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**ARTIGOS – ARTICLES**

# Putting Science to Work[1]

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**Abstract:** Although it is incontrovertible that there is an intimate relation between theoretical science and technological progress, the relation is persistently misrepresented. What is especially poorly understood is how indirect is the application in technology and engineering of scientific laws. This is not to diminish the importance of the 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.

**Keywords:** Theoretical Science. Technological progress. Applied Science.

**Resumo:** Embora seja incontestável que existe uma relação íntima entre a ciência teórica e o progresso tecnológico, a relação é persistentemente deturpada. O que é especialmente mal compreendido é quão indireta é a aplicação em tecnologia e engenharia de leis científicas. Isso não é diminuir a importância da ciência básica, mas situá-la corretamente. Permite-nos também identificar o sentido em que a tecnologia é uma aplicação da ciência, e explicar como ela participa plenamente de sua racionalidade.

**Palavras-chave:** Ciência teórica. Progresso tecnológico. Ciência aplicada.

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[1] This paper began as the inaugural lecture, given in Spanish under the title 'Haciendo trabajar a la ciencia', of a weekly seminar organized by Professor Alexánder Gómez Mejía in the Faculty of Engineering of the Universidad Nacional de Colombia (Bogotá) in the second semester of 2006. The lecture has been repeated, enlarged, and varied, on many subsequent occasions, usually in English, and for fifteen years it has been my party piece. It has never been published before. This final version contains many substantial variations and additions.

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## 0 Introduction

The question of how theoretical science, and similar disinterested activities, have an influence on technology, and similar practical and directed activities, continues to be a topical one. Governments, in particular, confronted by the soaring cost of scientific research, insist more and more that, in order to receive financial support, a scientific project (and in the United Kingdom, even a project in the humanities) must outline in advance how the anticipated results of the research will contribute to the economic reinvigoration of the nation; the application for funding must promise an *impact*, or what the British Academy chastely calls a *public value* (Roberts 2010, p.2). Most thoughtful scientists think, correctly, that this is a risible policy, since no one can foresee the outcome of any piece of research that is worth undertaking. I believe, however, that the impossibility of enunciating today what we shall not know until tomorrow is not the only obstacle to seeing how future scientific discoveries may applied in practice. In this paper I wish to explain those simple logical considerations that show that, contrary to popular opinion, there is no routine procedure or set of procedures by which scientific laws, however well articulated and understood, can be applied directly to the solution of outstanding technological problems. In other words, even if we could predict accurately what we are going to discover, we should still not be able to predict whether it will be of practical utility. Political orthodoxy on the prospects of research is at least two steps away from the truth.

## 1 Basic Sciences and Applied Sciences

Everyone can, I hope, provisionally agree at the outset with the following simple characterizations of the difference between the basic sciences and technology and engineering:

In science we investigate … reality; in technology we create a reality according to our design which has been proposed by the philosopher Henryk Skolimowski (1966, p.374), and Technology, unlike science, is not concerned with things as they are but with things as they might be which has been proposed by the Canadian political scientist Jack Grove (1989, p.46). In dwelling on this difference, I do not deny that science and technology also have a good deal in common. Like most other human activities, such as politics, marriage, football, and so on, science and technology are devoted to the solution of problems; and the similar manner in which they go about solving problems, sometimes loosely called *the scientific method*, is doubtless what led C.P. Snow to describe as 'untenable the distinction … between pure science and technology. If you actually see someone design an aircraft,' he wrote (1964, §3) 'you find him going through the same experience — aesthetic, intellectual, moral as though he were setting up an experiment in particle physics.' I concede that the attitudes of an engineer and of a scientist, especially an experimentalist, may be similar, but their aims differ, as the quoted passages from Skolimowski and Grove indicate: a scientist, especially a theoretician, endeavours for the most part to answer the question *why?*, while a technologist or engineer endeavours to answer the question *how?*. In §4.0 below I shall point out an aspect of technology that experimental science does not share.

