HOW SCIENCE IS APPLIED IN TECHNOLOGY

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Distinctive to basic sciences, scientific research in advanced technologies aims to explain, predict, and (mathematically) describe, not phenomena in nature, but phenomena in technological artefacts, thereby producing knowledge that is utilized in technological design. This article first explains why the covering-law view of applying science is inadequate for characterizing this research practice. Instead, the covering-law approach and causal explanation are integrated in this practice. Ludwig Prandtl's approach to concrete fluid flows is used as an example of scientific research in the engineering sciences. A methodology of distinguishing between regions in space or phases in time that show distinct physical behaviours is specific to this research practice. Accordingly, two types of models specific to the engineering sciences are introduced. The diagrammatic model represents the causal explanation of physical behaviour in distinct spatial regions or time phases; the nomo-mathematical model represents the phenomenon in terms of a set of mathematically formulated laws.

1.   Introduction

It was in my early high school days when the idea that technology has its basis in science got hold of me. I still remember how absorbed I was in a book on technology, and how I tried to figure out the inner workings of machines and apparatus that were explained in diagrams and pictures. I remember how I imagined that it must be possible to explain what happens in these machines by fiddling around with formula derived from the basic laws of nature—similar to how examples of physical systems in physics and chemistry textbooks were solved. It may have been recognizing the analogies between the workings of Nature and the workings of machines, which convinced me that the design of machines is based on science. Like nature, machines and apparatus were also governed by an underlying and hidden structure that could be made visible by opening the black box. Due to an implicit ontology born in early physics and chemistry classes, I believed that the underlying structure in machines was grounded in basic laws and basic building blocks of nature. This may have been how I came to the exciting and beautifully simple idea that machines such as automobiles, refrigerators, light bulbs, dynamos, radios, and televisions could be designed by just applying scientific knowledge.

The idea that understanding technological artefacts required basic scientific knowledge was strengthened in my first years at university where I studied chemical engineering. Along with many subjects in mathematics, the major part of the engineering curriculum consisted of basic scientific subjects such as physical chemistry, thermodynamics, mechanics, and quantum mechanics. Thus, becoming a professional engineer seemed to require mostly mathematical and scientific knowledge.[1] However, my view that science provided access to hidden structures that

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[1]   My view on how science and technology were related became more refined of course, since it became clear that the natural world was much more recalcitrant than it had appeared in high-school. In the real world, for instance, chemical reactions between components A and B produced the desired product, P, but also undesired 'waste', W. Therefore, the task of the engineer was to find physical conditions that would prevent the production of W and stimulate that of P; moreover, it required additional technologies to separate P from W and remainders

bring about physical phenomena relevant to technology, was severely challenged at the end of the second year when doing the subject 'transport phenomena' (i.e. 'applied' hydrodynamics). As usual, the textbook started with neat fundamental laws. Using a deductive approach, it aimed, for instance, at deriving a general equation for describing fluid flow between parallel flat plates. However, when taking the same approach in deriving equations for other cross-sections, a correction factor suddenly appeared in the equations. The textbook stated that: "values of the correction factor could be found in figure xx", and figure xx showed a graph with smooth lines that represented the correction factor for different types of cross sections and served as a function of geometrical ratios. It became clear that such correction factors could not be theoretically derived and that their values needed to be measured. What started as a nice deduction from fundamental scientific laws (e.g. conservation laws) unexpectedly ended up in equations with empirical factors in them. It became apparent that when applying fundamental scientific laws to concrete technological artefacts, one cannot abstract from the geometrical shape of that artefact. Suddenly, the laws derived from fundamental laws appeared to have very limited application. However, with my reference of science that had been presented in textbooks of my early education in physics, it was very hard to understand and accept why this deductive scientific approach failed.

This anecdote involves at least two presuppositions. The first is that science is a pre-requisite for technology. The second is that technological systems are governed by scientific laws, and that understanding technology involves discovering the responsible scientific laws. In this article, I will refer to the first presupposition as the thesis that technology is applied science; the second presupposition will be referred to as the covering-law view of applying science.

2. Technology is not applied science

This story and the resulting view of how science and technology are related may be recognized by others who also had an early admiration for science and technology. According to Paul Gardner (1997 and 1999), this view may indeed be instilled in us by the way we received physics teachings. He claims that physics textbooks are dominated by an idealist storyline, which insists that science precedes technology, that is to say that the human technological capability depends upon the prior acquisition of scientific knowledge, and the concepts, laws and theories generated by scientists provide the basis for useful technological products. In this idealist view, scientists do research and technologists apply this knowledge for practical ends, and "technological fruits fall from scientific trees" (Gardner 1997, p. 14). This idea is appealing and it is easy to point to numerous examples in the history of technology that seem to underpin it.

Representatives in science and industry may have played a significant role in the proliferation of this idea. Vannevar Bush, for instance, was a mathematician and engineer, but also an important adviser of President Franklin Roosevelt. After World War II, he wrote an influential report that articulated the indispensable role of science in technological development:

> 'Basic' or 'pure' research, [which] is being performed without thought of practical ends, leading to general knowledge and understanding of nature and its laws [....] leads to new

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of A and B. Nevertheless, finding optimal conditions and developing refined technologies could still be approached with scientific means, it seemed.

knowledge. It provides scientific capital. It creates the fund from which the practical applications of knowledge must be drawn. New products and new processes do not appear full-grown. They are founded on new principles and new conceptions, which in turn are painstakingly developed by research in the purest realms of science (V. Bush, 1945, *The Endless Frontier*, as quoted in Layton, 1976, p. 689).

Another example is Hendrik Casimir (1983), a scientist and research manager in industry, who claimed that: "technology today *always* draws upon earlier scientific results" (p. 297). In his autobiographical monograph, he describes many cases that seem to underpin this view, for instance:

> Engineers construct electric motors and dynamos, but they only started doing this after Ørsted and Ampere had discovered the force between electric currents and magnets and after Faraday had discovered electromagnetic induction. Maxwell predicted and Hertz discovered electromagnetic waves; it was only then that Marconi began to apply them for telecommunication purposes. Vacuum electronics was preceded by J.J. Thomson's discovery of the electron, solid-state electronics by the quantum theory of electrons in metals and semiconductors. ... [Therefore,] the idea that science and technology are independent of each other may hold for older industries, like ceramic industry, but is foolish for technology today. (Casimir, 1983, p. 295).

