# ON STRUCTURAL DIFFERENCES BETWEEN SCIENCE AND ENGINEERING

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## 1. INTRODUCTION

Philosophers, in most cases, do not deal with such dirty things as technology. They prefer to discuss the rationality of *animal rationale* instead of the products of *homo faber*. Scientists, in most cases, look down on technology as a kind of scienceless application of science; only if they need some sophisticated new measuring instruments do they accept technology as an auxiliary science. All this is not only far from Benjamin Franklin's insight that to be a *tool-making animal* belongs to the essence of human beings; it is far from the real conditions of human life today. It is not science at all which brought the participants of our conference to Karlsruhe or Mr. Armstrong to the moon; it is technology. And it is technology, too, to which most of us owe our lives—if, for example, we think of our lunch, not to speak of our last sickness. Sciences, on the other hand, are the coddled child at least of philosophers of science, who, up to now, have developed a paradigm of science depending on their fixation on physics.

When the Kaiser of Germany, 100 years ago, introduced the "Dr. Ing." as an academic degree at the Technische Hochschule Charlottenburg at Berlin, the traditional universities strongly attacked this unacademic undertaking and forced engineers to write their title in Gothic instead of Latin letters. The problem is solved now, insofar as no printer today really is able to print something correctly with those letters; and even computers cannot. (Or perhaps they refuse to do so, in order to exclude this "letteral" suppression of the engineer's ingenium.) But even if engineering is a science formally—since it has been located in higher technical institutes and universities for a century—it is still a central question of philosophy, what technology means for the essence of human beings. It is also a central question of philosophy of science, what kind of science engineering is. The second question will be the topic of my paper. I shall take *engineering* to be a science, sometimes speaking of *technological sciences* synonymously, whereas *technology* shall mark *real processes* and *artifacts*.

The way I intend to go shall lead us via the traditional distinction between pure and applied science, with creativity as a possible discriminator, to rules instead of laws, to know-how against know-why, and on to technological hermeneutics, ending up with aims and values as the horizon of a culturally dependent world view.

## 2. ENGINEERING AS AN APPLICATION OF NATURAL SCIENCES

During the 19th century, engineering got the structure of a scientific discipline. This corresponds to a technological development, where *tools* had since the 13th century been substituted step by step by *machines*, which, during the 19th century, became connected to *systems*—think of electricity, telegraph, and railway systems, and of energy transmission in factories—whereas these systems now are *steered automatically* by means of artificial intelligence. Engineering, in the beginning, was understood as an application of the knowledge of the natural sciences—a view which continued to dominate the theoretical reconstruction of technological sciences at least until the end of World War II.

This narrow connection between natural sciences and engineering is historically and systematically misleading. I do not want to follow up the historical path of argumentation, which points out the fact that tools are much older than science and that even the so-called Industrial Revolution was the outcome of an elaborate craftsmen's tradition without connections to science. The only two examples of scientific results which had been of some influence had been the *Leibnizian calculator* (and, in fact, only at the end of the 19th century was it possible to build calculators in factories), and *Huyghen's perpendicular clock*, which, as a new principle of self-regulation, spread widely in a very short time.

What needs further clarification is the difference between empirical sciences and engineering. That this has not been done sufficiently, up to now, partly depends on the fact that engineers do not need such metatheoretical knowledge, and partly on the physicalistic viewpoint of philosophers of science even after the Kuhnian paradigm switch from positivism to history. Let us first discuss two seemingly fruitful proposals for the distinction in question.

## 3. SCIENCE OF NATURE AND SCIENCE OF ARTIFACTS

It is common among scientists to distinguish sciences from each other by their topics, and, depending on these topics, by their methods. The simplest kind of difference between science and engineering, then, could consist in a distinction between a science of nature and a science of artifacts. This would be in accord with one of the classical methods of philosophy of science, namely, to ask for the ontological status of the entities of a discipline; ontological conventions, as one knows since Stefan Körner, build up the categorical framework of a science.

Thinking of traditional technology, this seems to be true; recall the old standard example, that there are no wheels and axes at all in nature. But a second look makes clear that we run into problems here, not only with respect to stones used as a hammer, but especially with respect to the newest kinds of technology, which one could call the third technological revolution.

