Why Is Modern Science Technologically Exploitable?

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Abstract: This paper deals with the following question: What features of modern natural science are responsible for the fact that, of all forms of science, this form is technologically exploitable? The three notions: concept of nature, epistemic ideal, and experiment, suggest the most important components of my answer. I will argue, first, that only the peculiar interplay of the modern concept of nature with an epistemic ideal attuned to it can cast experiment in the specific, highly central role it plays in the pursuit of knowledge about nature. It will then become clear that the form of science in which experiment plays such a role will, necessarily, prove technologically exploitable.

Keywords: *science, technology, experiment, nature, epistemic ideal*

1. Introduction

The question this essay attempts to answer is as follows: What features of modern natural science are responsible for the fact that, of all forms of science, this form is technologically exploitable? Three concepts will play a pre-eminent role in my answer: the concept of nature, the epistemic ideal, and the experiment. These concepts denote the most important components of my answer. I will argue, first, that only the peculiar interplay of the *modern* concept of nature with an epistemic ideal attuned to it can cast experiment in the specific, central role it plays in the pursuit of knowledge about nature. It will then become clear that the kind of science in which experiment plays such a role, i.e., modern science, will, necessarily, prove technologically exploitable.

To draw attention to the specificity of the *modern* concept of nature, I begin in section 2 with an exposition of an older concept of nature, namely that of Aristotelian science. The contrast between the older and the newer concept of nature will prove to be highly illuminating. A discussion of the modern concept, in which both continuities and discontinuities with the Aristotelian concept will become apparent, follows in section 3. In section 4, I consider the divergent epistemic ideals of Aristotelian and modern science. On this basis, I can explain in section 5 why experiment can play its pivotal role in modern science. Finally, section 6 will illustrate why such science, proceeding, as it does, by experiment, must necessarily be technologically exploitable. Section 7 recapitulates the line taken in this essay.

2. The concept of nature in Aristotelian natural science

Aristotelian natural science[1] concerns itself not with the set of all in principle perceptible things, as today's physics, but only with a particular subset: the set of objects that exist by nature; these objects are called "natural objects". Collectively, this set is called "nature", and the Greek word for it, *physis*, derived from *phyein* that means to grow, signifies the contrast to artifacts. Nature in this sense set encompasses, above all, animals, plants, and their natural parts, as well as the Sun, the Moon, the Stars, and what was called the "elements," earth, fire, water, and air. What all these have in common, according to Aristotle, is that they contain the ground of change and motion peculiar to them within themselves, and instantiate such motion

[1] The primary source in this section is Aristotle's *Physics*, especially Book II (Aristotle (1980); besides the translation, a very useful commentary is contained in Charlton (1970). A suitable layman's introduction is Solmsen (1970); Broadie (1982) and Judson (1991) offer important discussions of individual issues. All of these works include extensive bibliographies.

and change by themselves.[2] This common feature seems quite plausible when the normal motion and change of such natural objects is contrasted with the motion and change of artifacts. Compare, for example, the growth of a tree with the growth of a high-rise. While the tree grows by itself, so long as certain conditions obtain, the growth of the high-rise depends on a persistent, external impetus: the activity of building. Similarly, massive bodies fall by themselves, fire rises by itself, the Sun, Moon, and stars circle the heavens by themselves, and people and animals can move or come to rest by themselves. Artifacts are thus excluded from the domain of natural science from the very outset by the fact that they do not become what they are by themselves. To be sure, they also undergo "natural" motion and change, as when a vase falls to the floor or a wooden beam rots, but such motion and change have to do not with their status as artifacts, but with the natural qualities of their component materials. Natural objects thus bear the grounds of their motion and change within themselves; these motions and changes are characteristic of them, or determined by their nature. The word "nature" must evidently be used in a second sense here; where, first, we used it to signify the totality of natural objects, we now use it to refer to the characteristics of natural objects. In Aristotelian terms, we may say that the grounds of motion and change peculiar to natural objects reside in their *essences.* Such essential or natural motions and changes include, for example, the orbits of heavenly bodies, the downward motion of massive bodies, and the growth of plants and animals to their full stature. The essence or nature of a natural object, as expressed in an essential definition given in response to the question, "*What* is this?" is something universal; it applies in common to all objects in the given class.

