Brit. J. Phil. Sci. 44 (1993), 423–442 *Printed in Great Britain*

Science as Technology

SRDJAN LELAS

ABSTRACT

It is usually believed that science goes with things like *theoria*, 'knowing that', ontology and representing, and that *techne*, know-how, technology and intervening are only instrumental to science or its beneficial but nonetheless accidental side effect. In this context to be instrumental means also to be eliminable, or at least transparent, something that leaves no trace. Following the historical development of experimentation, from simple observation to modern microscopic experiments, I try to show how that view loses its ground. To produce an artefact, scientific or other, is to be engaged in a complex dynamics, both ontological and epistemological in which at least two component processes, that of bringing forth and that of bringing into, are intertwined. The old dictum: 'Science discovers, technology invents', should be replaced by: science discovers because it invents. As a consequence scientific theory becomes an instrument of design.

1 *Introduction*
2 *Science as Ontology*
  2.1 *Theoria*
  2.2 *Observation*
3 *Science and Experiment*
  3.1 *Macroscopic Experiments*
  3.2 *Techne*
4 *Science as Technology*
  4.1 *Microscopic Experiments*
  4.2 *Experiment and Theory*

1 INTRODUCTION

It is traditionally believed that a clear distinction can be drawn between such things as *theoria* and *techne*, 'knowing that' and know-how, ontology and technology, representing and intervening. Science, intuition says, is associated with the former members of each pair. This intuition might be spelled out in the following four theses.

A All scientific knowledge is knowledge that something is the case. Science provides us with a description of the structure of the world, real or phenomenal; it says, literally or metaphorically, of what the world is constituted.

B All know-how is instrumental to scientific knowledge. Scientists must know how to think, calculate, observe and make experiments, but the final outcome of their activity is an independent symbolic representation of the structure of the world (real or phenomenal), in respect to which know-how is an eliminable means.

C Representation is a mental process based on sensory experience, so it is the mental activity which really matters. Making instruments and experimental devices manually is an ancillary exercise; *per se* it has no cognitive value.

D The requirement that theories should be tested through observation and experiment does not make know-how an integral part of the body of knowledge; theory is about the world, not about our testing, that is, not about our interaction with the world.

Most contemporary philosophy of science is still based on this intuition, which also means that it is 'theory oriented' and impregnated by a 'spectator theory of knowledge'. The opposition from some sociologists of knowledge and authors such as R. Rorty, I. Hacking, A. Franklin and P. Galison spreads rather slowly. Caught up in their debates over theories, neither theoretical scientists nor philosophers of science have challenged the intuition or paid due attention to the changes science has undergone in the course of its history. For gradually it has left the ideal of Aristotelian contemplation far behind, has passed through Baconian mechanistic experience and intervention, and has entered a subtle and comprehensive technology of contemporary science. Using ever new apparatuses, science has become so dependent on them that it is appropriate to ask again: What is science about?

In this paper I would like to propose that the reader should consider, in contrast to the previous four theses, the following.

A Science is not only about what is, but also about what can be. What can be is made visible by doing, not by contemplating.

B Know-how is a legitimate, constitutive and indispensable part of scientific knowledge. Science is as genuinely technology as it is ontology.

C The activity of making (producing) is not just relevant for science but is crucial to it. Scientists discover as they implement; implementation has a peculiar and important cognitive role.

D Testing by producing makes know-how an integral part of scientific theory; theory is about making. Creating phenomena in artificial devices, explaining them by hypotheses, testing the hypotheses, and building apparatuses is a single process.

In arguing for these theses I will follow the historical line from the time when science was considered as *theoria* aided by observation (Chapter 2), through the Baconian dicta exemplified in the classical experimental method (Chapter 3), to contemporary experimentation (Chapter 4). *En route* I will offer three main arguments. First, I will argue that the request that scientific theory should be experimentally testable makes theory essentially technological (Section 3.1). The second argument shows that building an experimental apparatus means being engaged in complex cognitive dynamics where knowing that and know-how are intertwined, as is the case with any invention and implementation or an artefact (Section 3.2). The third argument refers to the situation in quantum physics in which theory, in its most basic formulation, cannot avoid reference to experimental arrangements (Section 4.1). Finally, in Section 4.2 I will try to explicate the meaning of my four alternative theses by presenting how I see know-how becoming an integral part of the theoretical structure of science.

2 SCIENCE AS ONTOLOGY

2.1 *Theoria*

Science is usually conceived as an attempt to explain phenomena by justifiably postulating the world 'behind' them, the real world. Science is, therefore, concerned with what exists, or what really exists, or what exists independently and unconditionally; it is ontology.

Since what is behind is hidden, the postulated world must somehow be *brought forth* from concealment into unconcealment, and must *reveal* itself to the scientist or to anybody who wants to take a look and see. In ancient times this mode of revealing was called *theoria*. The word *theoria*, coming from *thea* and *horao*, means, first, the outward appearance, the aspect under which something shows itself, reveals itself, becomes known to whoever takes the appropriate stance toward it. Second, it means that very effort to focus closely on something, to look attentively at a particular outward appearance (Heidegger [1954]). *Theoria* then designates the form of vision which penetrates beyond ordinary sense perception and, due to the power of reason, strips away the veils and allows essences to become visible, *i.e.* present to the mind. According to the ancients, *theoria* is a cognitive contemplation of the hidden eternal unchangeable essences of sensible things or processes in the world; it is the power and the state by which an individual mind is brought into correspondence with hidden reality.