Whereas traditional engineering aimed at mechanical or chemical artifacts and at processes produced by these artifacts, we are today confronted with technologies where it is not adequate to speak of artifacts in the traditional way. Is a cloned sheep an artifact? Or does the transplantation of a heart or the implantation of a cardiac pacemaker make an artifact of me? Is the production of natural enzymes or of resistant tomatoes by means of gene-mutated plants an artifact? Maybe we can count a computer as an extended Leibnizian calculator, but is the information transformed by such a calculator—or, as might be the case in the future, by a bio-calculator—something which differs from "normal" or "head-made" reasoning? The switch from physicalistic to biological technologies, including neuronal research and its realization in information systems, demands a metatheoretical view which differs from the traditional one in philosophy of science.

A further reason not to focus the distinction between science and engineering on artifacts is this. Since experiments count as the cornerstone of every empirical science, there is no laboratory without manipulation of the objects of experience and without extended technologies for experimentation and measurement. Moreover, in many cases even the objects of the sciences are produced by humans, whether it be isotopes or macromolecules, or polarized or monochromatic light. All of this shows that we have to concentrate on methods, not on an ontology of artifacts, in order to mark the difference between science and engineering.

## 4. CREATIVITY AS A DISCRIMINATING QUALITY?

A very emotional plea for a difference between science and engineering points to the genius, the ingenium, which an engineer needs to have—or, more precisely, to the engineer's *creativity*, his or her capacity to make inventions in order to bring about new artifacts. In Renaissance times, one admired such inventors as Leonardo or Michelangelo, and the well-known characterization of human being as *homo faber* mirrors this view.

Even if this is of great importance for a cultural philosophy of technology—since it goes hand in hand with the idea of progress in contrast to the ideal of a static society—creativity as a quality cannot be used to distinguish the sciences from engineering.

During recent decades, detailed methodologies of construction have been published (see Müller, 1990; Dylla, 1990; Hubka, 1981), which show that one can develop models of the engineer's undertaking in order to get, step by step, the final constructive solution of a given problem. (Along the way, the problem might have undergone some slight modifications, depending on the possibilities at hand, but we can neglect that here.) These attempts depend on heuristic methods, in the tradition of an *ars combinatoria* or a Leibnizian *ars inveniendi*. They presuppose that it is possible to develop a strategy about how to get to the intended aim as an output by means of an analysis of the given situation and of rational decisions concerning the means to be combined in the most sufficient manner. What is shown by these formal attempts is the possibility of heuristic methods such that normally there is no need to speak of creativity as an urgent faculty of engineers. They only have to learn how to combine their tools (though it may be in a way which nobody has done before). The plea behind this is that technology as a science does not need a quasi-magical or unique creativity; it is possible to teach and to learn engineering sciences. This does not exclude creative breakthroughs, but not as a methodological part of engineering.

Furthermore, there is no difference in creativity if one compares a scientist and an engineer, for to find new hypotheses (which are better than stupid inductive generalizations) or to find new technological solutions (which are better than stupid combinations of well-known rules) makes no difference at all. So creativity as such is no distinguishing quality between science and engineering.

## 5. ENGINEERING AS AN APPLIED SCIENCE

The traditional distinction between *pure* and *applied* sciences was picked up by Mario Bunge 30 years ago (see Bunge, 1966, and revised versions in Mitcham and Mackey, 1972, and Rapp, 1974). In his well-known article he made the proposal to understand engineering as a specific kind of applied science. Bunge explains that it is not the orientation towards satisfying needs which marks the difference between pure and applied science, "but the limit must be drawn . . . between the investigator who searches for a new law of nature and the investigator who applies known laws to the design of a useful gadget." Whereas the former wants to understand things better, the latter wishes to improve our mastery of them (see Bunge in Rapp, 1974, p. 20). This makes clear that these theories and laws are imbedded in an absolutely different normative and intentional context, as the engineer is aiming at practical ends, whereas the scientist intends cognitive knowledge. As an engineer, we do not want to get better and deeper knowledge, but *better ends*.