For Aristotle, natural motions must be understood teleologically, as directed at some goal (*télos*). This understanding is plausible when we consider the growth of animals and plants; their developmental processes may appear organized (up to a point) with a view toward their adult forms. It is less plausible for us when we recall the motions of stones or stars; for Aristotle, the motion of a stone is directed toward the stone's natural resting place, the location dictated by the stone's essence, which coincides with the center of the Earth. As for the *télos* of stellar motion, its explanation lies so deeply embedded in Aristotelian metaphysics that, for present purposes, we may disregard it. At any rate, we have now presented the objective of Aristotelian

[2] Aristotle has one single word for what I render as "motion and change", namely *kinesis*, and he saw it as one natural kind. In the transition to modern science, the notion of *kinesis* was taken apart, fundamentally separating loco-motion, i.e. motion in space, from qualitative change, quantitative change, generation, and decay.

natural science: Aristotelian natural science examines natural objects with a view toward their natural motions and changes. Implicit in this project is the suggestion that even natural objects may undergo certain kinds of motion and change whose study lies outside the realm of natural science. Such motions and changes are those that are not indicated by the essence of the natural object in question. Such processes must instead be ascribed to "violence", something we would call today "external force." Again, this ascription is easily understood given the Aristotelian conception of the natural motion of natural objects. A stone may undergo upward motion, but only when "forced" to do so, say by someone throwing it. This is an unnatural motion for the stone. Natural science, in Aristotle's sense, does not investigate such unnatural motions and changes. To be sure, it does not deny them, either, though it excludes them from "nature," its proper area of study. For nature encompasses only the totality of natural objects, conceived in terms of their essential motions and changes. One might say that, in some sense, the task of "basic natural science" thus consists in finding the essences of natural objects; for the other features of natural objects may all be derived from their essential definitions.[3]

To summarize:

1. Aristotelian natural science aims at knowledge of universals.
2. These universals are one-place predicates, namely those that specify the essential attributes of the members of a given class of natural objects.

More briefly still, Aristotelian natural science examines nature with a view toward *predicative universals*. The underlying understanding of nature is thus that the fundamental order of nature is constituted by the essential properties of kinds of things.

3. The concept of nature in modern natural science

The modern understanding of nature (conceived as a set of objects) is deeply shaped by the appearance of a concept unknown to Aristotle, the concept of a natural law.[4] The precise history of the introduction of this concept into science and its philosophy is controversial among historians.[5] However, it seems to be that for the modern natural sciences, René Descartes' discussion of laws of nature in the 1630s has been most effective.[6] Today, we

[3] It should be noted, however, that Aristotle, in his scientific writings, seldom follows this axiomatic scheme.
[4] See, e.g., Ott (2009), p. 21.
[5] See, for instance, Zilsel (1942), Reich (1958), Milton (1981), Ruby (1986), Steinle (1995), Henry (2004), Ott (2009), Kedar and Hon (2017a), and Kedar and Hon (2017b).
[6] The earliest occurrence of the concept of natural law in Descartes seems to be in a letter to

have come to take this notion completely for granted, along with the view that it is the job of natural science to determine the natural laws with whose help we engage in scientific explanation and prediction. In the 19th century, the natural sciences (in opposition to the social and human sciences) have even been defined as the "nomothetic" sciences, which means the sciences that set up laws. Nonetheless, a long debate has been carried on over the precise definition of the notion of a natural law, an issue on which there is still no consensus.[7] Two features of natural laws, however, have not been disputed: natural laws are meant to be both *universal* and *relational*. For our purposes, it will suffice to insist on these two features. The *universality* of natural laws asserts the constancy of nature at all places and times, in the following sense: ceteris paribus, nature will behave in the same way, irrespective of time or place. The *relationality* of natural laws asserts that such regularities hold *between* the elements of one class and the elements of another (not necessarily distinct) class of objects or properties of objects. For example, Newton's law of universal gravitation states a relation between the gravitational force that acts upon one particle due to the mass of another particle, and the two masses and their distance. The formula describing this relation is $F = G \cdot m_1 \cdot m_2 / r^2$, where F is the gravitational force, m_1 and m_2 are the two masses, r is their distance, and G is the so-called gravitational constant. In general, the relations expressing natural laws can be described as functions, in the most simple case as the dependence of a (dependent) variable y on an (independent) variable x, thus $y = f(x)$, where f denotes the kind of dependency.

