the Military Compass. ... the most significant difference that distinguishes Galileo's curriculum concerns the long and detailed explanation of the uses of mathematical instruments like the compass for military purposes"[10]. Therefore, Galileo demonstrated how to develop scientific knowledge so that it could be used for technical purposes. Galileo's works paved the way for the formation of engineering thinking and activity in practice as well as theory.

(The first such educational Institute, ***École Polytechnique***, was founded in 1794 in Paris by Gaspard Monge. The *Polytechnique* was oriented to the theoretical instruction of students from the initial period of its existence. For the first time students were introduced there to genuine mathematics and genuine theoretical science. The School's first graduates – polytechnic engineers (Poinsot, Poisson, Cauchy, Navier, and others) – have made a great contribution to the development of experimental and engineering science. This was the first time that the curriculum of a higher technical school included a course in machine design. The *Polytechnique* proved to be a standard for many engineering schools in Germany, Spain, Sweden, and the USA).

Galileo not only related a geometrical scheme to physical reality, but also to the construction of different complex machines. But it was

[10] M. Valleriani, *A view of Galileo´s Ricordi Autografi. Galileo practitioner in Padua*, Montesinos J., Solís C., (eds.). Largo campo di filosofare, Fondación Canaria Orotava de Historia de la Ciencia, La Orotava, 2001, pp. 285–288.

Euclid geometry. In the next phase of the development of the theory of mechanisms (kinematics of machinery) as an engineering science, the descriptive geometry instead of Euclid geometry was elaborated: by Gaspard Monge. The theory of mechanisms comprises now the general classification of mechanisms and the description of the structure of different mechanisms by means of the cinematic geometry as consists of cinematic pairs, chains and gears in order to multiply the structural schemes of the new technical systems. But in both cases the scientific engineering education is a decisive factor for the development of the theoretical basis of the codification and systematization of the practical technical knowledge.

The specificity of the engineering theory is based on that its findings are used largely for constructing technical systems rather than explaining natural processes. The requisite condition of the productivity of engineering theory is the presence of practical methodological knowledge, i.e. engineering recommendations stemming from theoretical research, in its empirical basis.

The science of kinematics has its origins in the need to systematically analyze and design machines at the beginning of the industrial age. For example, Robert Willis in his "principles of mechanism" that in the engineering science is important to reduce the Constructive Mechanism (or Machine Design) as real technical system to the various combinations of Pure Mechanism (sometimes called Kinematics of Machinery) as ideal model of this system and "*to investigate them upon geometrical principles alone*"[11]. Franz Reuleaux in his "Kinematics of Machinery" wrote that Kinematics or Phoronomy (pure Kinematics or Kinematics Geometry) is "the study of geometric representation of motion"[12] and that "the geometrical abstraction of machine" is "the soul of machine"[13].

The Galileo´s geometric-cinematic theoretical schematic model of machines was a beginning and precondition of the application of the natural scientific theory to the first special engineering science – the theory of the mechanisms and machines or Kinematics. Thus, Galileo personified a new figure, *the engineer-scientist*. He's works paved the way for the formation of

[11] Robert Willis, *Principles of mechanism. Designed for the use of students in the universities, and for engineering students generally*, London, Longmans, Green, and Co., 1870. Introduction.

[12] Fr. Reuleaux, *Kinematics of Machinery: Outlines of a Theory of Machines* (trans. by A.B.W. Kennedy), London, Macmillan and Co., 1876, p. 56.

[13] *Ibid*., pp. 56, 85, 84.

engineering thinking and activity in practice as well as theory. Galileo did more than just observe natural phenomena. He was the first constructor of an idealized experimental situation, leaving aside the question of its technical feasibility (the situation itself, while not existing in nature, was, however, reproducible in principle). Then he has designed an ingenious project of the technically feasible experimental situation, say a pendulum (a mass suspended from a string), where the gravity force was separated from the force applied to the solid. Based on this project, a real experiment could be devised and conducted.