In this quote, Casimir argues against critics who rejected the view of technology as the application of scientific ideas and who claimed that this view is simplistic and over most human history, untrue. These critics have examined the issue from a variety of case studies of how science and technology interact. Thomas Hughes (1976) for instance, examined the evolving technology of the high-voltage transmission system – a major chapter in the history of electric light and power. He rejected the strong tendency in the history of science and technology to explain complex technological change with primary reference to antecedent scientific discoveries. His major thesis is that the evolving technology of the high-voltage transmission system can be best explained by reference to needs arising within that system rather than by scientific discoveries. Other authors who took this case-based approach and came to similar conclusions are Smith (1961), Kohlmeyer and Herum (1961), Küppers (1978), Basalla (1988), Hoddeson (1990), Vincenti (1992), Kroes (1992), and de Vries (2002). Based on historical and empirical approaches, writers have also proposed models of the interaction between science and technology that can explain cognitive change in technology without assuming that science is a prerequisite of technology, e.g. Layton (1971), Böhme et. al. (1978), Rapp (1981), Laudan (1984), Constant (1984), de Solla Price (1984), Staudenmaier (1985), Basalla (1988), Kroes and Bakker (1992), Mitcham (1994), Smith (1994), Gardner (1997), and Ihde (1997). These studies have shown that modern technologies result from the interweaving of both scientist's and technologist's contributions, and additionally, along with science, social, political, and economic factors also play an important role in the development of technology. In short, these critics have shown that the linear or deterministic model of the science-technology relationship, which postulated a linear, sequential path from scientific knowledge to technological invention and innovation, is fundamentally flawed. Science is not the 'prime mover' or 'springhead' of technology; it is not as if scientific discovery necessarily implies technological innovation, and technology only involves the responsive activity of applying science. (see also, Kroes and Bakker, 1992, p.1, and Faulkner, 1994, p. 427).

Scientific versus technological knowledge.

In a thorough review of the literature, John Staudenmaier (1985) analysed the most common ways in which historians of technology have contrasted science and technology. Based on this analysis, he claims that "historians of technology are less concerned with the science-technology relationship, but with the nature of Technological Knowledge." (p. 85). He finds support for this hypothesis in how authors have criticized the thesis that "technology is applied science". According to Staudenmaier, this thesis was not criticized because these authors wanted to denigrate science, but instead, because they wanted to establish the unique character of technological knowledge [ibid p. 99]. What these authors rejected is the idea that all progress in knowledge is synonymous with scientific progress, which would imply that "all forms of human consciousness are destined to be overtaken by science in a triumphant process through which they are eventually governed by scientific knowledge." (p. 102). If, on the contrary, "science is seen as a limited style whose methodological constraints and particular historical traditions make it helpful for some cognitive tasks and not for others, then science takes place as a peer in the family of human cognitive styles." (p. 102). In this view, technology is an autonomous cognitive enterprise next to science, with it own cognitive style, and therefore, "science cannot claim the role as technology's sole source of knowledge." [ibid p. 103].

Günter Ropohl (1997) proposed a set of epistemological characteristics of knowledge for analysing the distinction between science and technology. They were the *objectives* of the epistemological activities, the *objects* of knowledge, the *methodology*, the *characteristics of the results*, and the *quality criteria*. Much of what has been written on the distinctions between science and technology can be captured and ordered within these characteristics of epistemological activities. Along the lines of Ropohl's analysis, the *objective* of science is theoretical cognition for its own sake; technology, on the other hand, is interested in cognition just as far as it is useful to optimize the function and the structure of technological systems. The *object* of scientific research is natural phenomena as distinguished from human-made artefacts in technological research. Regarding *methodology*, isolation, idealization, and abstraction with respect to the objects under study are common methods in science. Technology, on the other hand, deals with real technical objects, and its common methods are simulation and testing prototypes. With regard to the *characteristics of results*, science produces isolated hypotheses and idealized theories, whereas technology generates complex and realistic rules of design; in a realist version, science produces true scientific theories and universal laws, whereas technology produces productive knowledge and useful laws. About these characteristics, several authors have proposed detailed taxonomies for classifying types of technological knowledge, e.g. Bunge (1966), Carpenter (1974), Staudenmaier (1985), Vincenti (1990), Bayazit (1993), Faulkner (1994), Ropohl (1997), de Vries (2003). In these classifications, various types of technological knowledge such as technological laws, theoretical tools, properties of materials, operational principles of devices, functional laws, structural laws, design-criteria, and technological know-how were introduced. For an overviews of taxonomies, see also Mitcham (1994, pp. 199-208). Finally, scientific and technological practices employ different *quality criteria* or *epistemological norms*. Depending on one's position on the realism debate, norms in science are truth, universality, theoretical consistency, coherence, simplicity, empirical adequacy, and approval by the scientific community. Quality in technology means the practical success of a technical solution and approval by the engineering

and industrial practice. Other epistemological norms in technology are applicability, reliability, effectiveness, and efficiency.

These distinctions between scientific and technological knowledge can be found with many of the authors who debated the relationship between science and technology. Besides those already mentioned in this article, there are Feibleman (1961), Rase (1961), Bunge (1966), Skolimowski (1966), and Bunge (1983).

The relationship between scientific and technological knowledge

Although I agree in many respects with the proposed distinctions between scientific and technological knowledge, there is a particular point that bothers me. This relates to the role of scientific knowledge in technological knowledge. It is my impression that scientific knowledge has sneaked into several of the proposed categories of technological knowledge, but its position and role are unclear. How did scientific knowledge cross the bridge between the two autonomous cognitive practices? If—in the realist version—science aims at true, universal theories of natural phenomena, whereas technology aims at practical knowledge of technological artefacts, why then, should scientific knowledge be incorporated into technological knowledge? Some authors admit that in current practices the boarders are blurred, but that is not a very satisfactory explanation.

Let me give a few illustrations. In Vincenti's (1990) taxonomy, "laws of physics may be used to analyze such things as airfoils, propellers, and rivets once their 'operational principle' [one of Vincenti's categories] has been devised, and they may even help in devising it" (p. 209). Next to this use of science in technological knowledge, principle scientific laws are part of the 'theoretical tools' [another of Vincenti's categories], which are used in making design calculations [ibid. pp. 213-216]. Faulkner, in her typology of knowledge that is used in technological innovations, also incorporates 'scientific theories' and 'natural laws,' which knowledge types are both explicitly regarded as being about the natural world (Faulkner, 1994, p. 447). In Ropohl's (1997) distinction between four types of technical knowledge, the role of scientific laws is in 'technological laws': "A technological law is a transformation of one or a few natural laws with regard to the real technical process." (p.68). De Vries (2003) proposed 'physical nature knowledge' as one of the four categories of technological knowledge: "this category combines with Vincenti's categories of theoretical tools as far as knowledge of scientific laws is involved." (p. 13). In these examples, scientific laws and theories—either about the natural world or about technological artefacts—happen to be distinct categories in several of the proposed taxonomies of technological knowledge. This, however, involves a conceptual problem. What if scientific laws have technological artefacts as their object? This latter knowledge type is neither scientific nor technological knowledge; or is it both?

An example of this conceptual problem is found in an article by Peter Kroes. He analyzed the role of Carnot's research in the development of steam engines, among other things. According to Kroes (1995, p. 29), "Carnot is interested in the *laws* governing the production of motion (work) by heat 'independently of any mechanism or any particular working substance.'" Kroes maintains that "the problem posed by Carnot is itself not a strictly *technological* problem, although it clearly is a problem which arises from the technological context of steam engines." (p. 29). Kroes concludes that the knowledge produced by Carnot is scientific rather than technological because "Carnot's theory applies to any kind of heat engine, that is, any

kind of physical system converting heat into mechanical work." (p. 29). The problem is that the knowledge produced by Carnot meets several of the characteristics of scientific knowledge, for it produces 'fundamental' laws about an idealized system, and these laws hold for all ideal heat engines. On the other hand, the knowledge concerns a certain type of technological artefact, not a natural phenomenon, and it would therefore be technological knowledge.