All this does not exclude that engineering sciences make use of *idealizations* or of *theoretical concepts*; otherwise they would not be able to predict aims resulting from the application of technologies. But these predictions do not function as tests of the theories in question; the idea behind them is to "find out *what ought to be done* in order to bring about, prevent or just change the pace of events on their course in a preassigned way" (p. 23). This has as a consequence that there is no need of *true* laws or theories; what we need are *sufficient* ones with respect to ends. For cars, for example, classical mechanics instead of relativity theory is sufficient; so, a theory can be successful in practice, but false (p. 25). Therefore, engineering as an applied science cannot consist in the application of pure science, even if the sciences might be and are helpful with respect to theoretical boundaries. Applied sciences have their own goals, and, consequently, their own methods.

## 6. AIMS, MEANS, AND FUNCTIONS

If an engineer does not want to try to test the truth of what he uses as a theory, what, then, is it that he wants? The answer is quite clear: he seeks *means* to get to a goal. To speak of ends and means needs some clarification. *Means* are processes or artifacts which transform a situation A into a situation B, where A is understood (or interpreted) as a situation which is not satisfactory with respect to a given value V; whereas B is a situation, understood as an *aim* of such a means, that is an instantiation of the value V. The given values behind may be of very different kinds; but at the moment it is enough to say that they come into play if one has to argue for a normative dimension of the aim in question.

This very simple picture which we have drawn here is devoted to the level of action itself; it contains *situations* together with their *interpretation*. What the means consist in is systematically open, as the essential condition they have to fulfill is to transform A into the intended situation B as the aim in question. This implies some further conditions, such as technological realizability, disposability of the means, know-how of the actor with respect to the means, etc. (See Ropohl, 1979, pp. 202ff.) These we cannot discuss here, even if they grant the real possibility of the means in question and even if this kind of *technological possibility* marks an interesting problem of modalities of action, which are the platform of Ellul's (1954) thesis on technological dynamics.

The most important aspect here is that it is nothing but the *functioning* of the means which is demanded.

All of this is well known from the practical syllogism and from von Wright's (1963, 1972) discussion of its conditions of adequacy. The *cognitive premise* of a practical syllogism formulates sufficient means with respect to the required function, and it is far from postulating exclusivity. So there might be a different (and normally there are infinitely many) sufficient means, perhaps even located in different disciplinary spheres. (To get from one city to another, transportation means include cars, trains, and airplanes, but possibly also rockets or genetically-altered whales named Jonas.)

Means have to fulfill functions. But philosophy of science always tries to avoid functions and to reduce them to classical causes in order to be able to apply the Hempel-Oppenheim scheme of scientific explanation in order to feel at home. This is totally misleading, for even if a machine works on mechanical and thermodynamical laws or causes, we never would understand it if we could not understand its function. This might be seen as a superfluous distinction within traditional technologies (where mechanical or chemical causes explain what is going on), but one really would miss the point if we did not use the concept of function in biotechnology, including gene technology, or with respect to the hardware and software of computers. Only on the level of functions can we understand that doctors can transplant hearts from one body to another or implant cardiac pacemakers; thinking in terms of functions allows the substitution of one means for an absolutely different one which fulfills the same function—as workers by industrial robots, or the steering of a whole factory by computers. If philosophy of science had taken biology as its paradigm case (as Aristotle did) instead of physics (as Descartes did), we would be much better off.

It is enough that we need functions. Human actions have an intentional, a *teleological* structure. Functions cannot explain that we are aiming at an end. If the function of a machine is to produce screws, we immediately combine this with ends reached by screws. The irritation, which Joseph Beuys caused with his senseless "honey pump" is the best illustration one can think of; for we always take technological artifacts in a teleological manner. That is, we would not understand what is going on if we did not make use of a *teleological interpretation*.

But what about the substitution of aims? This takes place, too. How can it correspond with a teleological perspective? The answer is quite simple. As long as we are fixed on aims without taking into account the given values, there would be no way out. But, in fact, even aims are intermediary means on the way to more global aims. The functional as well as the teleological view, therefore, allows us to substitute some aims in the light of more general ones. The structure of this, too, can be explained by the practical syllogism. We not only state or describe connections, but we can give *reasons* and *explanations* outside the Hempel-Oppenheim scheme. The theory of action has to be imported into the philosophy of the engineering sciences, because they are far from a mere application of empirical sciences.

## 8. LAWS AND RULES

Our analysis has taken place on the level of actions. Let us now turn to the level of engineering as a science. Evidently, we do not have to deal with situations and artifacts here, but with *propositions*. Instead of A and B as names for situations we have to look at *types* of situations, interpreted as *needful* or *sufficient* in light of the value in question. Instead of real means we will find *rules*.