Nor do I deny that science and technology continuously interact. Every time a technological project is successful, more reality is created for science to investigate; or in Grove's words, *things as they might be* turn into *things as they are*. On this point see §5.2 below. In the other direction, every promising scientific theory calls for experimental or observational tests, which in the modern era often require a wealth of specially designed and constructed equipment. Some fields of contemporary science would indeed hardly exist as empirical disciplines without enormously costly and enormously sophisticated technical apparatus. It is enough to think of astronomical observatories and particle accelerators; of the search outside the solar system for signs of life, and of the search at CERN for the Higgs boson. But what is of concern here is not this rather mundane sense in which science leads to technological advance, since almost all human activities are at times customers seeking technological assistance. No doubt bibliophily and golf contribute to technology by supplying it with problems. What is much more in need of discussion is the question of whether science, especially theoretical science, ever supplies technology with solutions.

My thesis is that it does not do this and that it cannot be expected to do this. Science and technology pose problems for each other, as just noted, but otherwise each of them promotes the advance of the other only indirectly. Technology facilitates those experimental tests that lead to the elimination of false theories, and in this way it does science, which is more than anything else a search for the truth about the empirical world, a mighty favour. What I shall suggest is that science does technology a similarly mighty favour, which is similarly indirect, by eliminating from serious consideration many proposals that would otherwise have to be tested laboriously in practice. But it does not do more than this, even in the modern world in which the involvement of theoretical science in technology is ubiquitous and incontestable (see the closing remarks in §2.4 below).

Despite my sense that the influence of the basic sciences on technology is almost universally misunderstood, to the detriment of technology, I have no wish to depreciate the practical value of the basic sciences. I hope that what follows will cast a more flattering (and more truthful) light both on the basic sciences and on their application in practice.

I ought to say that I eye the expression 'basic sciences', and especially the expression 'applied sciences', with much disquiet. They suggest something that I deny, that science precedes technology logically and temporally, and that the applied scientist, engineer, or technologist applies science in the way that we all apply the products of technology; for example, the way in which we apply a corkscrew to open a bottle of wine, or an implementation of a word-processing program to format the text that has been entered at the keyboard. If only it were so straightforward! Even I could be an engineer in such a world. I hope to show that the situation is markedly different. I shall accordingly prefer the expressions 'theoretical sciences' and 'explanatory sciences', or, when there is no danger of confusion, simply 'science', and I shall henceforth avoid the expression 'applied sciences' altogether. An effective distinction between 'engineering' and 'technology' will be introduced in §5.1 below. For the time being the two words should be understood to be completely interchangeable.

## 2 Science and Technology Disconnected

In this section I shall present three considerations that call into question the logical and temporal precedence of theoretical science over technology. One is simple-minded and zoological, the second is informal and commonplace, and the third draws on the history of science. In the next section I shall present a fourth consideration, the most eloquent of them all, which consists of a simple but telling inspection of the logical form of scientific theories. The first two considerations (§2.0, §2.1) indicate that scientific knowledge is not necessary for technology; the third and fourth (§2.2f., §3) indicate that it is often not sufficient.

## 2.0 Animal Technology

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. New Caledonian crows and primates of several species use tools such as sticks and stones in order to reach otherwise inaccessible scraps of food. More recent examples include veined octopuses, who have been observed collecting coconut shells discarded by humans and assembling them into shelters (Finn, Tregenza, & Norman 2009), and grass-cutting ants, who are able to employ a variety of materials to construct the porous turrets that ventilate their underground cities (Cosarinsky & Roces 2012). All these creatures work hard to adjust the world to their needs. They are engineers, but they are not scientists.

It seems to be generally agreed 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). The conclusion (stated but not explicitly endorsed by Basalla *loc.cit.*) that 'no technology whatsoever is required to meet animal needs' is, however, palpably incorrect.

## 2.1 Everyday Technology

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, sadly, it often fails to reach Skolimowski'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 is true for farming, bee-keeping, animal husbandry, metal-working, and other branches of technology that emerged long before the dawn of theoretical science.