Thus, the relationship between science and technology consists of a particular type of knowledge, which explains physical phenomena that occur in—or that are produced by—technological artefacts. This description needs further clarification since most phenomena in the empirical sciences are produced by technological artefacts. Nonetheless, in a realist view of scientific explanations, it is assumed that the scientific explanation (the explanans) of the observed phenomenon (the explanandum) can be detached from the technological apparatus in which the observed phenomenon is realized. Moreover, the explanans is meaningful beyond the explanandum. In fundamental or basic sciences, the technological apparatus and the observed phenomenon are only steps that can be thrown away as soon as the phenomenon is explained. What remains is the explanans, e.g. fundamental laws and building blocks of the universe. Scientific knowledge thus produced is assumed to be useful for explaining a wide variety of physical phenomena; phenomena in nature, but also phenomena occurring in technological apparatus (see Boon, 2004; Harré, 2003, and other contributions in Radder, 2003, for further discussion on the role of instruments in science).

This assumption is problematic in the case of engineering sciences. An important objective of scientific research in the engineering sciences[2] is to produce scientific explanations of a phenomenon as it occurs in—or is produced by—a technological artefact. The expansion-compression cycle of gases in heat engines is an example of a phenomenon that only exists in a specific type of technological artefact. Another example of a phenomenon that only exists in a specific type of technological artefact is reactive-absorption of toxic compounds from waste gasses.[3] (e.g. Schneider et.al., 2003). Scientific explanations of these phenomena incorporate properties of the technological artefact. In these cases, it would be meaningless to detach the explanans from the explanandum, i.e. the phenomenon as it occurs in the technological artefact.

This difference with basic sciences is reflected in a characterization of this knowledge type along the lines of Ropohl's (1997) schema. The *object* of this knowledge type is physical phenomena that are specific for, or relevant to, technological artefacts. Its *objective* is finding laws that explain the phenomenon as it occurs in the technological artefact. The *methodology* may be both science specific methodologies, such as idealization, isolation and abstraction, but may also involve methodologies specific to technological research. The *character* of this knowledge is,

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[2] The term 'engineering science' for indicating this research practice is problematic, particularly because actual research practices themselves are not very clear on this matter. Engineering sciences may be used in a rather narrow sense, indicating exclusive research into physical phenomena that occur in technological artefacts. But the term is also identified with systematic approaches in technology. In this latter denotation the engineering sciences produce different types of technological knowledge.

[3] The industrial aim of reactive-adsorption is sour gas purification. Toxic compounds such as hydrogen sulfide or ammonia are removed from waste gas by means of absorption into the washing liquid, where the toxic compounds react. The technological device (called a scrubber or absorber) consists of a column containing horizontal plates with holes in it. Washing liquid flows downwards through the plates, whereas the toxic gas rises upwards.

for instance, 'generality' in the sense that it applies to all technological systems of this kind (e.g. heat engines), but it may also be more 'local', in the sense that it accounts for more specific conditions in the technological artefact. The *quality criteria* often appear to be a combination of epistemological norms typical for scientific knowledge and those for technological knowledge such as applicability, reliability, effectiveness and generality..

In the context of my argument, it is important to realize that the observation of a phenomenon is usually indirect, that is, mediated by measurement instruments. With these instruments, only a limited set of physical variables such as mass, length, time, pressure, temperature, heat, wave length or frequency, electrical current, electrical potential, and electric and magnetic field forces can be detected. Thus, the only thing we observe of the phenomenon is lists of data, graphs, or visible images such as spectra, chromatograms, and traces on photographic plates and the like produced by technological instruments (e.g. Hacking, 1983 and Suppe, 1989). In processing the experimental data, the measured physical variables may be theoretically interpreted in terms of theoretical entities such as certain types of elementary particles or chemical elements or molecules; certain kinds of forces; concentrations of chemical compounds or elements; reaction or diffusion rates; or specific physical parameters. This produces additional lists, images, or graphs representing the behaviour of physical variables and theoretical entities.

According to this line of thought, producing a scientific explanation of a phenomenon as it occurs in a technological artefact also means producing a (mathematical) description of the behaviour (e.g. dynamics) of relevant physical variables and theoretical entities as it occurs in the technological artefact. Clearly, this type of scientific explanation of a phenomenon is only relevant for the behaviour of physical variables and theoretical entities at those specific physical conditions. This clarifies further why the explanans cannot be detached from the explanandum.

Generally speaking, scientific and technological knowledge have a very particular crossing, which is knowledge that consists of *scientific explanation of physical phenomena that occur in— or that are produced by— technological artefacts.*[4] Besides providing a scientific explanation of the phenomenon, scientific research also aims at producing a mathematical description of relevant physical variables and theoretical entities in the technological artefact. This will be explained further in section three and four.

In sum, we see that the knowledge that relates science and technology has characteristics of both scientific and technological knowledge. Therefore, this type of knowledge can neither be characterized as exclusively scientific, nor as exclusively technological.

Physical phenomena in technological artefacts

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[4]   From this expose, it is clear that instruments also constitute an important relation between science and technology. De Solla Price (1984) termed them 'instrumentalities', which are the crafts and techniques (such as the laboratory methods) of the experimentalist and inventor.
The advent of such instrumentalities has simultaneously opened up major new opportunities for scientific investigations and technological innovations.
The mathematical method of science may also be regarded as a bridge between science and technology (see for instance Vincenti's account of 'theoretical tools'), this view may however be disputed. (e.g. Staudenmaier, 1985).

Contemporary authors agree that technology is not simply applied science; instead, it is an autonomous cognitive enterprise. It remains the case, however, that modern technology is increasingly scientifically informed and it is widely assumed that advanced technologies such as materials technology, biotechnology, biomedical technology, nanotechnology, etc. are developed in close interaction with scientific research. This asks for an understanding of how scientific research contributes to technological design and development. In the first sections of this article, I have tried to become more precise about how scientific and technological knowledge cross, and I have argued that one of the relationships is a knowledge type that has characteristics of both scientific and technological knowledge. This results in a view that is coherent with many accounts of the role of science in technology as reviewed in this article, and also with my own experience in the engineering sciences. A significant part of scientific research in the engineering sciences aims at explaining, predicting and (mathematically) describing physical phenomena that occur in—or are relevant to—technological artefacts; in this research practice both scientific approaches and scientific knowledge are utilized. But, in meeting epistemological norms such as applicability, reliability, effectiveness, and generality, the standard scientific methodologies, which are disciplinary and allow idealizations and abstractions that disregard specific relevant conditions, are often inadequate. It is, I assume, this type of scientific research that deserves more attention from the philosophy of science perspective.

