Putting Science to Work

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Abstract

The purpose of this lecture is to shed some light on the relationship between the theoretical or basic sciences on the one hand and technology and engineering on the other. My thesis is that the relation is rather asymmetrical, that the influence of technology on science is for the most part positive, while the influence in the other direction is almost entirely negative. This is not to diminish the important service performed by theoretical science for technology, but to locate it correctly. It allows us also to identify the sense in which technology is an application of science, and to explain how it partakes fully in its rationality.

0 Introduction

This occasion is a great honour for me, and it is with much pleasure that I stand here before a captive audience of engineers. I suppose that all of us who are no longer young wish sometimes that we had excelled in some activity quite different from the one we practise. The physicist would like to have been an international footballer, the footballer

Under the title 'Haciendo Trabajar a la Ciencia', this was the inaugural lecture, given on August 10, in a weekly series organized by the Faculty of Engineering of the National University of Colombia (Bogotá) in the second semester of 2006. I should like to thank most warmly my host, Alexánder Gómez, and Andrés Tovar, the Chairman of the Department of Mechanical & Mechatronic Engineering, for the invitation to participate, and for the great hospitality they showed me throughout my stay. The content of the lecture is drawn, with many variations and additions, from Chapter 5 of my (2006). After it was delivered, Gómez (and later Jan Michl) drew to my attention George Basalla's *The Evolution of Technology* (1988), which I have read with reservations but principally with pleasure. Both its title and its content make clear that technology, no less than theoretical science, is an unending enterprise of trial and error. From this solid truth Michl (2006) draws some rather serious consequences for the doctrine of Intelligent Design.

would like to have been a learned doctor, the doctor would like to have been a concert violinist, and so on. In particular, as you will have noticed, many veteran scientists wish that they had been philosophers, while many veteran philosophers wish that they had been scientists. I have no illusions myself concerning my scientific capacity, and my lack of practical ability is startling. I have colossal admiration for the achievements of empirical scientists and engineers, but I could never have succeeded in either line of business, much as I should have liked to. This is why I value greatly the opportunity to speak to you on some philosophical questions that are relevant to your profession. As my teacher, the philosopher Karl Popper, often said (for example in 1972, Chapter 2, § 1), we all have our own philosophies, and these philosophies can have unnoticed effects on our thoughts and our behaviour. Nobody should allow himself the luxury of ignoring philosophy altogether.

What can a philosopher, or logician, or methodologist, say to an engineer? My lecture concerns precisely the question of the relationship between technology and theoretical science, and in what ways they exert an influence on each other. Their interaction is rarely well described, and behind the common misunderstandings it is possible to descry a philosophical error of great antiquity and notoriety. I hope today to be able to shed some light on this matter, and to resolve the question before us in a way that is both pleasant and interesting.

Everyone, I hope, can provisionally agree at the outset with the characterization of the difference between basic science and technology given by the Canadian political scientist Jack Grove, who wrote (1989, p. 46): 'Technology, unlike science, is not concerned with things as they are but with things as they might be.' The philosopher Henryk Skolimowski said in a similar vein (1966, p. 374): 'In science we investigate . . . reality; in technology we create a reality according to our design.' What these observations do not explain is how science is used in technology, or how technology is used in science. Understanding the first of these influences constitutes our principal problem today.

Science and technology of course have a good deal in common. Both activities are devoted to the solution of problems, but that is not to say much. Politics too is devoted to the solution of problems, and sometimes so is marriage. The basic sciences and the practical applications of science are habitually conflated these days, in the public mind and in the press, so much so that science accumulates both the praise and the dispraise that properly belong to technology. The relation between the two is, however, not symmetrical. Although I shall maintain that the influence of the basic sciences on technology is almost universally misunderstood, to the detriment of technology, I have no intention of depreciating the practical importance of science. I hope that what I say will cast a more flattering (and more truthful) light on both fields of activity, the basic sciences and the applied sciences.

1 Basic Sciences and Applied Sciences

I ought to say that I have used the terms 'basic sciences' and 'applied sciences' with much disquiet. Together they suggest that science precedes technology logically and temporally, and that the engineer does nothing more than but apply basic science in the way that, for example, I apply a corkscrew to open a bottle of wine, or a word processor to format the text that I have entered at the keyboard. If only it were so straightforward! Even I could be an engineer in such a world. But as you know, and I need hardly spell it out, the situation is quite different. I shall therefore prefer the expressions 'theoretical science' and 'explanatory science' or, when there is no danger of confusion, simply 'science'. I shall henceforth avoid the expression 'applied science'. As for the terms 'engineering' and 'technology', I shall later distinguish the development of artifacts that are suitable for mass-production, which I shall call 'technology', and the undertaking of particular construction projects, which I shall call 'engineering'. For the moment the two words may be understood interchangeably.