What I just used as a matter of course deserves more attention, namely the quantification of variables. Relations often lend themselves for quantification, and functions relating quantified variables make the use of calculus possible. In the Aristotelian case, mathematics could not play any substantial role in physics because essential qualities of things are of a qualitative nature. Only after the introduction of relations as the fundamental elements of nature in the 17th century, mathematics had its most important entry point into physics, and in parallel with the development of physics, calculus was developed. Universal quantified functional dependencies were now seen as the central elements of nature to which calculus could be applied, and

Mersenne of 15 April 1630: "it's God who has laid down these laws in nature just as a king lays down laws in his kingdom", Bennett (2017), p. 16 ["c'est Dieu qui a establi ces lois en la nature, ainsi qu'un Roy establist des loi en son Royausme", Descartes, Adam, and Tannery (1897), p. 145]. In his published writings, the earliest occurrence seems to be in his *Discours de la Méthode* of 1637: "I have also observed certain laws established in nature by God", Descartes (2008 [1637]), part V. See also Ott (2009), pp. 1, 17, 51ff.

7 See, e.g., Carroll (2016) for a survey.

as a consequence, the search for the essential attributes of natural objects was banished from the realm of scientific enquiry. The reason is either that essential qualities are now seen as unimportant in comparison to natural laws, or that it is held essential qualities are unattainable within the bounds of natural science.[8]

With the introduction of the concept of a natural law, certain distinctions central to Aristotle's understanding of natural science become inconsequential.[9] First, the distinction between "that which is by nature" and artifacts, i.e. what has been produced by human intervention, loses its scientific relevance. The universality of natural laws makes it irrelevant whether objects came about with or without mediation by human agents. All that counts is whether the conditions under which a natural law determines certain values for its dependent variables are fulfilled; in which way they may have been fulfilled is of no importance. Secondly, the notion of unnatural motion and change becomes scientifically meaningless. In the new sense of "nature", in which it is conceived as the set of all physical objects in accordance with natural law, there cannot, on purely logical grounds, be anything unnatural, for such would contradict the very idea of natural law. The notion of some motion being "unnatural" (in the old sense of nature), however, becomes obsolete, for the same reasons as the distinction between natural and artifactual objects.

These consequences of the introduction of the concept of a natural law can be well illustrated by the example of mechanics. For Aristotle, the natural motion of terrestrial bodies is always vertical; heavy bodies move toward the center of the Earth, and light bodies move away from it. Celestial bodies naturally move in orbits. When we look for the analogue of such natural motion in Newtonian mechanics, we find Newton's first law of motion, on which "every body continues in its state of rest, or uniform motion in a right line, unless it is compelled to change that state by forces impressed upon it."[10] "Natural" kinetic states would now appear to be rest and uniform, linear motion in an arbitrary direction, where such states certainly are not normal in the sense of frequently observable; in fact, strictly speaking, they never occur at all. Obviously, it would be absurd to restrict mechanics to the examination of such motions at the cost of denying it all objects of study.

[8] Consider, for example, the first sentence of Newton's Preface to the *Principia*: "… the ancients (as we are told by Pappus) esteemed the science of mechanics of greatest importance in the investigations of natural things, and the moderns, rejecting substantial forms and occult qualities, have endeavored to subject the phenomena of nature to the laws of mathematics", Newton (1934 [1686]).

[9] On this issue, compare Heidegger and Gendlin (1985).

[10] Newton (1934 [1686]), Lex I.

And so, under the new conception of nature, the distinctions constitutive of the Aristotelian conception lose all meaning.

After Descartes, the concept of natural law has been, in a sense, generalized. First, unified collections of natural laws, like the collection of laws in Newtonian mechanics, were introduced and called theories. In addition, general regularities that did not quite merit the denomination "natural laws" because of a somewhat restricted scope were admitted, often under the title of "general hypotheses". Furthermore, from the 19^{th} century on, something like simplifying general assumptions were introduced in science and called "models". Finally, also from the 19^{th} century on, fundamental mathematical relations of a lawlike character were simply called "fundamental equations", like "the Schrödinger equation" or "the Dirac equation", leaving their lawlike character implicit. What all these entities have fundamentally in common with natural laws is their nature as *general relations*, and this is what I shall call them furthermore in this paper, although their generality may be of a more local kind and thus restricted. Besides the original natural laws, these entities have become, and still are, the central targets of scientific investigation.