Another example 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 at all essential. We should 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 the course made his students into 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 were applying any chemical theory.

According to Hatfield (1948, p.59): '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 the steam engine, and Viking ships, whose 'lines … can hardly be improved upon today'. The production of silver in ancient Athens is another striking example of elaborate and far-reaching technology unilluminated by theoretical knowledge (Rihll & Tucker 2002, especially §§5f.). In all these cases, the paucity of relevant scientific theories anyway obliged the inventors to proceed without theoretical help, but there are more forceful examples of independence from science. Writing in 1948, Hatfield cited '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). Meyers (2007) documents a huge number of advances in modern medicine that did not emerge directly out of science. The early telescope was not a byproduct of geometrical optics, whose study advanced rapidly in the 17th century, but the outcome of experimentation with spectacle lenses by opticians (such as Lipperhey) who were not theoreticians (van Helden & al 2010). Most of the improvements in the design of the telescope were the result of work by lens grinders and instrument makers, rather than of theoretical considerations. Indeed, some of the innovations that were nurtured by scientific work, such as Newton's reflecting telescope, were rather unsuccessful. In short (Basalla, *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.'

### 2.2 Atomic Energy

There are several examples in the history of science of distinguished scientists who had thoroughly mistaken ideas concerning the practical potentialities of the physical phenomena brought to light by the theories that they had created. Lord Kelvin [William Thomson] and Lord Rayleigh, who independently made significant contributions to the science of fluid mechanics, 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. He was undoubtedly aware of the immense amount of energy that may be stored in atomic nuclei. In 1933, nonetheless, he stated publicly on several occasions that '[a]ny one who expects a source of power from the transformation of these atoms is talking moonshine'. This opinion has been reported by several authors, including Jungk (1958, p.49), DeGroot (2004, p.11), Zahar (2007, p.20) and Pasternak (2012, p.92). Jenkin (2011) has raised some doubts about the extent of Rutherford's scepticism. Calling it 'the only major bloomer in scientific judgement Rutherford ever made', Snow (1969, p.33) added that '[i]t is interesting that it should be at the point where pure science turned into applied'. Snow's remark may be contrasted with his repudiation some four years later (quoted and contested in §1 above) of any solid distinction between scientific practice and technological practice. It is perhaps equally 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 Bohr once said 'Rutherford is not a clever man; he is a great man' (Crowther & Whiddington 1947, p.122). Yet this great man, notwithstanding his intuitive understanding of how the world works, could not imagine a way of setting free the energy stored within the atom.

Rutherford was not isolated in his scepticism. Although Soddy had intimated as early as 1904 that a man who found a technique for liberating and controlling the energy in the atom 'would possess a weapon by which he could destroy the earth if he chose', he did not believe that any such technique would be found (Rhodes 1995, p.44). According to the Nobel laureate Igor Tamm, '[a]t the beginning of the 1930s everyone considered nuclear physics to be a subject having absolutely no relation to practice or technology' (Holloway 1994, p.36). Einstein's doubts about the military exploitation of his famous equation $E=mc^2$ varied from incuriosity and detachment in 1905 (Calaprice 2011, p.281) to dismissiveness in 1919 (Frank 1948, pp.211f.) to amusement (Rhodes *op.cit.*, p.172). In a letter written not long before his death in 1955 he stated bluntly that '[t]here was never even the slightest indication of any potential technological application [of $E=mc^2$]' (Calaprice *op.cit.*, p.284). At the end of World War II he admitted that although he had recognized its theoretical possibility, he had not expected any controlled release of atomic energy to come about during his lifetime (*op.cit.*, p.273) … 'a chain reaction … was not something I could have predicted' (*loc.cit.*).