To begin with, I shall present four considerations that call into question the logical and temporal precedence of science over technology. One is simple-minded and zoological, another informal and commonplace, the third draws on the history of science. The final consideration, which is the most eloquent, consists of a simple but telling inspection of the logical form of scientific theories. The first two considerations (§ 1.0, § 1.1) suggest that scientific knowledge is not necessary for technology; the others (§ 1.2, § 2) suggest that it is not sufficient.

1.0 Birds, Beavers, and Moles

Birds build nests for their eggs and their chicks. Beavers build dams in order to control and redirect streams. Moles, voles, and other animals dig intricate systems of underground tunnels — that is, they too try to adapt the world to their needs. These creatures are engineers, but they are not scientists.

We may concede that 'there are no fire-using animals nor are there animals that routinely fashion new tools, improve upon old tool designs, use tools to make other tools, or pass on accumulated technical knowledge to offspring' (Basalla 1988, p. 13). We must resist the conclusion (stated but not explicitly endorsed by Basalla) that 'no technology whatsoever is required to meet animal needs' (*loc. cit.*).

1.1 Cookery, Music, and Hairdressing

A branch of technology that is familiar to us all is cookery, which is surely an activity that is not essentially different from other human interventions in the environment. In Grove's words, cookery 'is not concerned with things as they are but with things as they might be', though, unfortunately, it often fails to reach Skolimowksi's aspiration of creating 'a reality according to our design'. Cookery can of course be described as applied chemistry, but this description manifests exactly the sense of the verb 'apply' that I have objected to. Few successful cooks know the the elements of chemistry (or of the physics of materials, or of anatomy). The same may be said about farming, bee-keeping, animal husbandry, metal-working, and other branches of technology that emerged long before the dawn of theoretical science.

Another example, a little different, is music. Music is perhaps better described as a technique rather than a technology, but it exhibits a similar contrast between theory and practice. The science that is relevant to music is in part a mathematical theory (known to the ancient Greeks), in part a collection of physical theories (of waves, of elasticity, of sound, of acoustics). What is true in this case is that some knowledge of musical theory is usually an advantage to a musician, whether performer or composer. Folk music shows that such knowledge is not essential. Let us not forget that, a few months before his untimely death at the age of 31, Schubert enrolled in a course in counterpoint (Gombrich 1982/1996, p. 563).

What these everyday examples make evident is that we cannot characterize familiar cases of technology as applications of scientific knowledge. Animals possess no scientific knowledge, but we may suppose that they possess unconscious skills that have developed in the course of evolution. Even if there exists theoretical knowledge that impinges on his practical tasks, it is unlikely that a cook is aware of it either implicitly or explicitly, and it is certain that he does not apply such knowledge directly and automatically. In the case of a cook, in contrast to that of a musician, it is not obvious that it is worth his while to obtain the scientific knowledge that explains his achievements, for example, successful baking. A former colleague, an engineer who is now a Fellow of the Royal Society, told me that in his youth he was assigned to teach a course entitled 'Chemistry for Hairdressers'. I sometimes wonder if his students became better hairdressers, even if they understood better the effects of the dyes and peroxides used in the salon. Although diligent students were surely enabled to apply chemical substances with some scientific understanding, it does not follow that in doing so they applied any chemical theories.

1.2 Kelvin, Rayleigh, and Rutherford

There are several examples in the history of science of distinguished scientists who had thoroughly mistaken ideas concerning the practical potentialities inherent in their theories. Lord Kelvin [William Thomson] and Lord Rayleigh, who independently made significant contributions to the science of hydrodynamics, did not believe in the possibility of flying machines heavier than air; that is, in the feasibility of aeroplanes (Meurig Thomas 2001, p. 105). In 1902, together with his colleague Frederick Soddy, Lord Rutherford used the theory of the spontaneous disintegration of atoms to explain the mysterious phenomenon of radioactivity, and a decade later he proposed the nuclear theory of the atom. In 1933 he nonetheless wrote (*loc. cit.*): 'Anyone who expects a source of power from the transformation of [the nuclei] of atoms is talking moonshine.' In this connection it is interesting that Rutherford did not have a special reputation for abstract thought, divorced from material reality. On the contrary, he was a profoundly practical man, of whom Niels Bohr once said (Crowther & Whiddington 1947, p. 122): 'Rutherford is not a clever man; he is a great man.'