We can now summarize the concept of nature, as it is conceptualized as the intended object of modern natural science:

1. Modern natural science aims at knowledge of universals. This respect of the goal of scientific inquiry is shared with the predecessor mode of science, Aristotelian science. However, the second aspect represents a deep and consequential break with the Aristotelian conception.

2. These universals are relations, namely those that specify the lawful (or at least regular) associations between elements of given classes of physical objects or aspects of them.

More briefly, modern natural science examines nature with a view toward *general relations*. The modern understanding of nature is thus that the fundamental order of nature is constituted by universal functional dependencies.

4. The Aristotelian and the modern epistemic ideal

Up to now we have been considering what natural science takes as its topic (i.e. whatever one conceives as nature), without considering how this topic is to be approached. To view this latter question as asking only after the methods of science would be over-hasty; we must first ask which epistemic ideal guides the scientific tradition in question.[11] For scientific

[11] For a schematic overview over the historical changes of epistemic ideals see Hoyningen-

methods are meaningful and warranted only relative both to an object domain conceptualized in a certain way, and to a corresponding epistemic ideal. The epistemic ideal and the conceptualization of the object domain are mutually dependent, since the epistemic ideal must be viewed as in principle attainable, if it is to provide any meaningful guidelines for scientific efforts. The epistemic ideal of modern natural science, for example, does not demand apodictic proofs (in the mathematical sense) for candidate natural laws, not because apodictic proofs are in any way despised, but because they are thought unattainable in the study of nature. Roughly speaking, one might say that the concept of nature determines which questions may be asked in a specific kind of science, while the epistemic ideal determines which answers are legitimate.

The *Aristotelian* epistemic ideal is that of science-as-proof, exactly like that of the axiomatically structured Euclidean geometry.[12] It demands "first principles," which include the essential definitions of the given scientific field's objects of study. The essential definition of an object lists those attributes that necessarily pertain to the object, in virtue of its being what it is. In addition, we need general rules of deduction (formal logic). Further propositions may then be logically deduced from the first principles. An acceptable proposition of science is thus one proved from first principles. The first principles themselves cannot, of course, be justified in this way. We are persuaded of their necessary truth by a special process of induction, distinct both from complete, mathematical induction, and from modern science's generalizing induction. In this process, the intellect somehow distills what is essential out of a range of remembered individual perceptions, thus allowing us to determine the essential definition, a necessary truth.[13]

To be sure, one might doubt whether this epistemic ideal can ever be attained, or whether the explanations it helped to provide would satisfy us. These issues need not concern us here. For our present purposes, we must recall two features of this epistemic ideal. First, it corresponds to the Aristotelian concept of nature in the sense that any enquiry that is guided by this epistemic ideal could legitimately explore all knowable features of Aristotelian nature. Secondly, while this project of enquiry demands some

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Huene (2013), pp. 2-6.

[12] The most important source on this issue is Aristotle's *Posterior Analytics*, Aristotle (1960). Barnes (1975) contains, in addition to a translation, very useful commentaries. An excellent book length study is McKirahan (1992). Berti (1981) contains discussions of several relevant topics. – The identity of the Aristotelian and the Euclidean epistemic ideals is, of course, no accident. They emerged roughly at the same time, and Euclidean geometry was the undisputed paradigm of a successful science.

[13] See Aristotle (1960), II.19 and Chapter XVIII of McKirahan (1992).

empirical effort in the sense of systematic observation, it does not call for experiment. Systematic observation may include, as it does in Aristotle, the dissection of organisms, say for the purpose of determining certain differences between species. However, the Aristotelian study of nature does not grant scientific experimentation any pride of place. I shall discuss this feature of Aristotle's science in the next section, after having discussed the main features of experiment.