Rules name sufficient and concrete means to transform an A-type situation into a B-type situation. The means given by the rules must be *effective* in the sense of technological possibility. This includes that the rules have been shown to be successful, but there is no necessity for a rule to be true. Moreover, rules can be neither true nor false. In the light of philosophy of science, we therefore have to admit that the justification of technological rules differs from justification within the empirical sciences. They do not aim at truth, but efficiency. But it is evident that there are such conditions, and engineering does obey methodological conventions (which Kurt Hübner, 1978, p. 85, has called the *judicial conditions* which are the conditions sine qua non of a scientific undertaking).

## 9. KNOW-HOW AND KNOW-WHY: THE PROBLEM OF EFFICIENCY

Just here we are confronted with Rorty's (1980) view—and a similar one is to be found in Toulmin's *Cosmopolis* (1990)—that there is no truth at all within the sciences; the best we can hope for is the efficiency of a hypothesis. To some extent this results from Larry Laudan's sophisticated way out of Lakatos's sophisticated falsificationism. In science we deal with problems and problem solutions, accepted for awhile. The outcome, then, would be the efficiency of an accepted problem solution; and this seems to imply that there is no methodological difference at all between science and engineering.

Years ago, a group of researchers (Böhme, van den Daele, and Krohn, 1974) at the Starnberg Institute of the Max-Planck-Gesellschaft offered the so-called *Finalisierungsthese*, which fits into the same framework even if the arguments are different. They meant that all sciences, including technology, will in the future have an absolutely new and different structure—namely, an anti-Cartesian one. It will depend on nothing but efficiency, since reality is much too complex and research much too expensive to be able to give causal explanations, whereas it would not lead to any practical consequences to ask for laws and explanations everywhere. The Starnberg group believed that we already possess sufficient basic knowledge, so that it is generally enough to know that A leads to B, that "Aspirin relieves a headache." These rules express an efficient *know-how* without any *know-why*.

As the development of pharmacology has shown—think of AIDS, Parkinson's disease, and cancer—just the opposite has happened. There has been no efficient means of solving the problems without any know-why, and the only way out is what already follows from von Wright's analysis of the cognitive premise of the practical syllogism. If we do not possess a rule to get from A to B, we have to enlarge our knowledge. We must start with foundations and not mere applied research; we need research which is devoted to universal laws of the chemistry of cells, namely, a search for truth, at least as a regulative idea. This shows that the *Finalisierungsthese* is wrong and that postmodernist songs are bewitching songs of the sirens. But it indicates, too, that our analysis of technological rules is not sufficient; it is not enough to speak of efficiency. Even engineering needs foundational scientific research bound by classical scientific standards. Rules which indicate means to an end will be grounded, if they are based on this kind of research. Effectiveness, then, depends on the success of the adoption of the results of basic research to a means for an intended end (see Skolimowski, 1974, p. 85).

No doubt, science and engineering have different methods and aim at different goals. Whereas science seeks for universal truth, technology is fixed on neither truth nor universality. But if we look at an institute of solid state physics or at a laboratory for gene technology, we must confess that their universal aims do not differ. Both are keen on technological rules and both try to get them via hypotheses which are highly corroborated and which aim at truth. So the traditional difference between technology and other sciences is far from being a sharp one; moreover, it depends on the problems which one tries to solve—that is, it depends on the context. Years ago, one could use astrophysics as an example of a kind of science without any connection to technology; today, an engineer who wants to construct a fusion reactor will ask a plasma physicist whether a high energy state of a special type is possible or not, and the plasma physicist will ask the astrophysicist whether such a state has taken place sometime during the history of the universe. What differs are the *intentions* (see Agazzi, 1995, p. 82). The plasma physicist tries to give a solution which is true for the whole universe; the engineer wants to produce cheap energy.

## 10. TECHNOLOGICAL HERMENEUTICS

If we were to stop here, we would miss engineering all together. It is not (or not only) grounded efficiency which counts; what is needed here is what I like to call *technological hermeneutics*. This takes place on different levels. The first is the *level of real action*. As we saw, to understand a situation A as needed and a situation B as satisfactory presupposes an *interpretation* of the situation in question. This interpretation presupposes a norm or a value as a measure and hermeneutic-methodological rules about how to interpret an absolutely singular situation—which we can describe as an instantiation of a value—which we cannot describe but only prescribe. In doing so, we add a normative component to our understanding of a situation. To say it in a classical philosophical manner, the kingdom of facts and the kingdom of norms have to meet in a singular instance.