In the year in which he shared the Nobel Prize for Physics with Clinton Davisson, George Thomson wrote (1937, p.144):

One may sum up the chances of atomic energy as a practical proposition as follows. It is practically certain such energy exists; it is very likely that it is being released on an enormous scale in the stars. It is somewhat doubtful whether suitable material exists in the earth. If it does, it is perhaps not unduly optimistic to suppose that man will some day be able to imitate this most violent of natural processes, and as late as 1940 a group that he chaired advised the British Government that '… it is much better that they [the Americans] should be pressing on with this than that our people should be wasting their time on what is … probably a wild goose chase' (DeGroot *op.cit.,* p.25).

### 2.3 The Steam Engine, Fuel Cells, Vaccines

The individual contributions, at the turn of the eighteenth century, of the British engineer Thomas Newcomen and the French scientist Denis Papin to the invention and development of the steam engine reinforce the view promoted here that the details of technological innovations are to a great extent independent of contemporary scientific knowledge, even when knowledge that looks pertinent is available. According to Basalla (*op.cit.*, 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. … 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.

There are plenty of more recent examples of science's inability to deliver technological goods. According to the engineer Henry Petroski, '[t]he basic science of fuel cells … has been known for over a century, but that has not been at all sufficient to lead the way to mass-producing an efficiently functioning cell' (2010, p.122). Although '[t]he gene that gives rise to cystic fibrosis was discovered several decades ago', no attempt 'to cure sufferers by administering the correct version through relatively straightforward procedures … has so far been successful' (Pasternak 2012, p.34). Viruses (*op.cit.*, pp.52f.) are similarly equivocal. A few years after its identification in the 1980s as an RNA retrovirus, the entire genome of HIV was sequenced …; the function of every protein produced by the virus was elucidated. A scientific tour de force? Analysis proved easier than synthesis. A quarter of a century after the isolation and characterisation of HIV, we still do not have an effective vaccine against it. This illustrates the unpredictability of producing vaccines against infectious microbes. A vaccine against smallpox virus (it happens to be a DNA one) was produced without knowing any of the details of its component DNA or proteins. By 1976 smallpox was virtually eradicated throughout the world. Today 40 million people are infected with HIV ….

## 2.4 Discussion

It is generally supposed that the scientific revolution of the 17th century was a necessary preliminary to the industrial revolution of the 18th century; and that the theories of radioactivity and relativity were no less necessary preliminaries to the building of the atomic bomb. These are just two examples that are often cited to illustrate the doctrine that it is scientific discovery (rather than necessity) that is the mother of invention. Bacon's message that *knowledge is power* has attracted many supporters, and even Popper, who offered the more humane alternative that 'knowledge is something far better than power' (1979, §VI) regarded it as 'undeniable that science has become the basis of technology' (1969, §III). Bacon's rallying cry has recently been repeated by Deutsch (2011, pp.55f.):

Since the Enlightenment, technological progress has depended specifically on the creation of explanatory knowledge. People had dreamed for millennia of flying to the moon, but it was only with the advent of Newton's theories about the behaviour of invisible entities such as forces and momentum that they began to understand what was needed [presumably Deutsch here means 'sufficient' rather than 'necessary'] in order to go there. … The ability to create and use explanatory knowledge gives *people* a power to transform nature which is ultimately not limited by parochial factors, as all other adaptations are, but only by universal laws.

The introductory textbook in the philosophy of science by Ladyman makes much the same claim (2001, p.1): 'It is possible to develop ploughs, wheels, bandages and knives without much in the way of theory, but without the scientific theories and methods developed mainly in the last few hundred years there would be no electronic devices, spacecraft, microsurgery or weapons of mass destruction.' According to the book's back board (for which the author may not be directly responsible), '[f]ew can imagine a world without telephones or televisions; many depend on computers and the Internet as part of daily life. Without scientific theory, these developments would not have been possible.' Unfortunately neither Deutsch nor Ladyman explains what the difference is between contraptions that allegedly could not have emerged in the absence of theory and those that did. Given the remarkable innovations made by Nature in what can be called reproductive technologies (and in all other areas of biology) without the assistance of scientific theory, something more ought to be said. David Dahmen has pointed out to me that the invention of the vacuum tube, which is not a primitive item of equipment, was free of theoretical considerations.Theory is of course required to explain how the vacuum tube works, but initially it was a mystery how it works. That scientific theories are inextricably involved in explaining the workings of our inventions does not imply that were either necessary or sufficient for the invention of those inventions. I do not see why the various sophisticated appliances cited by Ladyman could not have been developed, though much more slowly, by relentless trial and error, in the same way in which bicycles and beer were developed. Basalla (*op.cit.*, p.49) and Michl (2002) have demonstrated the extent to which every new invention is a modification of an earlier one.