Having thus covered my early high-school view of how science and technology are related, it is now time to find out how scientific approaches and knowledge are applied in explaining and (mathematically) describing physical phenomena in technological artefacts.

3.   The covering-law view of applying science

The view that technology is applied science is often related to the assumption that in technology problems are solved and new things are created by means of the application of basic scientific laws. The following quote of H.F. Rase (1961), a professor in chemical engineering who wrote a monograph *The Philosophy and Logic of Chemical Engineering*, is an illustration of this:

> The basic laws commonly used in chemical engineering are laws of chemistry and physics and, therefore, chemical engineering has no basic laws per se. .... Chemical engineering is an applied science; and its genius lies in its ability to apply these laws of science, not only those listed but laws from any science that are needed to solve a process problem. Competent chemical engineers have always succeeded in creating useful things for society by applying the laws of science (p. 29.).

Feibleman (1961) also maintains that "Pure science has as a result the furnishing of laws for application in applied science. [...] Applied science puts to practical human uses the discoveries made in pure science." (pp. 305-6); and Bunge (1966) states that "Substantive technological theories are essentially applications, to nearly real situations, of scientific theories: thus, a theory of flight is essentially an application of fluid dynamics" (p. 331). Another one who shares this view is Casimir (1983), and see also scientists and engineers quoted in Layton (1974). According to these authors, applying science in technology consists of applying—basic—scientific laws: science produces basic scientific laws that explain and predict natural phenomena, and technology applies those laws in designing technological artefacts by filling them out

at specific boundary conditions determined by the properties of a technological artefact.

The quoted authors may very well agree with my refinement, which claims that scientific laws are not applied to technological artefact as such, but that instead, scientific knowledge is used for explaining, predicting, and describing physical phenomena that occur in technological artefacts. They may even come up with illustrative examples. Researchers such as Carnot and Rankine, for instance, produced laws for describing thermodynamic cycles (i.e. the physical phenomenon) in heat engines (i.e. the technological artefact); these laws were mathematically deduced from basic laws of thermodynamics. Classical hydrodynamics is another example. Here also, laws for describing flowing fluids were mathematically derived from fundamental principles such as conservation of matter and momentum. In engineering curricula, these are paradigmatic examples of how basic scientific laws are applied in technology. Application of science in technology is thus placed under the general umbrella of the covering-law view of science. In this view, explaining or predicting a concrete phenomenon—such as heat cycles—requires both finding a general law that covers the phenomenon, and finding appropriate boundary conditions. I will call this idea 'the covering-law view of applying science'.

Arguments against the covering-law view of applying science

Edwin Layton (1976) reports how engineers have explicitly rejected Rankine's deductive approach. In these engineers' experience, Rankine's laws could not be applied to concrete heat engines, and in their view this was because the laws represented abstractions and idealizations inadequate to the thermodynamic cycles in *actual* heat engines (pp. 691-92). In the case of classical hydrodynamics, not only engineers, but also a famous scientist, Ludwig Prandtl, objected to the deductive approach. He argued that "analytical results obtained by means of 'classical' [or theoretical] hydrodynamics usually do not agree at all with the practical phenomena." Examples of these practical phenomena are "pressure drop in pipes, or resistance of a body moving through the fluid." These phenomena occur in technological applications such as when fluid flows through pipes, or when screw propellers are immersed in water. For these cases, theoretical hydrodynamics predicts that "pressure drop and resistance are both zero!", which would imply that pressure drop in pipes is zero, and that bodies moving through fluid experience no resistance; this is at odds with what happens with real flowing fluids. "[Theoretical] hydrodynamics thus has little significance for the engineer … because of the negligible possibility of applying it" (Prandtl and Tietjens, 1934a, p. 3).[5]

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[5] This problem of hydrodynamics needs some further explanation. Basic laws for describing flowing fluids are 'conservation of momentum' and Newton's law of viscosity. However, when applying these laws to concrete flow phenomena, it is not possible to analytically solve the mathematical equation thus derived. Applying the principle of conservation of momentum to flow phenomena involves translating this principle to an inventory rate equation (in order to describe the dynamics of this conserved quantity). The rate equation for any conserved quantity φ takes the form (in words):

Rate of input of φ – Rate of output of φ + Rate of generation of φ = Rate of accumulation of φ.

The application of this equation to flowing fluids produces partial differential equations, which are non-linear, and therefore cannot be analytically solved. Therefore, the approach in

These examples from actual scientific practices show that the covering-law view of applying science for explaining or predicting the behaviour of physical phenomena in technological devices is at least problematic.

Nancy Cartwright (1974) was one of the first authors who criticized the view that basic scientific laws can be straightforwardly applied to concrete phenomena. In her early article *How do we apply Science?,* she emphasized that:

> Until recently, philosophers have either denied that there is such a thing as philosophy of technology or have held it in contempt ... [W]e still tend to overlook that applied science has conceptual problems – problems for the philosopher of science – independent of the moral, social, and aesthetic problems for technology. (p. 713).

Cartwright presented two arguments for her suggestion that the application of laws of nature to concrete phenomena is insufficiently understood in philosophy of science. I will summarize these arguments and discuss their consequences for understanding the epistemological relationship between science and technology. First, Cartwright (1974) argues that:

> [The covering-law view of science is mainly concerned with] *testing* theories and *explaining* specific [classes of] phenomena. In *applying* a general law we must *predict* what will happen under the boundary conditions in that concrete situation. ... [However,] in general it is not possible to determine directly from the theories bearing on a domain what follows from a given, natural, set of boundary conditions (p. 713, her italics).

As Cartwright articulated it in her later work, basic scientific laws are not true of phenomena. Applying scientific laws for describing concrete phenomena usually requires idealizations, approximations, simplifications, and ad-hoc extensions. (e.g. Cartwright, 1983, p. 111). As a result, in technological applications predictions based on scientific theories are problematic since boundary conditions not accounted for in the theory may be involved. Scientific theories do not give rules on how to idealize, approximate, simplify, and extend a scientific law in order to make it fit for concrete phenomena.

Cartwright's second argument is that "most of our laws are *ceteris paribus* laws." (p. 714). As a consequence, a theory only explains and describes a neatly isolated phenomenon ['element']. It is unknown how to apply laws to physical systems in which various well-understood isolated phenomena are superimposed or interact. Theories only describe and explain isolated phenomena. Interaction between phenomena often cannot be predicted on the basis of general scientific laws:

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classical hydrodynamics was to simplify this equation by assuming constant fluid density and constant viscosity, which is called a Newtonian fluid. These simplifications resulted in the Navier-Stokes equation. Unfortunately, when applied to concrete circumstances—i.e. filling-out the Navier-Stokes equation at the specific boundary conditions of a system—those equations can still only be solved for a few very simple cases. A further simplification of the equations ignores the viscosity terms, in other words, assumes that the viscosity of the fluid is zero. This simplification produces the Euler equation. This equation is only applicable to *perfect* fluids—i.e. Newtonian fluids with negligible viscosity. Mathematical solutions of this simplified equation are possible, and agree well with observed behaviour of several kinds of flows, but cannot appropriately describe flow past solid surfaces (e.g. Bird et. al., 2002). Since shear stress in the fluid is neglected, mathematical solutions of the Euler equations do not agree with observed behaviour of flows in channels and pipes, and of forces on solid bodies caused by flow past them, etc.