Notwithstanding his intuitive understanding of how the world works, this great man could not imagine a technique for liberating the energy stored within the atom. It is said that Max Planck, Albert Einstein, and Niels Bohr were of a similar mind. A less extreme example is to be found in the individual contributions of the British engineer Thomas Newcomen and the French scientist Denis Papin to the development of the steam engine. According to Basalla (1988, pp. 95f.): 'Newcomen had neither the education nor inclination to pursue the disinterested study of the vacuum, and Papin had neither the interest nor the technical knowledge and imagination to transform his small-scale laboratory demonstration into a practical engine.' Such examples surely cast doubt on the cliché that theoretical science provides the main inspiration for technology. As Basalla says (*loc. cit.*): 'It would be a mistake to conclude that Papin, in discovering the principle of the atmospheric engine, showed greater originality and genius than did Newcomen .... Nor is it correct to assume that Newcomen merely put theory into practice, that he did what was obvious in following the lead of Papin's work.' In short (*op. cit.*, pp. 91f.): 'Proponents of scientific research have exaggerated the importance of science by claiming it to be the root of virtually all technological changes.'

1.3 Summary

There are many other example that cast doubt on the common view that that 'invention [consists] ... solely in applying known science to technology', as Hatfield writes unbelievingly in his most informative book *The Inventor and His World* (1948, p. 59). He goes on: 'There is no more instructive case in the history of technology than the development of engineless flying. It is very doubtful whether Lilienthal ... ever dreamed of the possibility of flying without engines for hours on end. This development was in no way the result of the application of scientific principles ....' He mentions on the same page also Viking ships, whose 'lines ... can hardly be improved upon today', and the steam-engine. In these cases, it was the lack of scientific theory that forced the inventor to proceed without theoretical help, but there are more forceful example of independence from science. Writing in 1948, Hatfield invited his readers to consider 'the enormous developments in the use of catalysts which have taken place in recent years. Tomes of theory exist, but has anyone ever found the right catalyst by means of it?' (*op. cit.*, p. 146).

Yet the conclusion that science has no relevance for technology is unbelievable. I shall not dare to defy so radically your experiences as students of engineering. To illuminate matters further, we must look briefly at some of the logical aspects of the problem.

2 The Laws and Theories of Science

Since the time of Aristotle it has been realized that our scientific knowledge consists not only of a multitude of singular facts but also of empirical generalizations and universal laws. These generalizations or laws are universal because they assert something about all the elements of a class. A simple example is the putative law 'All asses are curmudgeonly'. For our purposes today, it does not matter if we choose examples that are not genuine laws; if there exist obliging asses, then we have only to find another example. To be sure, even Newton's law of gravitation is not universally true, but it is convenient to consider it as a law. What is important for us is that science aspires to formulate universal laws; initially empirical laws (such as 'All asses are curmudgeonly') that deal with everyday things, and eventually theoretical laws (such as the law of gravitation, or quantum mechanics) that deal with things that are remote from our ordinary experience. A typical law of modern physics asserts a functional relationship between numerical quantities. It should be noted that in many fields of physics, and of biology (for example, genetics), the stated aim seems to be over-ambitious and inaccessible; in these fields we aim rather for statistical laws. This point too is not of importance. The misunderstanding concerning the role of scientific laws and theories in technology does not dissolve if the laws are all statistical statements.

2.0 A Taste of Formal Logic

In order to write a universal sentence in formal logic we make use of various familiar mathematical characters together with two special technical symbols: a symbol $\rightarrow$ (a westerly arrow) that stands for the *conditional* expression 'if ... then ___ ', and a symbol $\forall$ (an upside-down capital A) that stands for the *universal quantifier* 'all'. By means of these symbols we can write the law 'All asses are curmudgeonly' as $\forall y\,(Ay \rightarrow Cy)$, where the letter '$y$' is called a *variable* that ranges over a domain of values (here not explicitly fixed). Any letter can serve this function, just as we may replace 'j' in the expression $\sum_{j=0}^{100} y_j$ and 'y' in the expression $\int_0^\infty f(y)dy$ by other letters. Notice that the sentence 'All asses are curmudgeonly', which in natural language asserts something categorical or unconditional about all asses (to wit, that they are curmudgeonly) is represented in the formalism by a sentence that asserts something conditional about all the elements of the domain (to wit, that they are curmudgeonly if they are asses). In a similar way, we may read the sentence 'Some ass is obliging' as 'Something is both an ass and obliging', and write it as $\exists y\,(Ay \,\&\, \neg\, Cy)$. The symbol $\exists$ (an upside-down E) is called the *existential quantifier*, and the hook $\neg$, with which we may represent the opposite not-C of an expression C, is called the *negation sign*.