The historical thesis that is contested, to various degrees, by many writers apart from myself, for example Hatfield *op.cit.*, Basalla *op.cit.*, Vincenti (1990), and Petroski *op.cit.*, is the thesis that in modern times 'technological progress has depended specifically on the creation of explanatory knowledge' (to use Deutsch's words). The main purpose of the present paper is to do something that, as far as I know, the other writers have not done, which is to give a simple logical explanation of why this historical thesis is false, that is, to explain why scientific knowledge could not have played, and cannot play, the germinal role that is customarily attributed to it. But since it is blindingly obvious that theoretical science is used all the time in contemporary technology, especially in nuclear engineering, in the development of new materials, and in biotechnology, there is an additional obligation to explain, and to evaluate, the role that theoretical science does play. In order to provide these explanations, we must first revisit some elementary logic.

## 3 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 the purposes of the present discussion, it does not matter if we choose examples that are not genuine laws; if there exist magnanimous 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 are satisfied if we can formulate statistical laws that stand up to tests. 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.

## 3.0 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 → (a westerly arrow) that stands for the *conditional* expression 'if … then — ', and a symbol ∀ (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 $\Sigma_{j=0}^{100}\ y_j$ 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 each and every one is 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 asses are magnanimous* as a statement that asserts something about some unspecified element of the domain, that is, that it is both an ass and magnanimous (not curmudgeonly), and write it as $\exists y(Ay \,\&\, \neg\, Cy)$. The symbol ∃ (an upside-down E) is called the *existential quantifier*, and the hook ¬, with which we may represent the opposite not-$C$ of an expression $C$, is called the *negation sign*. It is worth observing that other natural language quantifiers, for example 'most' and '50% of', are not so painlessly accommodated in the formalism. *Most asses are curmudgeonly* is not easily understood to be a statement about most elements of the domain of interpretation.

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 measures $m_x$ and $m_z$ of the masses of $x$ and $z$, divided by the square of the distance $d_{xz}$ between $x$ and $z$; compactly, $\forall x \forall z[(B(x) \,\&\, B(z) \,\&\, x \neq z) \rightarrow f_{xz} = Gm_x m_z / d_{xz}^2]$. 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, $\forall x \forall z[(B(x) \,\&\, B(z) \,\&\, x \neq z) \rightarrow \exists f[F(f) \,\&\, fxz = Gm_x m_z / d_{xz}^2]$. Other formulations, both more explicit and more exact, are possible for the law of gravitation, as well as for other laws. The simplified version given here is quite exact enough for present purposes.

In the conditional $A \rightarrow C$ the formula $A$ is called the *antecedent*, and the formula $C$ is called the *consequent*. In a slight abuse of language, we shall extend this terminology to universal conditionals, calling $Ay$ an antecedent of $\forall y(Ay \rightarrow Cy)$, and $Cy$ the corresponding consequent. Logicians say that, in the presence of a (universal) conditional, the antecedent is a *sufficient condition* for the consequent, and the consequent is a *necessary condition* for the antecedent. Note that the logical force (or meaning) of the conditional $A \rightarrow C$ is different from the logical force of its *converse* $C \rightarrow A$, but is identical with the logical force of its *contrapositive* $\neg C \rightarrow \neg A$. Three rules of logical inference need to be noted. The rule of *modus (ponendo) ponens* permits us to infer $C$ from $A \rightarrow C$ and $A$. The rule of *modus (tollendo) tollens* permits us to infer $\neg A$ from $A \rightarrow C$ and $\neg C$. The rule of *universal instantiation* permits us to infer $Ay$ from $\forall y Ay$, whatever $A$ is, and therefore to infer the conditional $Ay \rightarrow Cy$ from the universal conditional $\forall y(Ay \rightarrow Cy)$. Given a law $\forall y(Ay \rightarrow Cy)$ and an antecedent $Ay$, we may use this rule, and then *modus ponens*, to infer the corresponding consequent $Cy$.