> [In experimental testing] we guard against 'external' forces such as electromagnetism, sometimes literally, by erecting shields. ... In application, however, we cannot usually concern ourselves with the tiny closed systems of which the theories speak. We want to work in the heterogeneous domains of different theories and we lack a practicable hyper-theory that tells us the upshot of interacting elements (Cartwright, 1974, p. 714).

This argument stands in particular for phenomena in technological devices. Since technological devices often involve complex phenomena (i.e. several isolated phenomena that are superimposed or that interact within the device), experimental research and new theories are required for explaining and describing those complex phenomena and their relationship to the physical conditions in the device. This is at odds with the covering-law view of applying science.

In sum, the covering-law view of applying science involves serious problems. The given arguments (i.e. scientific theories) do not (a) give rules on how to idealize, approximate, simplify, and extend a scientific law in order to make it fit for concrete phenomena, and do not (b) tell how isolated phenomena interact—indicate that the covering-law approach produces laws that merely apply to the ideal experimental systems the theory originated from. Thus, understanding how scientific knowledge is applied to concrete phenomena requires something more.

Covering-law and causal explanations of phenomena

Sciences aim at explaining physical phenomena. Engineering sciences aim at explaining, predicting, and (mathematically) describing concrete physical phenomena that occur in technological devices. What is meant by 'explaining' in the engineering sciences will need further clarification.

According to Cartwright (1983), explaining a physical phenomenon involves two quite different kinds of activities: (i) explaining the phenomenon in terms of a causal story, and (ii) explaining the phenomenon by fitting it into a theoretical framework that consists of a set of fundamental equations —or abstract formula (p. 11). This view seems to be at odds with an ongoing debate concerning the character of scientific explanation. In that debate, defenders of the claim that a phenomenon is scientifically explained when it is subsumed under a general law (i.e. the covering-law view of explanation) usually disagree with the idea that scientific explanation involves causal explanation. Cartwright suggests that the two activities are complementary; both are needed to provide the different types of knowledge mentioned above. Prandtl's methodology in hydrodynamics is an illustration of how the two activities go together in producing knowledge of concrete phenomena.

Prandtl's approach

Prandtl criticized classical hydrodynamics, and argued that explaining concrete phenomena requires a methodology that makes proper use of both empirical and theoretical knowledge, which required a synthesis of classical hydrodynamics, a scientific discipline and hydraulics, a discipline exercised by engineers. Prandtl explicated the differences in purposes, methods, and results of these disciplines: "Hydrodynamics, in an attempt to formulate the behaviour of the whole fluid mass from that of its elements, starts with simple principles and making assumptions about the mechanical properties of fluids." The method of classical hydrodynamics is theoretical, that is, mathematical derivation by starting from basic principles. The

problem of this approach is that it "loses contact with reality", since "simplifying assumptions were made which were not permissible even as approximations." "Hydraulics, on the contrary, starts with simple facts of experience and tried to explain complicated processes in terms of these." The method of hydraulics is empirical, treating each problem as a separate case. The problem with this approach it that it "lacks an underlying theory by which problems can be correlated." As a result, "Hydraulics disintegrated into a collection of unrelated problems; each individual problem was solved by assuming a formula containing some undetermined coefficients and then determining these so as to fit the facts as well as possible. Hydraulics seemed to become more and more a science of coefficients." (Prandtl and Tietjens, 1934a, pp. 3-4).

Prandtl aimed to overcome the difficulties of the separate approaches by integrating them by means of a third. The three approaches are as follows: (a) the theoretical approach of hydrodynamics in which simplified fundamental equations are used for describing idealized phenomena. It is important to realize that in this approach, simplifications and approximations are heavily guided by the need for *mathematical* simplification that are required for finding solutions of the equations; (b) the empirical approach of hydraulics, in which correlations between measured variables and parameters are used for explaining observed behaviour. This approach lacks a theoretical framework and only produces knowledge for particular cases, without a possibility to somehow generalize, unify, or extend it to other cases; knowledge thus obtained consists of formulas or rules containing coefficients that need to be empirically determined for every particular case; and (c) in addition to the existing theoretical approach of 'classical' hydrodynamics and the empirical approach of hydraulics, Prandtl developed a phenomenological approach. In this approach, flow-patterns in the fluid were observed in experiments; these observations allowed for making distinctions between spatial regions in the fluid on the basis of showing distinct physical behaviour. In Table 1, the characteristics of the three approaches are summarized.

Table 1	Approaches in Prandtl's work		
	Empirical	**Phenomenological**	**Theoretical**
Method:	Correlations between variables and parameters measured in experiments.	Observation of flow-patterns in experiments	Mathematical derivation of formula from simple fundamental laws
Produces:	Formulas or rules containing coefficients which need to be empirically determined for every particular case.	Causal explanations of observed physical behaviour	Formulas that do not necessarily apply to concrete phenomena.
Lacks:	Generality		Applicability
Requires:	Fitting into theoretical framework		Use of physical knowledge in simplifying the equations

An example of how Prandtl integrated these approaches is his boundary-layer model; this model explains and describes the motion of low-viscosity fluids past a solid surface. Margaret Morrisson (1999) explained in detail how Prandtl developed this model (pp. 53-60). Here I will outline aspects of Prandtl's work relevant for illustrating how (i) the phenomenon is explained in terms of a causal story, and (ii) how the phenomenon is explained by fitting it into a theoretical framework that consists of a set of fundamental equations, and how these approaches are integrated.

In their phenomenological approach, Prandtl and Tietjens (1934b) were able to design experiments in which streamline-patterns along solid objects were made visible. Based on photographs of these streamlines, Prandtl conceptually divided the fluid into two regions and causally explained the behaviour of the fluid in each region (see photographs on pp. 279-306). "(1) Surrounding the surface of the solid body there is a thin layer where the velocity gradient [perpendicular to the direction of the flow and to the solid surface] generally becomes very large, so that even with very small values of the velocity the shear stresses cannot be neglected. (2) Outside of this layer there is a region where the velocity gradient does not become so large, so that the influence of viscosity is negligible. [In this region the fluid can be treated as ideal (i.e. zero viscosity).]" [ibid. p. 59].

The next important step in Prandtl's method is fitting this causal explanation of the observed phenomenon (i.e. the observed streamlines) into a theoretical framework. Prandtl used the Navier-Stokes equation for mathematically describing laminar flow of the boundary layer along the solid surface, whereas the simpler Euler equation was sufficient for describing the turbulent ideal fluid outside the boundary layer. (See also Morrison, 1999, pp. 55-60 for more details of this mathematical derivation). Prandtl was very successful in applying the method of dividing the physical system into separate physical regions and then adapting to other problems the causally explained physical behaviour of distinct regions into a theoretical framework of scientific laws. It is now necessary to explain how the causal explanation (of the phenomenological observation) fits into the theoretical framework.