Although *theoria qua* 'vision' has a touch of the mystical in an individual's experience, it is fully verbalizable and objectifiable. The mind is able to externalize experienced essences or the laws of nature it discovers in an independent objectified symbolic and linguistic form. In this century it has been claimed that only then may we speak about truth, or more precisely about truthful description or representation. A representation is truthful if it corresponds to that something which experience is about. The experience, the vision itself and the cognitive subject become accordingly mere mediators which assure and establish the correspondence between linguistic structures and the world and which can be eliminated after the process is completed.

Theoria does not depend on any kind of external action that the cognitive subject might perform. The paradigm view sees the subject as a spectator who can change only the time and place at which (s)he looks at the object, and who can eventually influence accidental and inessential aspects of the object but not its immutable essence. At most, a spectator is allowed to enlarge or augment the capacities and accuracy of her senses, using instruments like a microscope or telescope, so long as their use does not cover rather than reveal the essences of things. All external actions are considered as tricks to aid vision and are dispensable, traceless and purely instrumental, as is vision itself.

In the same vein the orthodox view sees the goal of science as the effort to achieve objective knowledge, that is, a veridical representation of hidden reality. Objective knowledge is considered as 'knowledge without a knowing subject'. Science, therefore, aims at subjectless knowledge, which then requires that, like vision, observation and experimentation should be carried on as purely instrumental, eliminable, traceless activities and interpreted accordingly. This is the crucial requisite; so let us see how far it can be satisfied.

2.2 *Observation*

Observation has been considered a part of *theoria qua* vision although not the most prominent part; it could never compete with reason. Being regarded as veridical, if controlled by reason, it was always welcomed as the provoking agent which starts the internal motion of the mind. Furthermore, as an element of justification, observation enters in as a means of establishing the truth of a claim. Here its role is exhausted when the subject has made the decision to accept or reject the claim in question. Hence the instrumental status of observation seems well entrenched, and supported on good grounds. How correct is this view?

Grosso modo observation in science follows the scheme of visual observation which is the application of various kinds of radiation to objects in order to extract information about them from reflected, refracted or re-emitted—in a word, transformed—radiation. An observation then consists of: (1) a source of radiation, (2) incident radiation, (3) an object interacting with it, (4) transformed radiation and (5) a receptor. There are two crucial interactions here: between the incident radiation and the object, and between the transformed radiation and the receptor. They are completely separate, and whatever happens to the receptor has no influence on the first interaction. In this sense all observations are objective.

However, the essence of observation is the reconstruction of the object from the effects which the first interaction leaves on the transformed radiation and the second brings about. This is the task of our nervous system, of which a receptor is an integral part. Since receptors interact with transformed radiation and not with objects, i.e. with the messenger and not with the source of the message, reconstruction is essentially *interpretation*. Therefore, what we see in an everyday situation is an interpretation which has been developed and embodied through the long course of organic evolution and which is shaped by definite biological and cultural constraints. It serves its purpose, the survival of the species, even if it is not as veridical as a naive realist would like it to be. It was believed that, when completed with appropriate reasoning, it could serve science equally well or even better.

But modern science has gone far beyond everyday situations. As soon as it was discovered that in transformed radiation there is more information than naked human eyes can capture, scientists tried to extract it by aiding, extending, correcting and supplementing the eye by instruments, *i.e.* by technical devices. Technical devices acting as scientific instruments are human artefacts and they differ from other artefacts only in their purpose, and in the requirements which the purpose imposes upon their construction. In short, besides correcting and stabilizing human sensory input, they aim to bring about something that our senses alone cannot detect, something that is not part of the sensory input to which we are biologically attuned. Furthermore, to observe, with or without instruments, means to bring an object or an event into the foreground, to make it manifest to our attentive inquisitive minds whenever they concentrate upon, or take a closer look at, it. However, during the process of attending, part of the information reaching the senses is passed over as noise or pushed into the background as unimportant. Similarly, in an instrument of observation what passes from concealment into unconcealment is selected and moulded according to the purpose.

In securing this passage, scientific instruments, such as a microscope or a telescope, take light that has already been altered by the object and transform it once again from whatever it was into an optic array visible to the naked eye. Bacon speaks of 'evoking' devices which 'reduce the nonsensible to the sensible', that is, make manifest things not directly perceptible, by means of others which are' [Bacon, *Novum Organum* Secs. xxi–lii]. Instruments of observation do not interfere with the object; they 'work', so to speak, on transformed radiation making visible what is hidden *not in the object but in the messenger*. What goes on in them is pure information flow materialized in radiation.

This leaves an impression that scientific instruments of this kind are intermediaries as good as light is in everyday situations, in spite of their purposiveness. They refine and extend human senses, changing neither the senses nor the object observed. Using Pierce and Rorty's expression, one might claim that instruments of observation have a 'glassy essence'. So Ackerman [1985] says: 'Instruments, like eye glasses, are used to see things, but they need not be noticed (unless they malfunction or break) once what is seen through their use takes on independent existence' (p. 132). To be unnoticed, as light is by the eye, means also to leave no trace of oneself on the final interpretation, notwithstanding the fact that what counts as transparent in this context is historically and culturally constrained.

Space permits discussion neither of the species relativism of unaided observation nor of the cultural determination of the transparency of an instrument. I put these important issues aside because, instead of discussing what has been discussed so many times, I would prefer to add one more item to the same story.

In science nowadays simple instruments are history. There have been changes in all elements of observation, some of them more interesting than others. Firstly, the source of radiation is often artificial. If the source does not radiate visible light but another part of the electromagnetic spectrum, or even if it radiates a totally different kind of radiation, as in solar neutrino experiments, or we use a nonstandard aspect of radiation, like polarization, all we need is an additional interpretation. Only for ordinary ambient light and for some natural sources of the visible spectrum are we equipped with a natural interpretation built into our nervous system. Nonstandard sources introduce a whole host of problems but do not make the situation essentially different.