The epistemic ideal of *modern natural science* is a consequence of the "hypothetico-deductive" aspect of science.[14] This aspect consists firstly in the fact that in modern science, the upmost premises of scientific derivations are natural laws, theories (possibly fundamental ones), general hypotheses, models, or fundamental equations, to which I am referring as "general relations". However, it is impossible to certify in any way these general premises directly, contrary to what Aristotle had hoped. Instead, all confirmation of general relations in science must be indirect.[15] For this purpose, concrete empirical claims about reality must be (approximately) derived from the general relations, usually with the help of additional concrete (initial or boundary) conditions and auxiliary theories (a concrete example will follow in the next section). It is these derived, concrete empirical claims that can be confronted with empirical data. If the claims significantly disagree with the data, then something in the premises must be wrong (whose precise localization may be difficult). If the claims agree with the data, then a partial confirmation of the premises, from which the claims were derived, results. However, this confirmation can never be final; it can never be excluded that other empirical consequences of the said premises will prove to be incorrect. The result is that the highest premises of science, i.e. the general relations in the given sense, always remain hypothetical, and this explains why the epistemic ideal of modern science is qualified as hypothetical. In summary, we may describe the transition from the Aristotelian to the modern epistemic ideal as a transition from the ideal of certainty of scientific knowledge due to proof, to hypothetical validity of scientific knowledge due to inductive support.

It should be stressed, however, that in modern science the insight into the permanently and fundamentally hypothetical nature of general scientific

[14] I am aware of the fact that the hypothetico-deductive aspect of science is very coarse, incomplete, and potentially misleading. However, it is useful at this point because it encompasses features of the epistemic ideal of science that are relevant for our understanding of the role of experimentation.

[15] I am using the term "confirmation" in its wide, everyday sense, not in the technical sense of philosophical confirmation theory. Confirmation in this wide sense may therefore, for example, result from failed falsification.

relations, that holds of natural laws and theories, emerged historically comparatively late. From the mid 18th until the late 19th century, the belief in the finality of the discovered scientific laws, i.e. the body of Newtonian physics, was practically universal. Only in the late 19th century, doubts arose among some physicists about the finality of classical physics.[16] After the introduction of special relativity theory, general relativity theory and quantum mechanics and the ensuing concussion of the foundations of physics, the scientific climate changed drastically, at least in physics. The majority of physicists who care about the issue has given up the idea that physics could reach unshakable results.[17]

Three features of the epistemic ideal of modern science must be emphasized. First, as in the Aristotelian case, it fits the pertinent concept of nature, by doing justice to the specific central role of general relations. Secondly, this epistemic ideal is clearly weaker than that of Aristotle, for it contents itself with hypothetical truth, where Aristotle required insight into the necessary truth of first principles. Thirdly, experiment now becomes relevant in addition to systematic observation, a circumstance we must consider more closely.

5. The role of experiment in modern science

Before we can analyze the role of experiment in modern science, we should become clear what an experiment is.[18] It is essential to distinguish between observation, measurement and experiment. An *observation* may involve an instrument, like the observation of a cell under a microscope, or it may not, like the observation of a lunar eclipse with the naked eye. An observation usually does not interfere with the objects observed;[19] it is not an intervention into the course of nature. The result of an observation may be qualitative or quantitative; the latter is primarily the case if something is counted. A *measurement* does also usually not interfere with the measured object; it is also meant to produce a result that is not dependent on the act of measurement,[20]

[16] See, e.g., Schiemann (2009).

[17] However, it should be noted that there is also a counter-movement in physics. Many string theorists believe that they are at least on the way to a final theory of everything; see, e.g., Weinberg (1992) and Greene (2000).

[18] There is a large literature on experiments, see, e.g., Franklin (1986), Franklin (1989), Franklin (1999), Franklin (2008), Galison (1987), Gooding (1990), Hacking (1983), and much earlier the little discussed Weizsäcker (1952 [1947]).

[19] I say "usually" because the situation may be fundamentally different in quantum mechanics where the quality of an observed phenomenon may depend on the particular kind of observation.

[20] If the measurement itself changes the measured object noticeably, one tries to compensate

but only on the properties of the measured object. A measurement always involves a measuring instrument, and its result is mostly quantitative. The measuring instrument embodies the unit in which the pertinent quantity is measured. For instance, a ruler is the simplest instrument to measure lengths, and the unit length is engraved on its surface. In contrast to observation and measurement, an *experiment* always involves an intended intervention into the course of nature. Typically, an experiment aims at creating a phenomenon under fairly well-defined conditions, and that phenomenon is subsequently observed or measured. In an experiment, the experimenter is in control of the observed or measured phenomenon, at least to some degree, because she creates the conditions under which the phenomenon occurs, which is not the case in mere observations or measurements. In the most schematic form, the experimenter creates conditions C, and then phenomenon P ensues. If the experiment is reproducible, i.e., if the creation of C regularly produces P, then we may write $C \rightarrow P$.