Scientific theories may be formulated as *universal conditionals*, even though the majority of them are conditionals of a more complex form. Newton's law of gravitation, for instance, may be written: if x and z are any two distinct bodies, then the force f between x and z is equal to the product of the constant G and the masses m_x and m_z of x and z, divided by the square of the distance d_{xz} between x and z; compactly, $\forall x\,\forall z\,[(B(x)\;\&\;B(z)\;\&\;x \neq z) \rightarrow fxz = Gm_xm_z/d_{xz}^2]$. A more strictly correct formulation of this law takes the form of a mixed quantification: 'if x and z are any two distinct bodies, then there is a force f between x and z whose value is ... '; in symbols, $\forall x\,\forall z\,[(B(x)\;\&\;B(z)\;\&\;x \neq z) \rightarrow \exists f\,[F(f)\;\&\;fxz = Gm_xm_z/d_{xz}^2]]$. Other formulations, both more explicit and more exact, are possible. The simplified version is quite exact enough for our purposes.

In the formal expression $A \rightarrow C$ the formula represented by A is called the *antecedent* of the conditional, and the formula represented by C is its *consequent*. Logicians say that the antecedent is a *sufficient condition* for the consequent, and that the consequent is a *necessary condition* for the antecedent. Note that the meaning and the logical force of the conditional $A \rightarrow C$ are different from the meaning and the logical force of' $C \rightarrow A$.

2.1 Cause and Effect

What is crucially important for an accurate appreciation of the role played in technology by scientific laws is that in the great majority of laws of nature that we know of, the logical antecedent A is also a temporal antecedent of the consequent C, or, more generally, the antecedent A provides a method by which we may in principle realize the consequent C. It is commonly said that the antecedent A of a law of nature describes a *cause* of the *effect* described by C. The temporal order is of course not reversible: if A precedes C, or is a cause of C, then C does not precede A and it is not a cause of A. We do well to assume also that in most cases the instrumental order is not reversible either.

A merely illustrative example is the law 'Whenever an automobile A spins out of control in a busy street, there is soon a collision C'. Releasing the brake of a driverless car is sufficient to produce a collision shortly afterwards. A is sufficient for C, and C can be brought about by bringing A about. An example of a law $\forall y(Ay \rightarrow Cy)$ whose antecedent A and consequent C are simultaneous is the psychozoological law formulated above: 'All asses are curmudgeonly'. It is perhaps stretching usage a little to say that being an ass is a cause of being curmudgeonly, but if the law is a true one, it provides a method, which is effective if not efficient, for procuring a curmudgeonly animal; that is, procure an ass. There is in contrast nothing in the law that suggests a method for procuring an ass. It hardly suffices to procure something curmudgeonly; there are other curmudgeonly creatures, for example all mules and some of my acquaintances. As I said a moment ago, the instrumental order is usually irreversible.

3 Why Science Does Not Tell Us What to Do

A law or a scientific theory tells us what effect follows (logically and chronologically) from what cause. In practice, however, in a typical situation, what we know, more or less, is the effect that we wish to produce, but we know of no cause of that effect. If we are very lucky, we know a law $\forall y\,(Ay \rightarrow Cy)$ that imputes the desired effect C to an earlier cause A that we are able to implement. In that fortunate situation, the technological problem is already solved, at least in principle. What is more likely is that we know of no relevant law. Or we know only of a law whose antecedent we are unable to implement; in short, we know a cause of the desired effect, but we do not know how to bring that cause about. Although the technological problem has doubtless been shifted, it has hardly been solved.

Given an effect C, how are we to discover a law $\forall y\ (Ay \rightarrow Cy)$ whose consequent is that effect C and whose antecedent is something that we can bring about? It is here, popular legend suggests, that science can help us.

My response is: Absolutely not!

I do not say that science never implies such an empirical generalization $\forall y\,(Ay \rightarrow Cy)$. On the contrary, a successful invention would not be scientifically explicable if there were no such true (or approximately true) logical consequence of the scientific theories in our possession. What I do say is that science can assist us only in rather unusual circumstances. I concede also that science (like nature, literature, myth, and even dreams) can provide happy suggestions for practice. But they are only suggestions, not inferences; atomic theory suggested the presence of a vast store of trapped energy, but it did not tell us how to release it. The position of the engineer is an acute form of the predicament faced by someone who wishes to identify a painting, or a poem, or a tune. If the name of the work is known, a catalogue or encyclopedia quickly delivers what it looks like or sounds like. But the catalogue is of only limited use if what is known is what the painting looks like, or how the tune goes, and what is sought is its name.

It should by now be evident why science is technologically sterile.