Secondly, the invisible part of the spectrum, and features other than intensity and wavelength, also need 'appropriate' (Shapere [1982]) artificial receptors. A receptor is appropriate and so is the whole instrument, if it transforms information carried by invisible radiation into information embodied in a 'humanly accessible' form of a visible effect *with minimal loss, distortion or addition to the original information*. Of course, the requirement that the final information has to be embodied in a humanly accessible form imposes definite constraints upon instruments and receptors, and ties the concept of scientific observation to human beings. This is probably all right for most of us, since there would be no sense in speaking about an observation which is not the observation of a definite observer.

Thirdly, an object usually has to be prepared for observation. Such an operation raises the question of the difference between observation and experiment which we shall try to answer in the next section.

Now, to transform the invisible into the visible and to make a contrast between a phenomenon and its background requires skill, both mental and physical: mental when we focus our attention and engage our abilities to recognize an object or event, and physical when an instrument is built according to definite requirements such as those expressed in phrases like '*clare et distincte*' or 'with minimal loss, distortion or addition'. Instrument builders and users must find the way to detect idiosyncrasies of the instrument, to recapture losses if possible, to eliminate additions, *i.e.* artefacts of the instrument, and to correct distortions, or at least to compensate for them or subtract them from the result. Before instruments of observation become transparent and unnoticeable they must be treated as technological objects, and that involves skill.

Ackerman [1985], therefore, is on the wrong track in trying to draw a sharp distinction between technological and scientific artefacts when he says: 'In technology and special skills such as cookie baking or horse breeding, an activity will be extended and refined. In science, it is our pure sensory apparatus that is extended and refined' (p. 127). Instrumentally aided observation mixes *theoria* with *techne*, vision with know-how, observation with engineering, although the important intervention concerns only radiation and not the object itself.

The ideas of an instrument's 'glassy essence', of the veracity of observation and of the objectivity of science rest upon the way instrument builders meet the requirements of securing clear and distinct phenomena and of minimal loss, addition or distortion. Consequently the important philosophical notion of objectivity as subjectlessness sinks into the depths of something called 'skill', into the realm of tacit knowledge, of know-how which is not always verbalizable. If this is so with observation, we should expect it to be even more so with experiment.

3 SCIENCE AND EXPERIMENT

3.1 *Macroscopic Experiment*

Modern science, particularly physics, was developed in opposition to Aristotle. This opposition did not only consist in its favouring a different picture of the world and in the new mathematical language. What Galileo, Bacon and Newton also felt is that the traditional contemplative approach on which Aristotelian common-sense physics was based has exhausted its potential and should be replaced by a more active experimental strategy. After all, it seemed that what could be seen with the naked eye and a few accessories guided by reason had been accounted for many times. Aristotle systematized most of it. In order to gain new knowledge about nature, it was felt, humans must interact with it because, as Bacon says, 'the nature of things betrays more readily under the vexations of art than in its natural freedom'. Science should become experimental, which means that nature must be agitated, challenged, cunningly induced and provoked to deliver its secrets. Furthermore, truth should be established by empirically testing scientific claims through action and work, not only through verbal disputes. Works, again says Bacon 'themselves are of greater value as pledges of truth than as contributing to the comforts of life'.

This aspect of 'scientific revolution' marks also the difference between observation and experiment. For something to be called observation, as described in the previous section, it is essential that the entire intervention is restricted to radiation, and that the object observed is not modified during its application. Even if the sample has been prepared, which is often the case, the energy transfer involved is not accounted for since the preparation is done before radiation has been applied. The whole energy flow is not the matter of concern; what does matter is information about the sample's structure.

Experiments, on the other hand, involve intervention in the object's dynamics. The flow of energy is the focus of interest, and the information extracted is about energy generation and redistribution. Following this line, J. C. Maxwell [1876] provided a general schema for classical macroscopic experiments. An experimental set-up consists of apparatuses performing three kinds of roles. First, an apparatus or a part of it is a source of energy; second, there are apparatuses or parts that function as transporters and distributors of energy (force is in fact a transfer of energy from one entity to another); and third, there must be in the arrangement apparatuses that highlight information, i.e. registering and measuring the effects of energy transfer. What flows from the source, through objects, to registering instruments is energy or matter or both, and what instruments monitor is a real substantial physical dynamics provoked and controlled by human action. The series of macroscopic, i.e. easily visible and thereby controllable, transmissions of energies (forces) from one set of elements that compose the system to another is elicited, and their course is followed with the help of pre-established conditions and arrangements.

The energy is supposed to flow in a law-like manner, part of it being stored and part dissipated. The flow is followed through its effects, which consist mostly of macroscopic motions, e.g. displacements of parts of the system over macroscopic distances, registered by instruments. This is the way classical experiments provide an informational outcome from which laws can be discerned. Laws of nature play in modern physics a role similar to that of essences in the ancient world picture, *i.e.* that of the immutable, eternal, inner scaffolding of the world. In classical macroscopic experiments what is 'brought-forth into unconcealment' is not the essential *eidos* of beings in a static hierarchical order, but the rules under which beings are engaged in ceaseless dynamics. In the artificial set-up described by Maxwell almost everything can be arranged and rearranged, but the laws exhibited or discerned cannot be changed, only followed.