## 3.1 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 are familiar with, 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, without pretension to technological significance, 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: it is sufficient to procure an ass. In contrast nothing in the law suggests a method for procuring an ass. It is hardly sufficient to procure something that is 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.

## 4 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. Stated more explicitly, from the law $\forall y(Ay \rightarrow Cy)$ and a statement of the cause *Ay*, we may infer the effect *Cy*. In practice, however, in a typical situation, what we know, perhaps only roughly, is the effect that we wish to produce, but we know of no cause of that effect. If we are unusually lucky, we may 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 of producing *C* is alread*y* solved, at least in principle. What is more common is that we know of no suitable law. Or it may be that we know only a law whose antecedent we do not know how to implement; in short, we know a cause of the desired effect, but we do not know how to bring that cause about.

## 4.0 The Logical Problem of Technology

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

My central thesis is that scientific knowledge cannot help the engineer or the technologist in this way. The position of the engineer is indeed 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 (which constitutes the available organized knowledge) can provide information about what the painting looks like or what the tune or the poem sounds like. But the catalogue is of only limited use if what is known is what the painting looks like, or how the tune or the poem goes, and what is sought is its name.

It should now be plain why scientific knowledge is almost always 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 $T$ represent our theoretical scientific knowledge, and let $C$ 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 seem to be only two possible ways forward: one is to enumerate the logical consequences of $T$ until there appears an appropriate law of the form $\forall y(Ay \rightarrow Cy)$, and the other is to make a guess at an antecedent $A$ and then to use logical (and mathematical) analysis to find out what $T$ says about the effects of $A$. For well known reasons the first possibility, although mechanizable, does not constitute a sensible task. 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 at all possesses the property $A$. Having a guess, that is, having a bright idea, is the only realistic possibility.

I do not say that in a typical instance our theoretical knowledge $T$ does not imply a suitable empirical generalization $\forall y(Ay \rightarrow Cy)$. On the contrary, a successful invention would not be scientifically explicable — although, as noted in §5.2 below, the workings of many inventions are not explicable — if there were no such true (or approximately true) scientific theories in our possession. What I do say is that it is only in unusual circumstances that science helps us to find an exploitable generalization. I concede also that science (like nature, literature, myth, and even dreams) can provide suggestions for practice. But they are only hints, not blueprints. Atomic theory suggested the presence of a vast store of trapped energy within the atom, but it did not tell us how to administer its release in a disciplined manner. That problem has been solved, but for the same problem regarding the safe use of seismic energy no solution is yet in sight.

We have reached a conclusion that all engineers know full well. *A scientific theory can be applied only when there is something specific to apply it to*, and that specific something $A$ comes from imagination and insight rather than from scientific knowledge. Petroski (*op.cit.*, p.47) sums the matter up perfectly: 'The design of engineering structures is a creative process in the same way that paintings and novels are the products of creative minds. Just as there can be no critical analysis of a work of art until it is at least sketched out, so there can be no scientific discussion of a bridge until there is a specific concept of a bridge laid down.' Similar statements are to be found on p.175 of the same book: 'Until the outlines of a design are set down, however tentatively, there can be no appeal to science …. Imagine wanting to build a bridge across a river. Clearly, Galileo's "two new sciences" are supremely relevant. … But knowing this does not produce a bridge. No matter how complete our knowledge of mechanics, without a geometric arrangement of the parts of the structure we have nothing to which to apply scientific knowledge ….'