The same holds for the *level of engineering*. As already mentioned, we cannot avoid a teleological view of the connections between types of situations, rules concerning functions, and types of output situations as ends. Here, the kingdom of causes (behind the rules) and the kingdom of purposes (behind the aims) meet. But this depends on interpretation, too; otherwise we would not be able to substitute aims.

There is a third and more general level of technological hermeneutics, the *level of local conditions*, and it also throws light on the difference between science and engineering. Science aims at an investigation of the whole universe, namely, in order to formulate the most general laws it obeys. Technology cannot leave out this framework; its boundaries are given by these laws. But technology does not deal with the whole universe; it is concentrated on local conditions and their transformation. So technology has to react to conditions which might be absolutely unique. For instance, if one wants to dam up a river, the geological conditions are absolutely singular. This presupposes that the engineer is able to recognize what normally is called an intellectual task of the humanities—of an historian, for instance—namely, *to interpret a given situation in its uniquenes*. This means that he or she cannot use the common rules of construction, but has to develop new and specific ones, answering to the interpretation of the local conditions. Seen from a methodological standpoint, this implies all the well-known problems of understanding uniqueness, to which hermeneutics intends to give an answer.

It would go too far if I were even to begin to sketch theories of hermeneutics (as they have been developed by Gadamer and his successors) or of interpretation (as they have been discussed by Davidson, Abel, Lenk, and others; see Davidson, 1984, and Lenk, 1993). I only intend to show that there is a dimension of technology which, for an adequate understanding, needs a kind of methodology, which, up to now, has been seen as the entire domain of hermeneutics (see Rorty, 1980, but also Irrgang, 1996).

## 11. AIMS AND VALUES

The philosophical problems of modern technology, as well as the roots of its critique in society, depend on a relation which we have not yet discussed, namely the relation between *values* and alleged *aims* as their instantiations (see Hubig, 1993, pp. 133ff). One could be inclined to say that this is no problem of a philosophy of the engineering sciences, since it does not belong to engineering at all. No engineer would discuss values. But at least he should, for nearly all criticisms of gene technology, of biotechnology, of nuclear technology, or of computer technology argue on the basis of values and norms, and not of technological standards. And if the guidelines which had been formulated by the VDI (Verein Deutscher Ingenieure) as Richtlinie 3780 (with the purposes in its intention described by Carl Mitcham, 1994, pp. 54ff) are to be successful, then it is unavoidable to bridge the gap between very general norms and values on the one side and technological standards on the other.

Formally speaking, this is the problem of how to elaborate criteria for the economic, social, psychological, and ecological conditions which technologies have to fulfill beneath their mere technological efficiency. But this presupposes that technological theories are far from Bunge's distinction between technologies as one-level concepts and science as characterized by him as many-level theories (see Bunge in Rapp, 1974, p. 26). Just the opposite must be true. Theoretical mechanics deals with nothing but the mechanics of idealized bodies, whereas gene technology has to take into account not only microbiology (which would be the one-level case) but also problems of the whole earth within an ecological (and that means normative) holism.

Modern technologies, therefore, must be many-level theories; otherwise technology assessment would be a farce. As it is impossible to introduce the complexity of the whole planetary system (as the region today affected by human technology) into each singular engineering science (which, then, would be an all-embracing Leibnizian *scientia generalis)*, it will be necessary to develop a kind of surrounding theory which transforms requirements depending on values into boundary conditions of technological rules. This can only be done in an interdisciplinary network, which allows predictions outside the technological disciplines to make technology assessment possible. And it requires a philosophical analysis of given values. Since they depend on cultural tradition—which constitutes the worldview of a time—and since a clarification of this kind traditionally is called metaphysics, it is necessary to say that a philosophy of the engineering sciences—via functions, means, and interpretations, intentions, action rules, and values—at the very end must be imbedded in a *metaphysics of technology*. We know that this will be no *philosophia perennis*, but a time-dependent clarification of the concept of *homo faber*. And we can hope that in doing so this will lead to a similar clarification of the concept of *animal rationale*.

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