Now, how is one going to interpret what physicists are doing when conducting classical experiments? The whole idea of experimentation is to investigate nature by putting it on trial, by forcing it to behave in a new, induced way so that hidden properties not visible in its 'natural' spontaneous behaviour may be discovered. The experimenter does this by tricks or cunning interventions, by setting appropriate conditions under which the internal working of nature might be forced into view. Because of that, the phenomenon contrasted with the background observations might be called 'an effect'. It is the experimenter who makes it manifest by provoking nature through intentional manipulation, and by setting a specific context; in short, by causing.

On the other hand one might say that the experimenter intervenes only in order to push impertinent elements of the situation into the background, to strip off inessential, irrelevant aspects from the phenomenon and to dampen down ineliminable surrounding noise. Simply put, an experimenter *purifies* and *simplifies* 'the ecological system' in which the phenomenon then *spontaneously* appears, in such a way that the contrast between it and the environment become sharp enough for clear description and understanding. He has to do this in a stable and reproducible way so that others can repeat the experiment. Thereby the independence of the experimental set-up from any particular experimenter, and from any particular place and time, is assured.

Although both of the above accounts are given in Baconian terms, classical macroscopic experiments are usually understood as being closer to the latter, that is, in a manner that follows almost exactly Heidegger's description of the essence of—surprisingly enough—*ancient technology* (Heidegger [1954]). With a slight simplification, this essence might be expressed by the metaphor of a midwife. Since in scientific experiments special care is always taken to ensure that we are dealing with genuine natural phenomena, that is with phenomena which in principle could happen spontaneously in nature albeit in somewhat 'impure' and complex circumstances, the experimenter can be seen as somebody who sets himself the modest task of removing obstacles, and setting free something to pass into 'full arrival' in circumstances controlled by him, as a baby is delivered under the midwife's care. The midwife's care ensures that what is already there, ready to be born, comes in its full appearance, and this is done by gentle stimulation, by removing impediments and by purifying the environment.

In the same vein physicists often interpret experiments as the prolongation of observation by treating them as tricks performed in order to make the observer better-placed to inspect the phenomenon. Instead of moving the observer around or adapting the radiation or receptor to the circumstances, the object is transformed in such a way that its inner structure and dynamics is open to the observer's examination.

In support of this interpretation one can refer to the procedure in experimental science which might be called *the hunch for systematic error*. It consists in a ceaseless endeavour to detect idiosyncrasies or bugs in the behaviour of the apparatus, to eliminate the so-called 'Schmutz-effects', *i.e.* the side effects caused by carelessness of the experimenter, to check any malfunctioning of the instruments or any 'mimicking' by the apparatus, etc. The detection and elimination of these unwanted artificial effects can be ensured by independent testing of parts of the equipment, by changing the equipment and design, *i.e.* by trying to get the same effect in another way, and by many other tricks of the trade. It is similar to the multimethod observation emphasized by Hacking [1983]. Galison's book [1987] shows beautifully the struggle against the possibility that an apparatus might fool us, and instead of a genuine natural phenomenon exhibit to us its own whim or systematic fraud. The book also shows how difficult it is to describe this struggle, because again, as is the case with all sophisticated instruments of observation, everything rests upon the experimenter's skill and technical expertise.

Both Ackerman and Galison are confident that, in spite of the enormous involvement of human artifice, in experimental science 'experiments can be replicated, bugs ironed out, and experimental results tied down definitively' that an apparatus can be constructed so that signals are insulated from noise, phenomena from background; uncontrolled background influence as the main source of systematic error can be blocked, or at least measured and calculated so that it can be subtracted from observation. In short, they believe that anything artificial can be extracted, and its traces erased so that the natural shines out in its full splendour to the glassy essence of scientific apparatuses.

Hacking, however, is more cautious. The difficulties he describes of producing stable and repeatable effects speak in favour of their artificiality. So considering the Hall effect, Hacking says: 'I suggest that the Hall effect does not exist outside of certain kinds of apparatus. Its modern equivalent has become technology, reliable and routinely produced. The effect, at least in a pure state, can only be embodied by such devices' ([1983] p. 226). This points to the problem that, once the object undergoes a process of artificial transformation and becomes part of an artificial experimental set-up—once the flow of energy is partly controlled and forced to become visible through instruments—can one be sure that the exhibited effect is not a human creation, a man-made event, nothing but an artefact?

A definite answer to this dilemma must be postponed to the next section. Before closing this one let me spend some time on the effect that the requirement, posed by Bacon and widely accepted, that theories must be experimentally testable might have on its structure.

It seems obvious that a theory or hypothesis, in order to be testable through work, as Bacon says, must meet certain requirements. However, what those requirements are is as yet unclear, and the traditional debate over testability is not much help. Tentatively one may say that only that theory which, in some way, contains in itself *a code of practice*, that is of experimentation, can be put on trial by practice; that only the theory which follows, or at least is compatible with, the structure of experiment-making can be tested by experiments. It is, therefore, not enough for theory to describe what is discovered or brought about in unconcealment; it must describe it in such a way that the description contains, somehow, instructions for building and interpreting the working of the experiment.

Jonas [1966] went a step further. He claims that modern science, or more precisely classical modern physics, has its characteristic structure because it has grown out of active experience and can be turned to the active changing of experience. Theories of modern science divide nature into the simplest dynamic factors and elements in such a way that they can be related, transferred, transformed and combined, showing how things are made up of these elements, and exhibiting the 'manipulative aspect inherent in the theoretic constitution of modern science'. After analytical reduction, Jonas continues, 'mathematics proceeds to reconstruct from them the complexity of phenomena in a way which can lead beyond the data of the initial experience to facts unobserved, or *still to come*, or *to be brought about*' (p. 341, italics mine), by manipulation, I suppose.