Whereas the laws and theories of science give us a licence to infer effects from causes, what we need is a licence to infer causes from effects. Let T be our theory, and C be the desired outcome. Finding a practicable state of affairs A such that T implies $\forall y\,(Ay \rightarrow Cy)$ is not a task within the province of deductive logic. There are only two possible ways forward: one is to enumerate the logical consequences of T until there appears a conditional whose consequent is C, and the other is to have a guess at an appropriate antecedent A. The first possibility, although mechanizable, does not amount to a sensible task, for well known reasons. It would produce a suffocating quantity of conditionals of no conceivable interest; for example, the theory T implies the conditional $\forall y\,(Ay \rightarrow Cy)$ whenever T says that nothing whatever possesses the property A. Having a guess, that is, having a bright idea, is the only realistic possibility.

This point may be put somewhat differently if we take into account that the contrapositive $\forall y\,(\neg Cy \rightarrow \neg Ay)$ of the law $\forall y\,(Ay \rightarrow Cy)$ is logically equivalent to it. If Ay temporally precedes Cy, then the antecedent $\neg Cy$ of the contrapositive comes after its consequent $\neg Ay$. Nonetheless, we cannot apply the contrapositive directly, since its antecedent is simply too vague to be use. To apply our scientific knowledge to the task of landing a man on Mars, for example, little is gained by assuming that the task has not been achieved and using this information to identify deductively some initiative that, our theories say, has not yet been implemented. *A scientific theory can be applied only when there is something specific to apply it to.*

In this way we reach a conclusion that you all know full well. To be a successful engineer, it is necessary to be insightful, imaginative, and shrewd. But as we all know, being inventive is not enough. After all, as well as having the required logical properties, the antecedent A has to be something that is practicably realizable. It has to work too.

Before proceeding to explain the sense is which, notwithstanding this negative conclusion, science can be of use in technology, I should like to mention some examples, both some characteristic ones and some that are exceptional.

3.0 Beer and Skittles

A thorough reading of a work of chemical theory will not help you much if you wish to manufacture the majority of the colloids found in the home: bread, butter, soap, glue, ink, beer. You will not find in any textbook laws of nature that say ‘If you do A, you will make beer.’ Once a method of brewing beer has been developed, of course, you can formulate a recipe made up of tiny steps; and when you apply the recipe you follow these steps. But you do not apply the laws of theoretical chemistry, except in the sense that you do not infringe them.

This case is typical. Our scientific theories do not instruct us how to make painkillers or skyscrapers, memory chips or tortilla chips, shuttles or skittles, or any of the innumerable things and substances without which modern life would not be recognizable.

3.1 The Pendulum

There are examples, however, of laws in physics and other sciences that state for an effect C a condition A that is both necessary and sufficient. We may represent these laws with the help of a double arrow: $A \leftrightarrow C$ is defined as the conjunction $(A \rightarrow C)$ & $(C \rightarrow A)$. It can be read as 'if and only if', and abbreviated by 'iff'. An example that is familiar to everyone is the law of the pendulum: 'every simple pendulum has the length l if & only if it has the period $t = 2\pi\sqrt{(l/g)}$'. We may apply this law (which is at most an approximation to the truth, as Wilson 1993, note 7, observes) to obtain a pendulum with the period t, since each period t is associated with a unique length $l = t^2 g/4\pi^2$. It is doubtless more natural to say that the length l of the pendulum is 'a cause' of the period t than vice versa, because the length is so much more easily taken care of than is the period. It would nonetheless be an interesting exercise in mechanical design to arrange for the period of a pendulum to determine its length (Wilson *op. cit.*, pp. 58f.).

I should mention that there is a trivial way in which we may turn any conditional sentence into a biconditional: $\forall y\,(Ay \rightarrow Cy)$ is equivalent to $\forall y\,(Ay \leftrightarrow (Ay\ \&\ Cy))$. In other words, all asses are curmudgeonly if & only if the set of asses and the set of curmudgeonly asses coincide. I trust that it is obvious that such a reformulation serves no technological purpose.

There is no other sense in which we can apply the law of the pendulum directly to technological problems; it seems that, eventually, José Arcadio Buendía realized this (García Márquez 1967/1972, p. 79; that is, near the end of the chapter that begins 'The new house, white like a dove, . . . '). If he imagined that the pendulum was a perpetuum mobile that could provide unlimited work, then he was wrong in more than one way about the potentialities of the law of the pendulum.

3.2 Life

In conclusion it must be acknowledged that there are some causal laws $\forall y\,(Ay \rightarrow Cy)$, in biology, cosmology, and other historical sciences, in which what takes place at a certain time is necessary, but insufficient, for something that takes place at a later time; that is to say, the consequent C, which is a necessary condition for the outcome A, is temporally antecedent to A. Until the invention of artificial insemination, sexual intercourse was necessary for conception. Couples who wished to have children knew well enough what they had to do. The usual problem was not ignorance of the *modus operandi*, but its fallibility. In the same way, if you wish to enjoy a noble oak tree in your garden, it is necessary, but not sufficient, to plant an acorn many years beforehand. If we are careful to avoid any suggestion that nature acts intentionally, we may say that she has already solved, by an extraordinary variety of different methods, the technological problem of the production of new organisms. All that we have to do is to push a button.