4.   The role of models

Cartwright's arguments were an influential factor in the emerging school of thought that rejects the picture of science based on the covering-law account of explanation and places emphasis on the role of models in science.[6] Philosophical explanation of the essential role of models in science has been further developed by many authors (see for instance Morrison and Morgan, 1999).

Morrison's (1999) aim in analyzing Prandtl's boundary-layer model was to argue (1) that it is models rather than abstract theory that represent and explain the behaviour of physical systems, (2) that models are autonomous agents in the production of scientific knowledge, and (3) that phenomenological and theoretical models cannot be clearly distinguished. In regard to the third point, she argues that models of phenomena have a rather hybrid nature. Morrison & Morgan (1999) conclude, therefore, that models mediate between theory and a phenomenon, and are made up of phenomenological as well as theoretical elements. I agree with Morrison's first and the second conclusion. Contrary to her third argument, I will contend that understanding the construction of concrete phenomena models in actual scientific practices requires making a distinction between models that represent the causal explanation of the phenomenon and models that represent the mathematical description of it or, in terms of Morrison, between phenomenological and theoretical models, and in terms of Cartwright, between models that 'present a causal story', and models that 'fit the phenomenon into a theoretical framework'.

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[6]   Cartwright's account of models, as well that of earlier authors such as Hutten (1954), Nagel (1961), Achinstein (1964), and Hesse (1966) is related to how models are used in actual scientific practice.

Prandtl's distinguished between spatial regions of distinct physical behaviours. Carnot distinguished between phases in time that show distinct physical behaviour: a heat cycle consists of addiabatic, isothermic, etc. phases. Distinguishing between regions in space or phases in time, specific to the technological artefact, in conjunction with the mathematical description of the causal behaviour in each space region or time phase, is specific for scientific approaches in the engineering sciences. I will now introduce two types of models specific to the engineering sciences, which represent the causal story and the mathematical description of the phenomenon: the *diagrammatic* and the *nomo-mathematical* model. The diagrammatic model represents a phenomenological and/or causal explanation of the physical behaviour in distinct spatial regions or time phases. The nomo-mathematical model represents the phenomenon as a set of mathematically formulated laws. My account of the distinction between the two model-types will focus on (a) Epistemological aims of the models; (b) Scientific knowledge utilized in the construction of the models; (c) Representative tools employed in the construction of the models; and (d) Intended use or application of the models.

Diagrammatic models

The diagrammatic model receives its name from the representative device that is employed. The core of this model is a diagram or graph-like schema. Diagrammatic models graphically show the relationships between physical variables and theoretical entities relevant to the physical phenomenon on the one hand, and geometrical parameters relevant to the phenomenon in the technological device on the other. Distinguishing between spatial regions or time phases with distinct physical behaviour requires phenomenological knowledge and/or causal understanding of the physical behaviour in a technological device. This means that a causal explanation of physical behaviour in a region or phase may be phenomenological, i.e. in terms of observable or measurable physical parameters such as pressure and temperature, or in terms of theoretical entities that 'underlie' or 'bring about' the phenomenon such as forces, molecules, fluid particles, etc.[7] The intended use of the diagrammatic model in technology is for explaining how the phenomenon can be physically produced or manipulated; this also involves properties of the technological artefact. Another use of diagrammatic models is in constructing the mathematical description. In sum, the diagrammatic model represents spatial regions or time phases of distinct physical behaviour and provides a causal explanation of that physical behaviour; it thus provides a causal explanation of the observed phenomenon such as pressure drop in pipes or drag of solid objects in fluids. (see also, Boon, forthcoming).

    An example of how a diagrammatic model is constructed is given for the reactive-absorption process. (e.g. Schneider et.al., 2003). What follows is a simplified account of how a diagrammatic model for reactive absorption in the column is constructed. In this diagrammatic model the gas-liquid mixture is conceptually divided into five regions of distinct physical behaviour: (1) a bulk of gas-phase that is ideally mixed within the slice; this assumption implies that the concentration of the

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[7]   A proper distinction between observable phenomena and theoretical entities is complicated and not essential for my account of models of phenomena. Intuitively, a clear distinction is possible between directly observable phenomena such as flow-patterns, and theoretical entities such as electrons. But when measurement techniques are available for determining the behaviour of theoretical entities such as viscous force or flow-velocity, a distinction between observable phenomena and non-observable (theoretical) entities becomes problematic.

toxic gas is equal anywhere in this region, (2) a very thin gas-film through which toxic X-molecules are transported by means of diffusion, (3) an interfacial area where X is physically absorbed into the liquid-phase, (4) a very thin liquid-film in which toxic X-molecules chemically react and are transported by diffusion simultaneously, and (5) A bulk of liquid phase, which, again, is ideally mixed, and in which toxic X-molecules that have entered this region react further. The diagrammatic model represents shapes of concentration profiles in these five regions (see Figure 2 in Schneider et.al., 2003). The construction of this diagrammatic model involves causal knowledge of physical processes such as diffusion, chemical reaction, and absorption of molecules involved in reactive absorption.

Nomo-mathematical models.

The nomo-mathematical model represents the phenomenon or process as a set of mathematically formulated laws.[8] The distinction between regions in space or phases in time of distinct physical behaviour in the diagrammatic model allows for the construction of distinct (sets of) mathematical equations for each region or phase. Several types of scientific knowledge play a role in the construction of a nomo-mathematical model. First are theoretical or fundamental principles. Examples are the laws of conservation of mass, momentum, heat, and chemical compound. Other theoretical principles are Newton's laws of motion, the basic laws of thermodynamics, and Maxwell's equations. These principles do not describe actual behaviour of phenomena; instead they determine the axioms and physical constraints that apply to the physical system. Scientific laws that (mathematically) describe quantitative relationships between physical variables, theoretical entities, and properties of the technological artefact constitute the second type of scientific knowledge used in the construction of a nomo-mathematical model. These laws consist of both theoretical and purely empirical components. Purely empirical laws are derived from direct measurement of the relationship between physical variables such as between pressure, temperature, and volume in a gas, or between flow velocity and pressure-drop of flowing fluids in tubes. Scientific laws that contain theoretical and empirical terms are usually derived by means of simplification of scientific laws—which, for instance, were deduced from theoretical principles—by means of adding or replacing terms in these laws by empirical formula. The third type of knowledge is provided with the diagrammatic model; this model 'guides' the construction of the nomo-mathematical model: the diagrammatic model tells which regions or phase can be treated separately, which physical processes occur in each region or phase, and which physical processes can be neglected. Causal understanding of the physical behaviour in a spatial region or time phase (phenomenological or in terms of the behaviour of theoretical entities) is utilized in simplifications, approximations, and extensions of the mathematically formulated laws. Knowledge of physical behaviour at the boundaries of the regions or phases, which is also

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[8]   The model is termed nomo-mathematical because the terms 'mathematical model' and 'theoretical model', which are used by several authors, are confusing. Theoretical explanation of a phenomenon may involve theoretical laws but also causal explanations in terms of theoretical entities. This confuses the required distinction between the causal story and the mathematical description. Another term in use for the mathematical description is mathematical model. However, mathematical models have their origin in mathematics and do not necessarily have a physical meaning. The chosen term is an analogy after Hempel's nomo-logical model. In a 'nomo-mathematical' model physical laws are mathematically related instead of logically.

represented in the diagrammatic model, allows connecting the mathematical equations of the distinct regions in space or phases in time.