In classical theory nature is seen as being created once with all its substantial entities, and then subject to a second spontaneous creation which cannot be achieved in any other way than by shifting the relations, by 'manipulating' the elements, by rearranging and recombining them. Nature's own mode of creation is a 'quasi-technical mode of making', and nature appeals as 'its own artificer and artefact' [Jonas, p. 343]. Therefore Bacon's famous dictum: *Natura parendo vincitur*, i.e. man masters nature by obeying or by imitating its 'quasi technical mode of making'.

This is certainly one possible description of the manner in which theory meets the requirement of experimental testability. Further investigation will reveal others. For the moment it suffices simply to recall the truism that theories must contain a code of practice if they are to be tested by practice.

3.2 *Techne*

The contrast between *theoria* and *techne* is well known. Heidegger [1954] brings *techne* close to, and compares it with *physis*. The comparison rests on the common base which is *poiesis*. Referring to Plato he describes *poiesis* as 'every occasion for whatever passes beyond the nonpresent and goes forward into presencing', as a 'bringing-forth'. He continues by saying 'Not only handicraft manufacture, not only artistic and poetical bringing into appearance and concrete imagery, is a bringing-forth, *poiesis*. *Physis* is indeed *poiesis* in the highest sense. For what presences by means of *physis* has the bursting of a blossom into bloom, in itself (*en heautoi*). In constrast, what is brought forth by the artisan or the artist, e.g. the silver chalice, has the bursting open belonging to bringing-forth, not in itself, but in another (*en alloi*), in the craftsman or artist' (p. 293). In other words, comparison ends in the contrast between *autopoiesis* and *allopoiesis*. Obviously, the emphasis on the close relation between *techne* and *physis* expressed in *poiesis* is intended to support the midwife metaphor mentioned earlier.

However, closer analysis shows that the process of making a human artefact, which *techne* essentially is, comprises two parallel sub-processes of which only one can be understood by analogy to *physis*. Let us call this one *bringing-about* or midwifery, and the other *bringing-into* or mastery. This is the crucial point, so we must elaborate on it.

As was already suggested, in the first component process something hidden is brought forward into appearance, something not yet fully present 'comes forth into presencing' (as Heidegger would say). The producer, whether artisan or artist, sets something that will become an artefact 'free to that place', (s)he 'starts it on its way, namely, into its complete arrival', 'lets what is not yet present arrive into presencing' by 'inducing it to go forward' (all from Heidegger [1954]). Seen from this angle, the producer merely starts or triggers a process, sets free or lets pass something from concealment into unconcealment; she removes obstacles and promotes the advent of an artefact, very much as a midwife helps in childbirth. The action of a producer is gentle mediation, rather than violent effecting. Craftsmen and artists can be seen as instruments by means of which an artefact travels from the realm of nonpresence to the realm of full appearance, or maybe from the realm of possibility to the realm of actuality.

There are many technologies in which this is clearly visible, such as almost all of agriculture, the generation and processing of energy, some chemical technologies etc. In these, humans start the process by selecting and planting seeds or breeding couples, or by liberating energy stored in molecular, atomic or nuclear bonds. Then they remove impediments by simplifying the ecological system or by setting proper conditions for the mechanical or chemical processes to continue in an orderly way according to its internal logic or law. This is certainly one way in which, as a result of more or less spontaneous and autonomous processes, aided by the parental care of the craftsman or artist, the artefact is born.

Not all artefacts are born this way. Think of flight without wings, or transportation by wheels. These technologies exemplify the second subprocess in artefact production which we can find—and this is an important point—in the technologies already mentioned. No cultigen, *i.e.* no domesticated plant or animal, could survive in its proper cultivated form if left untended; so alien is its new 'artificial' form to pre-existing nature. Human intervention brings these cultigens into existence and maintains them; they disappear when this intervention ceases. This shows that every intervention, however careful and gentle it may be, is a form of violence in the sense that it forces plants and animals to assume unnatural forms, imposes those forms upon them, and distorts the ecological system in an effort to simplify it and to create artificial condition for the survival of these cultural species.

Violence in the form of *bringing* something *into*, imposing, enforcing something new onto pre-existing forms, no matter whether that something comes from a separate platonic world (as in Dessauer [1927]), from some mysterious depth of Being (as in Heidegger), from the realm of possibility or simply from the human head, has been a part of technology since its inception.

Physically, a finished artefact of whatever kind is a well defined 'portion of space' wherein a definite amount of energy is accumulated and an ordered structure established; it is, therefore, a system of reduced entropy. This is possibly only because the human being, like Maxwell's demon, processes information and supplies energy, all of this being guided by the idea of the artefact in her mind. Whereas in living beings the local violation of the second law of thermodynamics is possible because of information handed down from previous generations in the form of the genetic code, an artefact can 'come into presence' and circumvent the second law because of the code which craftsmen and artists have in their brains, in the form of a design and related set of instructions. With the idea of an artefact in mind, the craftsman carefully 'conduces' (from *con-ducere*) his action and produces (from *pro-ducere*) the embodiment of the idea in the external world. He is bringing an idea into reality, introducing it into the material world by supplying energy or arranging for energy to be supplied in a controlled way.

Therefore, *allopoiesis* or artefact production *always* intertwines two complementary, but in some sense inverse, processes of bringing-forth the natural possibilities unrealized but 'hidden' in nature, and of bringing-into nature forms invented in human minds. The bringing-forth that elicits from nature its 'readiness' to accommodate certain alien forms never before present in nature *happens only* through bringing-into, through a violent attempt to impose preconceived forms onto nature. The two processes can never by completely separated.