These examples do not disturb my thesis one bit. In any case, they do not shed much light on the role of science in technology. I maintain only that such cases are untypical, and that in the majority of the cases of technological interest we are compelled to enlarge our knowledge in order to realize our practical objectives. That is, we have to think of something that we have not thought of before.

Let me repeat something that I said above, that the natural world, like theoretical science, can provide much inspiration for practice. It is the task of the engineer to invent ways of transforming these wild dreams into practical propositions. More than a knowledge of electromagnetic theory is needed for the sending of messages by radio. Since

Daedalus men have wanted to fly like birds, but aviation is a decidedly different business from the flapping of feathered wings. To say that birds and 747s obey the same principles of aeronautics tells us nothing, since stones obey them too.

4 How Science is Used in Technology and Engineering

I have pointed out that the possession of a theory T, and of a description C of a future state of the world, gives us no clue to any initial condition A such that the law $\forall y\,(Ay \rightarrow Cy)$ is amongst the consequences of T. Yet if the theory T implies $\forall y\,(Ay \rightarrow Cy)$, then T, together with the negation $\neg C$ of C, does imply the negation $\neg A$ of the antecedent A. The rule of inference here used, which permits the conclusion $\neg A$ of the antecedent A from the premises $\forall y\,(Ay \rightarrow Cy)$ and $\neg C$, is known as the rule of *modus tollendo tollens*. Its significance for our problem is tremendous.

If we know that our objective C was not achieved on an occasion when we made the intervention A, then we may conclude from $\neg C$, without further ado, that A, as a means of achieving C, is a failure. We may not conclude that a way to achieve C is to do $\neg A$ (or to omit doing A).

In circumstances where we are in possession of a theory T that implies the conditional $\forall y\,(Ay \rightarrow Cy)$, we need not implement A in order to find out whether or not C occurs when A occurs. And more generally, in order to determine whether A is a useful step, it suffices to consider its consequences in the presence of T. If any of these consequences are unacceptable, then again we may discard the intervention A. In other words, the laws and theories of science do not tell us what we should do, but what we should abstain from doing. Science does not prescribe, but it proscribes.

The plain truth is that the engineer or the technologist uses scientific knowledge in order to diagnose, to control, and to eliminate errors in his initiatives, not to generate these initiatives. Science has a critical function, not a constructive one.

4.0 Scientific Analysis of Technological Problems

The above job-description of theoretical science in technology as critical and interdictive is accurate even in those cases where a scientific analysis is able throw light on a practical problem before any solution is in sight. A microbiological investigation of the common cold, for example, shows that the affliction is viral rather than bacterial, which suggests (though it may not imply) that the administration of antibiotics is not a potential cure. A substantial class of possible solutions can accordingly be excluded simultaneously. Similar considerations hold for many other examples in medicine. An analysis of the hidden causes of the gross symptoms of a disease does not itself reveal a possible cure (unless the cure is already known in another context) but it may indicate that many lines of attack are not worth pursuing.

4.1 Technology Contrasted with Engineering

At the beginning of this lecture I suggested a distinction between engineering, whose job is to resolve a problem that is more or less unique or *sui generis*, and technology, whose job is to resolve, in a uniform manner, a multitude of similar problems. In this terminology, which is adopted solely for convenience, the engineer designs and constructs suspension bridges and linear accelerators, and the technologist designs and manufactures medicines, computers, pistols, and liquidizers. The technologist has to design and construct a device that tackles the practical problem adequately, test the device, and prepare a guide or manual (which should consist of instructions that can in principle be followed automatically) for its use. In sum, the technologist produces a new kind of physical object, and formulates in universal terms an empirical law (a technological generalization) outlining the details of its operation. The only universal aspect of an engineering project may, in contrast, be a quasi-temporal universality. Once a functioning artefact has been developed, however, we can try to formulate appropriate empirical laws, and one day even to give a scientific explanation of how it functions.

In these terms, pharmacology is a branch of theoretical science, pharmacy is a branch of technology, but medicine, surgery especially, is a branch of engineering.