An example is how Prandtl solved the Navier-Stokes equation in order to describe the laminar flow in the boundary-layer along solid surfaces, whereas the Navier-Stokes equation was simplified in order to describe the turbulent flow outside the boundary layer by assuming that viscous forces can be neglected. Another example of a nomo-mathematical model can be found in Schneider et.al (2003). These authors report that the final reactive absorption process in a scrubber is represented by a set of 30.000 differential and algebraic equations.

The intended use of the nomo-mathematical model is to mathematically describe the dynamics of the phenomenon in the technological device at varying physical conditions. Nomo-mathematical models can be the basis for computer simulations used in simulating the technological device at varying physical conditions (e.g. Schneider et.al.), or for control of technological devices. Characteristics of the two model types are summarized in Table 2.

Table 2.	diagrammatic model	nomo-mathematical model
a) Epistemological aim	Distinction in spatial regions or time phases and causal explanation of physical behaviour in it.	Mathematical description of behaviour of the phenomenon
b) Scientific knowledge utilized	Phenomenological knowledge and/or causal understanding of the phenomenon.	Theoretical principles, theoretical and empirical laws, and knowledge presented in diagrammatic model.
c) Representative tool	Diagram or graph-like schema	Set of mathematical equations
d) Intended use	i) Explaining how phenomenon in technological device is physically produced or manipulated. ii) Basis for nomo-mathematical model.	i) Quantitative description of physical parameters and variables relevant to technological device. ii) Basis for computer simulations

The connection between the diagrammatic and nomo-mathematical, and also between models and actual measurements, is provided by the physical variables and theoretical entities that are chosen to characterize the phenomenon. Examples of physical parameters and theoretical entities in the reactive-absorption example are mass, length, flow velocity, temperature, pressure, viscosity, diffusion-coefficient, chemical concentration, chemical reaction rate, boundary-layer thickness, and Reynolds-number.

5. Conclusions

Physical phenomena in technological devices are usually complex. Essential in the construction of models for explaining, predicting, and (mathematically) describing these phenomena is 'breaking them down' to more simple phenomena that are already causally and theoretically understood. This also involves distinguishing between regions in space or phases in time which are determined by phenomena that 'underlie' (or 'bring about') the observed phenomenon, whereas possible other 'underlying' phenomena can be neglected. The diagrammatic model represents the behaviour of relevant physical variables and values of theoretical entities in the distinct spatial regions or time phases in the technological artefact, and provides a causal explanation of the physical behaviour in each region or time phase. This model is used in constructing the nomo-mathematical model, which represents the phenomenon as a set of mathematically formulated laws, which describe the (dynamic) relationships between physical variables, values of theoretical entities, and properties of the technological artefact. The nomo-mathematical model can be applied in actual design or in computer simulations used in control of technological devices.

In this account, a distinction is proposed between model construction that involves knowledge of physical behaviour in terms of properties and causes that produce the observed phenomenon (the diagrammatic model), and model construction that involves fundamental principles and empirical laws (the nomo-mathematical model). The connection between the two models is provided with the use of physical variables that represent the physical phenomena in the context of an intended application in both models.

Prandtl's synthesis of methods is an example of how causal explanations and the covering-law view of explanation are complementary. In Cartwright's words, this approach consists of 'producing a causal story' and 'fitting a phenomenon in a

theoretical framework'. This approach provides us with an alternative to 'the covering-law view of applying science'.

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Note on contributor

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References

ACHINSTEIN, P. 1964. Models, analogies, and theories, Philosophy of Science, 31: 328-350.

Basalla, G. 1988. The Evolution of Technology. Cambridge: Cambridge University Press.

Bayazit, N. 1993. Designing: design knowledge, design research, related sciences, in: Design Methodology and Relationships with Science. M. J. de Vries, N. Cross & D.P. Grant (Eds.) Kluwer Academic Publishers 121-136.

BIRD, R.B.S., WARREN E. & LIGHTFOOT E.N. 2002. Transport Phenomena New York: Wiley.

BÖHME G., DAELE W. V.D. & KROHN W. 1978. The 'scientification' of technology, in The Dynamics of Science and Technology - Social Values, Technical Norms and Scientific Criteria in the Development of Knowledge. W. Krohn, E. T. Layton Jr. & P. Weingart (Eds) Dordrecht: D. Reidel Publishing Company. Part II, 219-250.

BOON, M. 2004. Technological instruments in scientific experimentation, International Studies in the Philosophy of Science, 18: 221-230.

Boon, M. forthcoming. Diagrammatic models in the engineering sciences. Model Based Reasoning. L. Magnani.

BUNGE, M. 1966. Technology as applied science, Technology and Culture, 7: 329-347.

BUNGE, M. 1983. The nature of applied science and technology. Philosophy and Culture **2**: 599-604.

CARPENTER, S. R. 1974. Modes of knowing and technological action. <u>Philosophy Today: a quarterly survey of trends and research in philosophy.</u> **18**(2): 162-168.

CARTWRIGHT, N. 1983. <u>How the laws of physics lie.</u> Oxford: Clarendon Press, Oxford University Press.

CARTWRIGHT, N.D. 1974. How do we apply Science? <u>PSA: Proceedings of the Biennial Meeting of the Philosophy of Science Association</u>, Dordrecht, Holland: Reidel Publishing Company 713-719.

CASIMIR, H. B. G. 1983. <u>Haphazard Reality - Half a Century of Science: Chapter 10 - *The Science-Technology Spiral*</u>. New York: Harper & Row Publ.

CONSTANT, E. W. 1984. The nature of technical knowledge: Are models of scientific change relevant? <u>Cognitive Change in Technology and Science.</u> R. Laudan, D.Reidel Publishing Company 27-46.

DE SOLLA PRICE, D. J. 1984. Notes towards a philosophy of the science/technology interaction, in: <u>The Nature of Technical Knowledge. Are Models of Scientific Change Relevant?</u> R. Laudan (ed) D.Reidel Publishing Company 105-114.

DE VRIES, M. J. 2002. <u>80 Years of Research at Philips. The History of the Philips Natuurkundig Laboratorium, 1914-1994.</u> Eindhoven: Stichting Historie der Techniek.

DE VRIES, M. J. 2003. The nature of technological knowledge: extending empirically informed studies into what engineers know. <u>Techne</u> **6**(3): 1-21.

FAULKNER, W. 1994. Conceptualizing knowledge used in innovation: a second look at the science-technology distinction and industrial innovation. <u>Science, Technology and Human Values</u> **19**(4): 425-458.