That was the ontological side of the matter. There is, however, an epistemological side as well. The ontological movement from 'concealment' into 'unconcealment' Heidegger calls 'revealing' and connects it with the Greek *aletheia* or 'truth'. He also points out that in ancient Greek the word *techne* was linked with *episteme*, since both meant 'to be entirely at home in something, to understand and be expert in it' (*ibid.*, p. 294). Ryle's treatment of know-how as a form of knowledge points to something similar. This relates very closely to the real meaning of the requirement that our claims should be tested by experiments.

The 'revealing' that happens in allopoiesis obviously is not epistemological in the standard sense. The movement called 'revealing' does not take place exclusively inside a cognizing subject, it is also an objective, external transformation of nature from one actual state to another. So we can put together the two aspects of the same process.

The series of transformations and, as will be shown, enrichments, runs parallel in the two domains. It starts with a human need, motive or hypothesis which has been formed somehow by natural, cultural or scientific urges. Through an internal elaboration, the need or motive or hypothesis must acquire the structure of a technological problem; it must be formulated in technical terms. Then by engaging previous experiences and accumulated knowledge, by pondering the environment and by activating the imagination, a tentative design of the artefact, *i.e.* a preliminary mental solution of the problem, is invented. An idea, in the form of *the design of an artefact*, is now about to be implemented, to be set on its way into the external world. Equipped with a set of instructions about the necessary technical operations, passing through human hands—whose movements are governed by the idea itself, by the set of instructions and by the emerging artefact—the idea forces itself onto pre-existent forms of the external world.

As the idea comes to be implemented, two transformations simultaneously occur. First, the idea must undergo adjustment to fit certain aspects of pre-existing forms which cannot be changed and predicted. Through this adjustment the idea reveals its aptitude or fitness to features of nature that already exist and are unchangeable. As the idea passes from the inner to the outer world, we discover the scope of the naturalness or truthfulness of the idea. Second, the natural, already existing forms get transformed in an alien being, i.e. into the artefact, revealing nature's capacity to accommodate the idea. Through this transformation we discover the ideality or constructiveness or potentialities of nature.

However, these are not simple discoveries, but enrichments as well. In the process the idea is enriched with reality or truthfulness; nature or reality is enriched with the idea embodied in a new being, the finished artefact. This I consider to be a cognitive process *par excellence*, a process which takes place not only in the inner mental space of the human subject but also and primarily in the external space of technical operations and their objects. It proves the first and third of my four alternative theses.

Hence, introducing itself into the open space of the visible world, through the indispensable mediation of human hands, the idea, a spiritual entity, brings forth at the same time what has not been present and what would otherwise never be present in nature, exposing *en route* the capacity of nature as it actually is to assume the new form contained in the idea. At the same time and in the same process, because of real physical transformations and not because of pure gazing, actual visible nature reveals features hitherto concealed from the human eye. What is revealed therefore, in the new *techne* is the actual and potential, the latent and possible nature of both human beings and the external things or creatures.

In allopoiesis knowledge, or as some people would still prefer to say, technical knowledge, is simultaneously the means of controlling the transformation of an idea from its internal to its external embodied form and a by-product of the same process; it is the precondition for, and the result of, artefact-making. If understood in such a way it cannot be mere know-how; it comes closer to scientific knowledge. This is because what happens in artefact-making happens also in scientific experiments. The cognitive dynamics described here is the real basis for our trust in experimentation and for our resistance to treating it instrumentally. Scientific artefacts are more than sheer means; they are places where truth happens. This answers the dilemma of phenomena exhibited by scientific artefacts being pure human creations.

4 SCIENCE AS TECHNOLOGY

4.1 *Microscopic Experiments*

Atomic theory, so long as it was based on classical observations and experiments, was treated by the majority of physicists as purely hypothetical. Experiments supposedly supporting the theory have used what Galison [1987] called 'the apparatuses of averages', i.e. 'instruments used to pry information about the small from experiments on the large' (p. 23). For example, the experiment exhibiting Brownian motion, which after Einstein's theoretical analysis convinced many physicists that atoms and molecules do exist, still displays an effect produced by an aggregate of molecules.

Since 1895, and particularly in the second quarter of this century, many new phenomena (or 'effects', according to Hacking, p. 225) have been 'discovered', and new equipment has been constructed which has allowed experimenters to register the macroscopic, and therefore visible, effects of *individual* microscopic, most notably subatomic, particles. The effects caused by the collective action of many micro-particles, like the movement of pollen, is now due to the Geiger–Müller counter, to the Wilson cloud chamber, to special photographic emulsion, etc., complemented by macroscopic effects caused by the action of a single microparticle suitably amplified. Together with other phenomena or effects like cathode rays, X-rays, radioactivity and the Zeeman-effect, which are produced in laboratories, they have created a new world for experimental physics.

As for the difference between classical macroscopic experiments and contemporary microscopic experiments, Maxwell (who, incidentally, thought that experiments could never handle individual atoms) distinguishes two methods: the historical and the statistical. The historical method relies on deterministic dynamical laws such as Newton's laws of motion and Maxwell's own laws governing changes in field configuration. These laws enable physicists to track an individual object, whether particle or field, from whatever time in the past to whatever time in the future. One never loses the possibility of identifying the object studied. It is like spotting the Moon by simply raising our eyes. The control of energy flow by exact dynamical laws makes all classical macroscopic experiments good examples, at least phenomenologically, of the historical method.

In microphysics, however, objects appear and disappear. They come from the emitter without having been traced before, and get lost in the detector; in this sense they exist only in the present, in the space between the two pieces of apparatus. Hence the historical method can at best be applied to the short period which the object spends between source and detector.