4.2 Scientific Explanation of Technological Success

The task of integrating into theoretical science an empirical law that describes the operation of an invention is seldom urgent, and it may not be fully accomplished for many years. An amusing illustration is provided by the marvellous article 'A Stress Analysis of a Strapless Evening Gown' (Siem 1956), which was published many years after the design and successful production of the first gown in this style. Another pretty example of 'a technological solution that defies current scientific understanding . . . ' (Basalla *op. cit.*, p. 28; see also Boon 2006, § 3.1) was volunteered by Sir Alexander Fleming in 1954 in reply to a request for an effective cure for the common cold: 'A good gulp of hot whisky at bedtime — it's not very scientific, but it helps.' There is an abundance of more important examples, for instance the mechanism by which aluminium hydroxide, when used as a pharmaceutical coadjuvant in certain vaccines, contributes to the production of a large quantity of antibodies (Bhattacharya 2008).

5 Why Is This Not Well Known?

In 1935 Karl Popper remarked that 'the more a statement forbids, the more it says about the world of experience' (1959, § 35). That is, the restrictive power of a law or theory is a measure of its content (and interest). In (1944), § 20, he wrote that

> every natural law can be expressed by asserting that *such and such a thing cannot happen*; that is to say, by a sentence in the form of the proverb: 'You can't carry water in a sieve.' For example, the law of conservation of energy can be expressed by: 'You cannot build a perpetual motion machine'; and that of entropy by: 'You cannot build a machine which is a hundred per cent efficient.' This way of formulating natural laws is one which makes their technological significance obvious and it may therefore be called the '*technological form*' of a natural law.

The doctrine that scientific laws have an exclusively negative force is therefore hardly a new one. Nobody, however, seems to appreciate how far-reaching this doctrine is. Popper himself went into reverse when, immediately before the passage quoted above with approval, he said that 'it is one of the most characteristic tasks of any technology to *point out what cannot be achieved*' (*loc. cit.*). And in his later years, when he discussed the so-called 'pragmatic problem of induction', he spoke time and again (as do almost all other philosophers) of scientific theories as a 'basis for action' (1972, Chapter 1, § 9). It is science whose characteristic task is to point out what cannot be achieved. The characteristic task of technology is to point out (by example) what can be achieved.

It seems to me that we can find four explanations of this general incomprehension; one is historical, one is psychological, one is sociological, and one is philosophical.

5.0 The History of Technology

The explanation that I call historical derives from the logical fact that in the most familiar cases the use of scientific laws and theories to exclude a technological proposal is never essential. In its place it is always possible to test the proposal empirically, in the way that a tailor works on a suit. If you believe that a sieve can be used to carry water, try to do it. There is no need for any prohibitive law to tell us to throw the idea out. In the past century, however, theoretical methods of criticism have become advisable, and in many cases unavoidable, because of the growing cost and the growing risk of direct tests. Years ago matters were different. A study of the history of the interaction of science and technology, emphasizing its critical dimension, would be most valuable. Like other writers, Basalla has noticed that '[b]efore the Renaissance, and for several centuries thereafter, technological advances were achieved without the help of scientific knowledge' (*op. cit.*, p. 102). Like those others, he omits to offer the simple explanation that, in earlier times, the task of elimination was more straightforwardly carried out by means of an empirical test than by means of a theoretical analysis.

I suggest that, for the great part of its history, technology learnt little from science, and that the traffic was mostly in the opposite direction; for example, in the design of laboratory equipment. Basalla is keen to investigate 'the nature of the interaction of science and technology' (*op. cit.*, p. 92), but at no point does he give his readers the details of any scientific action. Concerning the work of Newcomen, who was mentioned above, he writes: 'There is very little in Papin's apparatus that could have served as a guide to the English inventor as he contemplated the making of an atmospheric steam engine' (*op. cit.*, p. 95). The statement that 'science dictates the limits of physical possibility of an artifact, but it does not prescribe the final form of the artifact; . . . ' (*op. cit.*, p. 92) pleases me, but I do not know whether what is referred to is a physical proscription or a theoretical one. No doubt 'Ohm's law did not dictate the shape and details of Edison's lighting system' (*loc. cit.*), yet it is not to be doubted either that the world that is described by this law did dictate 'limits of physical possibility'. It is another question to what extent Edison's imaginative lucubrations were revised or refined by intellectual contemplation of Ohm's law.

In this way the critical potential of science, like the critical potential of mathematics, has been rendered almost invisible. The myth that science is more basic than technology has been insidiously strengthened, with the inevitable outcome that science receives all the credit for the instrumental successes of technology (and is held responsible for its failures and its horrors).

5.1 Repression

Another explanation of the anonymity of the negative influence of science is based on our propensity to consider the perpetration of errors not as an essential component of learning, but as something to be ashamed of. In consequence, when we have at last achieved an intellectual or practical goal, we are eager to forget how many mistakes we made on the way. 'It is so obvious', we tell ourselves, and we do not remember the difficulties that we experienced previously. It may be that we can explain scientifically or theoretically the content of our success, and we think wrongly that we can therefore explain its discovery in the same way. This aversion to errors is itself a grave error, even if it is a natural one.