FEIBLEMAN, J.K. 1961. Pure science, applied science, technology, engineering: an attempt at definitions. <u>Technology and Culture</u>, 2**:** 305-317.

GARDNER, P. L. 1997. The roots of technology and science: a philosophical and historical view, in: <u>Shaping Concepts of Technology - From Philosophical Perspective to Mental Images</u>. M. J. de Vries & A. Tamir (eds.), Kluwer Academic Publishers 13-20.

GARDNER, P. L. 1999. The representation of science-technology relationships in Canadian textbooks. <u>International Journal of Science Education</u> **21**(3): 329-347.

HACKING, I. 1983. <u>Representing and Intervening: Introductory Topics in the Philosophy of Natural Science</u>: Cambridge, Cambridge University Press.

HARRÉ, R. 2003. The materiality of instruments in a metaphysics for experiments, in: <u>The Philosophy of Scientific Experimentation</u>. H. Radder (ed.), Pittsburgh, Penn.: University of Pittsburgh Press 19-38.

HESSE, M.B. 1966. <u>Models and analogies in science</u> University of Notre Dame Press.

HODDESON, L. 1990. Innovation and basic research in the industrial laboratory: the repeater, transistor and Bell telephone system, in: <u>Between Science and Technology - Proceedings of the International Conference Between Science and Technology</u>. A. Sarlemijn & P. Kroes (ed.), Eindhoven, North-Holland**:** 181-214.

HUGHES, T. P. 1976. The science-technology interaction: The case of high-voltage power transmission systems. <u>Technology and Culture</u> **17**: 646-662.

HUTTEN, E.A. 1954. The role of models in physics, <u>British Journal for the Philosophy of Science</u>, 4**:** 284-301.

IHDE, D. 1997. The structure of technology knowledge, in: <u>Shaping Concepts of Technology - From Philosophical Perspective to Mental Images</u>. M. J. de Vries & A. Tamir (ed.), Kluwer Academic Publishers 73-79.

KOHLMEYER, F. W. & HERUM F. L. 1961. Science and engineering in agriculture: a historical perspective. <u>Technology and Culture</u> 2: 368-380.

KROES, P. 1992. On the role of design in engineering theories: Pambour's theory of the steam engine, in: <u>Technological Development and Science in the Industrial Age</u>. P. Kroes & M. Bakker (ed.), Dordrecht / Boston / London: Kluwer Academic Publishers 69-98.

KROES, P. 1995. Technology and science-based heuristics, in: <u>New Directions in the Philosophy of Technology</u>. J. C. Pitt (ed), Kluwer Academic Publishers 17-39.

KROES, P. & BAKKER M. 1992. Introduction: Technological Development and Science, in: <u>Technological Development and Science in the Industrial Age</u>. P. Kroes and M. Bakker (eds.), Dordrecht / Boston / London: Kluwer Academic Publishers 1-15.

KÜPPERS, G. 1978. On the relation between technology and science - Goals of knowledge and dynamics of theories, the example of combustion technology, thermodynamics and fluidmechanics, in: <u>The Dynamics of Science and Technology - Social Values, Technical Norms and Scientific Criteria in the Development of Knowledge</u>. W. Krohn, E. T. Layton Jr. & P. Weingart (ed.), Dordrecht: D. Reidel Publishing Company. Part II**:** 113-133.

LAUDAN, R. 1984. Cognitive change in technology and science, in: <u>The Nature of Technological Knowledge. Are Models of Scientific Change Relevant?</u> R. Laudan (ed.), D.Reidel Publishing Company 83-104.

LAYTON, E. T., JR. 1971. Mirror-image twins: The communities of science and technology in 19th-century America. <u>Technology and Culture</u> **12**: 562-580.

LAYTON, E. T., JR. 1974. Technology as knowledge. <u>Technology and Culture</u> **15**: 31-41.

LAYTON, E.T., JR. 1976. American ideologies of science and engineering, <u>Technology and Culture</u>, 17**:** 688-701.

MORRISON, M. 1999. Models as representational structures, in: <u>Models as Mediators - Perspectives on Natural and Social Science.</u> M.S. Morgan & M. Morrison (eds.), Cambridge: Cambridge University Press 38-65.

MORRISON, M. AND MORGAN, M. S. 1999. Models as mediating instruments, in: <u>Models as Mediators - Perspectives on Natural and Social Science</u>. M.S. Morgan & M. Morrison (eds.), Cambridge: Cambridge University Press 10-37.

MITCHAM, C. 1994. <u>Thinking Through Technology. The Path Between Engineering and Philosophy</u>. Chicago: University of Chicago Press.

NAGEL, E. 1961. <u>The Structure of Science; Problems in the Logic of Scientific Explanation</u> New York: Harcourt, Brace and World.

PRANDTL, L., TIETJENS, O. G. 1934a. <u>Fundamentals of Hydro- and Aeromechanics</u> New York: Dover Publications, Inc.

PRANDTL, L., TIETJENS, O. G. 1934b. <u>Applied Hydro- and Aeromechanics</u> New York: Dover Publications, Inc.

RADDER, H. 2003. <u>The Philosophy of Scientific Experimentation</u>. Pittsburgh, Penn.: University of Pittsburgh Press.

RAPP, F. 1981. <u>Analytical philosophy of technology</u>. Dordrecht, Boston, London: Reidel Publishing Company.

RASE, H. F. 1961. The Philosophy and Logic of Chemical Engineering. Houston, Texas: Gulf Publishing Company.

ROPOHL, G. 1997. Knowledge types in technology, in: Shaping Concepts of Technology - From Philosophical Perspective to Mental Images. M. J. de Vries & A. Tamir (eds.), Kluwer Academic Publishers 65-72.

SCHNEIDER, R., SANDER, F. & GÓRAK, A. 2003. Dynamic simulation of industrial reactive absorption processes. Chemical Engineering and Processing, 42: 955-964.

SKOLIMOWSKI, H. 1966. The structure of thinking in technology. Technology and Culture 7: 371-383.

SMITH, C. S. 1961. The interaction of science and practice in the history of metallurgy. Technology and Culture 2: 357-367.

SMITH, M. R. & MARX, L. 1994. Does Technology drive History? the Dilemma of Technological Determinism. London: MIT Press.

STAUDENMAIER, J. M. S. J. 1985. Technology's storytellers: Reweaving the Human Fabric. Cambridge, Massachusetts: MIT Press.

SUPPE, F. 1989. The Semantic Conception of Theories and Scientific Realism Urbana and Chicago: University of Illinois Press.

VINCENTI, W. G. 1990. What engineers know and how they know it; analytical studies from aeronautical history. Baltimore and London: The John Hopkins University Press.

VINCENTI, W. G. 1992. Engineering knowledge, type of design, and level of hierarchy: Further thoughts about *What Engineers Know*, in: Technological Development and Science in the Industrial Age. P. Kroes & M. Bakker (eds.), Dordrecht / Boston / London: Kluwer Academic Publishers: 17-34.