Given this characterization of experiments, we can now see why in Aristotelian science experiments in principle cannot play any epistemic role.[21] The possible entry points are, of course, either the premises or the rules of deduction. We can immediately dismiss the rules of deduction, which are a matter of logic and certainly not of experimentation. How about the premises, i.e., the essential definitions? There are two consideration that show that experimentation is necessarily irrelevant for the establishment of the sought essential definitions, one rather methodical and the other rather substantive.

The more methodical consideration concerns the fact that the essential definitions to be found assert, for some attribute A, that it essentially pertains to some natural object S because it is a member of a certain class. Essential definitions are thus statements of the form. "All S's are essentially A." Now in order to show that a given attribute A is essential, it is not enough to show that all S's have it. For example, all and only humans have earlobes, yet earlobes are not what makes them what they are; they are not an essential feature in the Aristotelian sense. The insight that a given feature of S is an

for that change, for instance by calculating the change of the measured object by the measurement and subtracting it from the result of the measurement. Again, in quantum mechanics the situation may be different.

[21] It is important to note at this point that although experiments did not play any role for Aristotelian *science*, they were indeed relevant for the *technology* of his times. Science and technology were sharply distinguished in Aristotle, science belonging to the *theoria* domain and technology belonging to the *poesis* domain; see, e.g., Parry (2014).

essential feature is an accomplishment of the intellect, and so it is obvious that experiment cannot aid in the production of such insights.[22]

The more substantive consideration concerns the fact that experiment must remain necessarily irrelevant for Aristotelian science because it is based on interventions into nature's course by "violence", or external force.[23] Aristotelian science aims at investigating how nature behaves by itself, unperturbed by external influence. Observing the consequence of an experiment, i.e. an *intervention* into nature, is thus necessarily irrelevant for what Aristotelian science wants to achieve. Experiment cannot contribute even heuristically to the essential definitions. For example, would not the electrical conductivity of metals, which is most clearly exhibited in experiment, be a good candidate essential property of metals? From the perspective of Aristotelian natural science, it would most likely have to be objected that attributes exhibited primarily in the experimental context simply are not candidate essential attributes. For it is precisely in the experimental context that a natural object fails to behave in accordance with its nature, since it is subject to external force. The upshot is that in Aristotelian science experiment does not and cannot play any cognitive role, as the former's subject matter is the undisturbed course of nature.[24]

This situation changes dramatically with the advent of modern science and its new concept of nature. It is no longer essences of natural things that are responsible for change (and constancy) in nature, but natural laws (and similar relations) that connect states and changes. These relations hold universally, and in the given context this means in particular, independent of the genesis of objects and states. In other words, there is no in principle difference any more between naturally occurring objects and artifacts, and no principal difference between motion and change occurring spontaneously in nature or triggered by human intervention.[25] Thus, experiments are no longer forbidden by the very nature of the scientific enterprise as is the case in Aristotelian science. Now we have to ask what the function of experiments is in the modern form of science.

The central elements of nature, according to the modern conception of science, are natural laws and similarly theories, general hypotheses, models,

[22] This is the line taken, for example, in Dingler (1928), p. 214.
[23] On this issue, compare Kuhn (1977 [1976]), p. 55.
[24] Compare my analysis of the absence of experimentation in Aristotelian natural science with that of Dijksterhuis (1986 [1950]), pp. 70-71, in which the conceptualization of nature plays no role.
[25] However, one should note that this does not deny the difference between *in vitro* and *in vivo* experiments, nor the possibility of distortions in (animal and human) behavior studies due to laboratory conditions. Such distortions only indicate that not all the relevant variables have been adequately taken care of.

and fundamental equations. All of these articulate *general relations*, as we saw earlier, that express the order of nature. Their relata are the elements of certain classes of objects (or of aspects of objects), and are usually (though not always) described quantitatively. Familiar examples include, for example, Newton's universal law of gravitation, which asserts a relation between force, masses, and distances between them, or Maxwell's equations that articulate a relation between electrical charges, their motions, and electric and magnetic field properties. From such very general relations, more specific relations may be derived, tuned to specific cases, by specializing the general relations to those cases (the derivation may only be approximate, but this is of no importance here). For instance, Newton's law of universal gravitation that I already mentioned above

$$F = G \cdot m_1 \cdot m_2 / r^2$$

may be specialized for the case of a body of mass m_1 situated close to the Earth's surface to the ground to

$$F_E = G \cdot m_1 \cdot m_E / r_E^2,$$

where F_E is the gravitational force acting on the mass m_1, m_E is the Earth's mass and r_E is the Earth's radius, neglecting differences of the distance between m_1 and the Earth's center, because they are very small (relatively speaking). This last formula can be rewritten as

$$F_E = m_1 \cdot g,$$

with $g = G \cdot m_E / r_E^2$, which is called the Earth's gravitational acceleration, relevant for Galilei's law of free fall.