Some similarities between fiction and scientific writing obscure a profound difference between the two styles of thinking, namely, the imaginative and scientific, which reached the acme of perfection in modern European culture during the Renaissance and modern time, respectively. The technical thought entering the engineering epoch was influenced by these two fundamental types of thinking, which was clearly manifest in Leonardo da Vinci's work, in which the imaginative thinking is predominant. Leonardo, however, was not only an artist, but also a scientist and, perhaps, chiefly a Master-cum-Engineer. For this reason, Leonardo's type of thinking may more correctly be called imaginative-scientific-technical and, hence, engineering. In modern time, the scientific, or, rather, scientific-technical type of thinking came to prevail in Europe. With Galileo, who was at the crossroads of these two crucial epochs in the evolution of modern human civilization, the style of thinking was still under the influence of Renaissance culture and might, therefore, be called scientific-imaginative, or, more exactly, scientific-imaginative-technical; this has manifested in a specific form of treatment of a scientific text (as distinct from the strictly scientific texts written by Newton). These two main styles of thought were instrumental in transforming the technical thinking of craftsmen into the engineering-imaginative thinking of the Renaissance Masters-cum-Engineers, and its evolution into the modern engineering-scientific style of thinking.

Further development of new technology required a new science.

Galileo Galilei was one of those who created this new science oriented to technical needs. He established the relation between scientific knowledge and the objects of practice. In Galileo's view, the real object corresponds exactly to the ideal object but is interpreted as a distortion of the ideal object's behaviour under the action of various factors, for instance friction. This made it possible for Galileo to modify the real object by acting on it in a practical way. As a result, its "negative" properties, which prevented it from being identical to the ideal object, became neutralized.

Before Galileo, the scientific studies followed the ancient standard of obtaining knowledge about an object that was regarded as unchangeable. It occurred to nobody to change practically the real object of investigation (as it would then be considered to be another object). On the contrary, scientists strove to improve their theoretical model so that it would fully describe the behaviour of the real object. Therefore, Galileo created more than a model of experimental activity; he demonstrated how to develop scientific knowledge so that it could be used for technical purposes.

That is why "technoscience" is an appropriate name for Galileo´s new science.

Nanotechnoscience: A New Theory of the Modern Technology

The sphere of scientific-technological disciplines, which are intensively elaborated today, along with the natural-scientific, mathematical, social disciplines and humanities, incorporates a great number of the most varied fields of research, engineering, and design. They have at present or are founding disciplinary organizations (a specific range of publications and a limited research community), and now have a stable position in science. In addition, as shown above, by the second half of the 20th century, a majority of the scientific-technological disciplines had begun their own theoretical studies, which have received the status of a technical theory. We have today in the scientific community more connection between science and technology (also in the basic research sphere). We are saying already about "technoscience". In the modern scientific landscape we can see yet more a special type of scientific discipline – a *scientific-technological* discipline. New scientific-technological disciplines are unique in that they emerge at the interface between the scientific and engineering activities and are supposed to ensure an effective interaction of the two aforementioned types of activity. Characteristic of the scientific-technological disciplines is a more close relationship with the engineering practice.

The divided development of physics (electrical engineering – electronics – microelectronics – material design – quant effects), biology (cell biology – molecular biology – functional molecule design) and chemistry (complex chemistry – supra-molecular chemistry) in perspective must be integrated in the nano level. Such a cluster of different theories is exactly nanotechnology which at present seems to be the most typical representative of the modern technoscience. "As a simple example we can take a Biosensor which allows the detection of DNA sequences by turning the surface Plasmon resonance of nanosized gold particles in a suspension. It can be easily seen that in such a problem *quantum physics*, *chemistry*, *biology and finally microtechnology* are involved"[14]. The object of the nanoscience exists first of all only as computer model that simulates in the definite form the operation of the oncoming system that is to say the designer's plan. Scientific investigation is always connected with the computer simulation and all, what we see in the display, is already determinate from some theories and their mathematical representations that defined in the software of the simulation modelling. And what do really integrate all of these heterogeneous theories from a large number of different disciplines, including physics, chemistry, biology, medicine, and engineering sciences? It is only the orientation on the general or maybe even "universal" world view – "*nano-ontology*". In the so called "teleological" definition nanotechnology is defined in terms of future goals.