But even there, if we want to follow the track of an object and get some information about it, we must interact with it. Interaction, however, changes the state of the object. Of course in principle we can use that change to prepare the object in a certain state. It turns out that with macroscopic devices and manipulations (the only ones we have at our disposal), the best we can do is to prepare an ensemble of objects and thereby deal with a well defined distribution of the individual objects over a set of complete dynamical states. This is the statistical method.

In consequence, the identity of atomic and particularly subatomic objects is blurred. But this is not the only consequence nor the only interesting feature of experimentation in microphysics. With a bit of ingenuity, almost every experiment in microphysics can be described as a so-called 'scattering experiment'. A set-up for a scattering experiment consists of: (1) an *emitter* producing a beam of micro-particles of a certain kind which are prepared in a certain state, (2) a *target* against which the beam is scattered, which may be just another beam, and (3) a *detector* detecting scattered particles and registering their states. The schema is almost exactly that of observation, except that the 'target', as in classical optics, is usually not itself the object of investigation, but has become a means by which we study what was hitherto the means of study.

Now, depending on the 'target', which for the purpose of this discussion is better seen as a 'filter' in accordance with Feynman, experiments in atomic physics form two groups. The first group might be called 'semiclassical'. In it the kinematics of the micro-object has been made visible, in the sense that each path registered by the apparatus belongs to one individual object classically called 'a particle'. As is well known, in that case the fine control and details of the dynamics, i.e. of energy and momentum, are not available. For example, in a Wilson chamber traces of particles are clearly and individually visible, and the path of the particle is describable with an accuracy of the order of magnitude of the diameter of a droplet of water. Momentum and energy are then known within an interval determined by Heisenberg's uncertainty relations.

In the second group, experiments, which we might call 'quantal' use the same microscopic objects (which means they use the same emitter), but do so inside an arrangement that displays an interference or wave-like phenomenon which enables us to be more precise about momentum and energy at the expense of the kinematics of individual particles. For example, in the Davidson–Germer experiment the beam of electrons is scattered onto a suitably prepared crystal. The array displayed on the photographic plate provides the best possible information about the wavelength associated with the beam, but gives us no information about the path an individual electron has travelled through the crystal.

In both groups of experiments some information, if we judge by classical standards of the historical method, are missing. To paraphrase the cybernetic expression, both kinds of apparatuses are 'grey boxes'. Although full statistics about the input and output are provided, there exists only partial information about what is going on inside the apparatus. Indeed, if we consider exclusively the dynamic or kinematic aspects, the apparatuses are in fact almost 'black boxes'. In the Davidson and Germer experiment we know that each scattered electron has passed through the crystal, but we have no idea where. Actually, in our calculation we have to presuppose that each electron was somehow present everywhere in the crystal simultaneously. *We can cope with this problem only if we make our description dependent on the experimental set-up.*

One more feature should be recalled. Remember, the aim of every scientific apparatus is to make something visible, possibly by creating a firm visible mark, or 'document', as von Weiszacker would call it. The apparatus that needs to transform a microevent into a macroscopic mark, therefore, harbours essentially an irreversible process that then completes the experiment but at the same time 'destroys' the object of investigation.

All these aspects of microscopic experiments—their historical or statistical nature, their indeterminacy and duality, their irreversibility and finiteness—point to something Bohr wanted to express by talking of the 'wholeness' of a quantum phenomenon. What makes a quantum phenomenon an integrated whole, according to Bohr, is the fact that it necessarily entails an experimental arrangement. Theoretically, the wholeness of quantum phenomena is the consequence of the impossibility of ascribing to the microobject a state function (which contains all possible information about the situation) independently of 'the environment', which is of course the experimental set-up. It is true that one can avoid reference to the experimental arrangement and the touch of anthropocentricity connected with it by taking refuge in an abstract 'natural' environment composed of objects describable by quantum mechanics. But then, because of the nonlocality and inseparability involved in quantum mechanical description, the environment should be so conceived as to include the whole universe. This is, however, unattainable; and the only way to circumvent this consequence is to adopt Bohr's restriction of the environment to an experimental arrangement which is classically very well defined and which has clear and sharp boundaries with the rest of the universe.

Furthermore, a complete quantum mechanical description, if related to an individual object, is best understood as pertaining not to the actual but to the possible outcome of an experiment in which, because of complementarity, not all possibilities can simultaneously be realized. The explicit reference to possibilities, nonexisting in classical theory, underlines our analysis of scientific artefacts as the realization of potential features of nature discovered or invented through implementing human ideas.

The new situation points almost explicitly to the central role of the experimental apparatus in science, at least as far as twentieth-century physics is concerned. When considering this we should bear in mind that experimental apparatuses are *inventions*, imaginative trials that use continually improved, perfected and sophisticated technology. Scientific *allopoiesis*, not only in the case of quantum physics, presupposes that nature is not rigid and forever fixed, that what is is not only what is actual at any particular moment. The ontology of modern science is so indeterminate and open because of technology. Objects of modern science are immersed into scientific artefacts, becoming thereby *an aspect of the behaviour of the equipment.* The old slogan: 'science discovers, technology invents' is no longer accurate. On the contrary the accurate one is: *science discovers because it invents.*

4.2 *Experiment and Theory*

In a situation where object and equipment, natural and artificial, discovery and invention are no longer clearly separable, one is forced to reconsider the nature of scientific theory and its relation to experiment and reality. Standard descriptions of scientific theory see it as a set of concepts interconnected through laws in the manner, if possible, of an axiomatic conceptual structure akin to the Euclid's *Elements* or Russell-Whitehead's *Principia Mathematica.* Other parts of the symbolic output of scientific endeavour are considered to be instrumental. These, however, are now of special interest to us. In considering them, instead of 'other parts', I will speak of layers of symbolic output. There are three of them.