5.2 The Scientist Today

A third explanation of the misunderstanding of the way in which science is applied is that nowadays the majority of those who are called scientists, even in universities, are disguised technologists or engineers. They take part in an activity that Thomas Kuhn called *normal science* (1962, Chapter 3); not in the development of new theories, but in the resolution of puzzles, and in the extension of the explanatory empire of the theories that are current. When we read in a newspaper that scientists have made an advance, for example in the treatment of cancer, we may be sure that the discovery is in reality a technological invention. The same confusion is evident in the phrase 'science fiction'. There can be no doubt that this literary genre ought to be called technology fiction or engineering fiction.

Here is an example that is more comical than profound. 'Scientists make an egg that tells you it's ready' screamed a headline on page 3 of the July 31, 2006, edition of the daily paper *Metro*, which is distributed free of charge in public transport throughout Great Britain. According to the journalist John Higginson, the trick is to use a dye that is sensitive in an appropriate way to the temperature, and changes when the egg is cooked.

To be fair, and to show that the distinction between science and engineering is not totally smudged, I should mention some other relevant news in the same edition of *Metro*.

(a) An item (p. 9) in a section entitled *Today's Science and Discovery in Brief* reports, a propos of the eternally fascinating Harry Potter, that '[e]ngineers are working on a shield that makes things invisible by bending light'. (It adds reassuringly that '[a]n object would still exist but it would be hidden from view . . . '.)

(b) Another column, called *Mythtakes* (p. 19) rebuts 'the myth' that a coin left overnight in Coca-Cola® 'will melt'. 'And the way to dispel it? Simply try it. Nope, doesn't work, does it? For those of a scientific disposition, Coke does contain both citric and phosphoric acids, but the acid content is nowhere near strong enough to dissolve a coin overnight.' It is disappointing that *Metro* makes no connexion between this revelation and the background information provided in the story about eggs that 'if a raw egg is submerged in vinegar for three days the shell will dissolve'.

This popular usage of the term 'scientist' may well be an effect as much as a cause of the misunderstanding of the relation between explanatory science and technology. Bad habits often flourish in pairs.

5.3 Inductivism

In conclusion, let me turn for a moment to the philosophical doctrine that is at the bottom of all these mistaken ideas, the ancient doctrine of *induction*.

I have explained above that what sustains the idea that theoretical science has a positive influence on technology is the misapprehension that it is possible to infer causes from effects. I emphasized that, if we possess a theory T and a potential effect C, then the identification of a useful sentence A such that T implies $\forall y\,(Ay \rightarrow Cy)$ is a task that is beyond the scope of deductive logic. Does this dead end not provide a motive for strengthening our arsenal of logical rules?

This is the fairy land of inductive logic, as it is called. Aristotle was the first to invoke a process that explains how we can rationally obtain universal scientific laws from our fragmentary experiences. Neither Aristotle, however, nor any of his successors, has yet been able to formulate a single general rule that does not assume as given what is not given, but is brazenly conjectural.

The dream of rules for inferring universal laws from brute facts, and rules for inferring causes from effects, is realized in statistics in the theory of *inverse inference*, as it is known; that is, a technique for inferring the composition of a population from the composition of a sample drawn from it. But unfortunately for their patrons, all these inference procedures seem to amount to little more than conjectures or guesses about the unknown state of the world. That is indeed to describe the matter precisely: they are nothing more than conjectures or guesses about the unknown state of the world.

Good. We owe to Karl Popper (1959, 1963) the liberating vision of science as an enterprise of acute conjectures and blunt refutations. For sixty years Popper stressed that what endows our investigations with rationality is not the security of their results, which is patently a treacherous security, but the accessibility of these results to criticism. Engineers know well, better than do others, that nothing is secure, although many things are safe, and that we cannot do more than persevere in the detailed scrutiny of our productions and our interventions.

Inductivism maintains that science emerges out of experience, and is based firmly on experience. This doctrine is, for logical reasons, mistaken. As Popper affirmed with great vigour: the principal function of experience in science is to eliminate mistakes. Our hypotheses are required to face the tribunal of experience, and those that are in conflict with experience are abandoned. Inductivism maintains also that technology emerges out of science, and is based firmly on science. This doctrine is also mistaken. The principal function of science in technology is again to eliminate mistakes. Neither experience in science, nor science in technology, can determine that a problem has been solved in an ideal way. The best that they can tell us is that we could have done worse.

These two doctrines of inductivism are expressions of superficial and dangerously misleading prejudices. I suggest that we abandon them.

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