In the Kyoto University Museum there is a superb collection of metal mechanical models imported from Germany at the end of the 19th century. One of them illustrates *quick return motion* using a constant (rotational) input to move an object along a fixed horizontal path, and at the end of the journey to return rapidly to its starting point. It is *a purely mechanical device*, using no chemical, elastic, electromagnetic, gravitational, or emotional energy, and a description of how the machine works is therefore derivable, using classical mechanics alone, from a description of how the machine is constructed. How does it work? I have asked several engineers how they would design such a quick return machine — there may be more than one solution to the problem —, and only one of them has been able to give an adequate answer, despite their being well acquainted with classical mechanics. *Knowledge of scientific principles is not enough for their successful application to specific tasks.* The original German model, and a modern animation, can be scrutinized on line at <https://www.museum.kyoto-u.ac.jp/english/materials/quickReturnEng.html> and at <https://www.museum.kyoto-u.ac.jp/english/materials/mech102.gif>.

### 4.1 The Pendulum

A word needs to be said about those laws of physics 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 ($A \rightarrow C$) & ($C \rightarrow A$), which is called a *biconditional*. It can be read as 'if and only if', and abbreviated by 'iff'. Laws that state a functional relation between numerical quantities can be put in the form of a biconditional. Familiar examples are the law of the pendulum $t = 2\pi \sqrt{}(l/g)$, which connects the period $t$ of a simple pendulum with its length $l$; the gas law $pv = RT$, which connects the temperature $T$ of a gas with its pressure $p$ and its volume $v$; and Ohm's law $V = IR$, which connects the potential difference $V$ across a circuit, the current $I$ in the circuit, and the resistance $R$. The law of pendulum may be written as the biconditional 'Every simple pendulum has the length $l$ if & only if it has the period $t = 2\pi \sqrt{}(l/g)$', and similar biconditionals express the other two laws. These laws typically do not have a temporal direction, and are not properly causal. the question arises of whether this allows them to be put to technological use.

It has to be conceded that the law of the pendulum (which is at most an approximation to the truth, as Wilson 1993, note 7, observes) may be applied rather straightforwardly to obtain a pendulum with the period $t$, since each period $t$ is associated with a unique length $l = t^2g/4\pi^2$. That this is an unusual case is made evident by the fact that there is no obvious way to use the law to obtain a pendulum of a desired length. 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, but 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.

### 4.2 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.

## 5 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 *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.

Zahar (*op.cit.*, p.18) has observed that for every scientific law $\forall y(Ay \rightarrow Cy)$ with a known consequent and an unknown antecedent there is an equivalent law, its contrapositive $\forall y(\neg Cy \rightarrow \neg Ay)$, in which matters are reversed: $\neg C$ is known, and $\neg A$ is unknown. But this does not imply that this law $\forall y(\neg Cy \rightarrow \neg Ay)$ can be found any technological employment. Even if our goal were to bring about the unknown outcome $\neg Ay$, implementing $\neg Cy$ would not be a way forward. For one thing, the temporal and instrumental order is wrong: it is not in general true that if $A$ can be used to bring about $C$ then $\neg C$ can be used to bring about $\neg A$. 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.

## 5.0 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.

## 5.1 Technology Contrasted with Engineering

At the beginning of this paper 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.

## 5.2 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).

## 6 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.

## 6.0 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 you 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).

### 6.1 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.

### 6.2 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. There is a similar report on page 3 of the Chilean edition of *Popular Mechanics en Español* for November 2006.

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, apropos 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.

### 6.3 Justificationism

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 that knowledge requires *justification*.

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 justify universal scientific laws by means of 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 justifiability, or 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 justified — shown to be reliable — by 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 justified — shown to be reliable — by science. This doctrine too is mistaken (if only because science is not reliable). 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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