The progress of the nanotechnologies demonstrates the increasing role of basic research, without which nano-production is impossible. Here, experiment merges with engineering, and nano-production becomes inseparable from scientific experiment. At the same time, many important contemporary physical studies have become realizable only due to the emergence of nanostructure fabrication technology. So when we designate nanotechnology as a nano-technoscience, we emphasize this very aspect without relegating theory to the level of handicraft practices.

The contemporary conceptions of scientific theory tend to understand it as a sort of technical theory. The classical theories of engineering and physics have much in common, but there are also differences. Engineering and natural sciences occupy themselves with the same subject area of phenomena measurable by instruments. At the same time, although they study the same objects, they study them differently. Engineering theory is not oriented toward interpreting and predicting the course of natural processes, but toward designing engineering artefacts. Natural-scientific knowledge and

[14] G. Schmid, et al. *Nanotechnology. Assessment and Perspectives*, Berlin, Heidelberg, Springer, 2006, p. 440.

laws must be considerably specified and modified in engineering theory to be applicable to practical engineering problems. In order to adapt theoretical knowledge to the level of practical engineering specifications, technical theory develops special rules that establish a correspondence between the abstract objects of engineering theory and the structural components of real engineering systems and operations that translate theoretical results into engineering practice. Engineering sciences are specific, because their engineering practice, in the rule, replaces experiments. It is engineering practice that tests the adequacy of theoretical engineering conclusions, and serves as a source of new empirical knowledge. Contemporary technoscience makes natural-scientific experimentation constitutive for design, while research results are oriented equally on interpreting and predicting the course of natural processes, and on designing devices. It is impossible to separate research from development and engineering design.

The combination of the natural and artificial tendencies in nanotechnology prompts the nanosystems engineer to seek support both in nanoscience, on which he draws knowledge about natural processes and in existing technology with its information on materials, constructions, their properties, methods of manufacture, and so on. By combining these two types of knowledge, the engineer finds points of convergence between nature and practice where, on the one hand, the requirements for the application of the product are met, and on the other, where the actions of the manufacturer can be brought into coincidence with natural processes. If an engineer manages to identify in this dual reality a continuous sequence of natural processes so that the system which is developing functions and can find material means and conditions to set off and maintain these processes, then he has achieved his objective. This dual orientation of nanotechnology both towards scientific research into natural phenomena and towards production, the embodiment of a conception by artificial means, by purposeful creative work, makes the nanotechnologist look at *any product* he develops as a *natural-artificial system*. On the one hand, nano-system is a phenomenon which obeys the laws of nature, and on the other, an object that needs to be created artificially (e.g., a nano-machine). In turn, the situations artificially embodied in an experiment must themselves be presented and described scientifically as natural processes. Hence, in an experiment of the classical natural science, even one clearly oriented to engineering thought, the emphasis must be laid mainly on its natural aspect.

Galileo also considered the "nature" of mechanical tools when he regarded their natural component. It was this introduction of the artificial into the natural that set the standards of natural science, on the one hand, and engineering, on the other. This dual orientation both towards scientific research into natural phenomena and towards production, the embodiment of a conception by artificial means, by purposeful creative work, makes the engineer to look at his product in a different light than do the artisan or the experimenter. Whereas for the latter their products are respectively an artefact or a natural object, the engineer regards any product he develops as a *natural-artificial system*. On the one hand, it is a phenomenon which obeys the laws of nature, and on the other, an object that needs to be created artificially (e.g. an implement, machine, and installation). While manufacturing activity is directly concerned with setting up the production of a technical system, the aim of engineering is primarily to determine external conditions and artificial means that influence nature in the required way, making it to function the way man has planned, and only then, based on the resultant knowledge, to draw up specifications for these conditions and means and to indicate the methods and steps to implement them. This allows a relationship to be established between engineering specifications and scientific research.

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