First, there are two kinds of symbolic structures involved in experimentation, either as a part or as an immediate outcome: the blueprint describing the set-up and data presented diagrammatically or numerically. Both need interpretation, and these interpretations must be related to each other. The former needs to be interpreted by other experimentalists and technicians; the latter by experimentalist and theoreticians. What is important to highlight is that both interpretations involve, as well as reasoning and verbal understanding, know-how, a technical intuition. To be able to see the instructive quirks or unexpected behaviour of this or that part of the set-up, to acknowledge their significance and their scientific meanings, to interpret the working of the apparatus correctly and to make the outcome of the experiment meaningful involves both manual and interpretative skill. In fact an observant experimenter (as Hacking calls the person in possession of these skills) engages in numerous circles of interpretation of the working and the outcome of the experiment, of making and remaking the experimental arrangement, until a certain point, intuitively determined, is reached.

The second layer of symbolic representation consists of the so-called phenomenological laws and models. These might be provided by an experimental or theoretical scientist, or result from their joint efforts. Much has been said in the literature about the role of this layer in science. Usually, phenomenological laws and models are expected to act as intermediaries between high theory and experimental outcomes. They provide the actual basis for applying the abstract mathematical apparatus of the theory, supplying also sorts of auxiliary hypothesis, initial and boundary conditions, etc. They serve as elements of the interpretation both of experiments and of abstract mathematical theory.

Finally we have the layer of high-brow theories, abstract notions, covering laws, symmetry principles, etc.; the stuff endlessly analysed by philosophers of science.

In real life we then face the following situation. On one side we have a sophisticated and sometimes very complex artificial apparatus, and on the other the equally sophisticated, abstract and often very elaborate, apparatus of a theory. They have somehow to match each other, and this matching is effected through a series of interpretations and translations which connects the concepts of high-level theory with the quantities and terms which experimentalists use in designing, implementing and interpreting their experiments.

The essential part of the process, the part which is almost always neglected, is the layer of the 'language' of artefact-making, which is what I call 'the blueprint describing the set-up'. This language contains instructions and descriptions mostly couched in terms of everyday speech but which are 'refined', as Bohr would say, by changes in meaning and the addition of some technical or even scientific vocabulary. I put 'language' in quotation marks because the information that needs to be conveyed by this language is not always verbalizable. The process involves a transfer of skill through imitation, supervision and training. Sometimes elements of this 'language' appear in scientific journals, but most of it is tacitly taken for granted and cultivated in the oral or other communications of the laboratory.

There is, then, and there must be, a full continuity between high scientific theory and the skill of an experimenter. The essence of contemporary science is not so much the abstract theoretical conceptual structure *per se* but rather the translation sequence that interprets and translates the language of concepts into the language of action, 'knowing-that' into 'knowing-how' and vice versa. The process repeats symbolically what goes on ontologically in the *allopoiesis* of scientific experimentation. Ontologically, modern experimental physics discovers what *is* actually in nature by inventing a possible experimental set-up, i.e. scientific artefacts, wherein nature is challenged to disclose not only what is already there but also what can be. Vice versa, it discovers what is possible in the real world by inventing and making an actual working experimental set-up. At the same time it is the processs by which an idea, an hypothesis or a theory as a conceptual structure formed inside a tradition and an individual human head goes through a series of translations, formulations and reformulations, and interpretations and reinterpretations until is slides down through the language of action or know-how and enters the real, actual world. After being implemented, *i.e.* after taking concrete form in the embodiment of an experimental arrangement and its outcome, it climbs back up the ladders of translations and interpretations, ending in the form of a fundamental principle or a law. If science is not only theorizing but making as well, then obviously, just as making is dependent upon theorizing, so theorizing is dependent upon making.

The analysis shows, I hope, that experiments cannot be considered only as traceless means by which one establishes the correspondence between theory and reality. Experiments, as Hacking says, have life, and, I would add, logic, of their own. Nor can the theory be treated as a mere instrument for calculation and prediction of the experimental outcome. It is much more than that. It is *an instrument of design*, and being that, it encompasses both ontology and technology. A theory can be considered as a condensed set of instructions of how to build an experimental apparatus, or, better, how to guide the production of experimental artefacts; it is part and parcel of scientific *allopoiesis*. If you happen to agree with this, the four alternative theses proposed in the introduction will seem obvious.

University of Zagreb

REFERENCES

ACKERMAN, R. J. [1985]: *Data, Instruments, and Theory*. Princeton, NJ: Princeton University Press.

DESSAUER, F. [1927]: *Philosophie der Technik; Das Problem der Realiserung*. Bonn: Fridrich Cohen Verlag.

GALISON, P. [1987]: *How Experiments End*. Chicago, IL: Chicago University Press.

HACKING, J. [1983]: *Representing and Intervening*. Cambridge: Cambridge University Press.

HEIDEGGER, M. [1954]: 'Die Frage nach der Technik', in *Vortrage und Aufsatze*. Pfullingen: Gunther Neske Verlag.

HEIDEGGER, M. [1977]: *Basic Writings*. New York: Harper and Row.

JONAS, H. [1966]: *The Phenomenon of Life*. New York: Harper and Row.

MAXWELL, J. C. [1876]: 'General Considerations concerning Scientific Apparatus', in *Handbook to the Special Loan Collection of Scientific Apparatus, 1876*. South Kensington Museum, London: Chapman and Hall.

SHAPERE, D. [1982]: 'The Concept of Observation in Science and Philosophy', *Philosophy of Science*, **49**, 485–525.