In these more specialized relations, dependent variables may be distinguished from independent ones. However, this distinction may be undertaken differently, dependent on context. Variables whose values can be fixed arbitrarily in a given situation may be counted as independent variables. Their values determine the values of the dependent variables by the given relation. Mathematically, the dependent variables are *functions* of the independent variables, described in an *equation*. In the above case, the gravitational force exerted by the Earth on a body near its surface is a function of the body's mass (it is proportional to the mass), described by the above equation $F_E = m_1 \cdot g$,

The fundamental point is now that under certain circumstances, such functional dependencies can be tested by experiment. If certain values of the independent variables are practically realizable, and if the corresponding values for the dependent variables can be measured, then these measured values can be compared with the values predicted by the equation. The experiment then consists of indeed realizing certain values of the independent variables and measuring the values of the dependent variables. Roughly speaking, if the measured values are in reasonable agreement with those predicted by the equation, the equation is "confirmed", otherwise "disconfirmed". The confirmation or disconfirmation, respectively, can now travel upwards to the general relation from which it was derived. The reason is that the (dis-)confirmation of a logical consequence of some premises also (dis-)confirms these premises. However, it should be noted that especially the confirmation of the general relation can never grow into a verification, i.e. the proof of its truth. In principle, the status of general relations remains forever hypothetical, no matter how many indirect confirmations one can adduce.

Now we can understand why experiments can play the epistemic role in modern science that I just discussed. A reproducible experiment establishes an empirical relation C ⟶ P (condition C regularly produces phenomenon P). The (dis-)confirmation of a general relation requires testing a relation of the form $y = f(x)$. If the values of x can indeed be experimentally fixed and the values of y can be measured, then an experimental situation is given: C is the fixing the values of x by experimental intervention, and P is measuring y. Thus, the *relational* character of natural laws, theories, general hypotheses, models, and fundamental equations fits the *relational* character of experiments. All special relations derived from the general relations that are confirmed by experiment contribute to the confirmation of the general relations by traveling upwards. If the epistemic ideal is now adjusted to this situation by dropping the rigorous (Aristotelian) demand of absolute certainty of the premises for deduction, then the (partial) confirmation of general relations becomes indeed scientifically relevant. The general relations can, in principle, be confirmed by experiment, and this is exactly what is needed according to the epistemic ideal of modern science. Thus, the epistemic ideal of modern science has been attuned precisely to what is epistemically achievable by a science that fundamentally uses experiment.

So far, I have only discussed the role of experiment for (dis-)confirmation of general relations. However, experiment has many more functions for science, and an important one among them is scientific exploration.[26] In situations where one does not yet know empirical generalizations about a certain subject matter, experimentally varying variables and observing its

[26] For a long time, philosophy of science discussed only the (dis-)confirmatory role of experiments. Especially Friedrich Steinle's work brought the possible exploratory role of experiments to the fore, beginning with Steinle (1997). I may note that I also became aware of exploratory experimentation when in December 1992, after a talk at the Institute of Physiology of the University of Berne, Institute members criticized me for only talking about the (dis-)confirmatory role of experiments and not their exploratory role, which is fundamental in physiology. Later, I applied what I had learned from the physiologists and criticized the philosopher of technology Friedrich Rapp for neglecting exploratory experimentation; see Hoyningen-Huene (1996), p. 453.

effect on other variables, is a common experimental practice for heuristic purposes.[27] Thus, experimentation is not only important for knowledge (dis-)confirmation, but also for knowledge generation.[28]

Let me summarize the structure of the argument in this section. The modern concept of science conceptualizes nature fundamentally as a set of general relations (laws, theories, etc.). These relations hold independently of the particular genesis of the pertinent objects or the way in which the values of certain variables are realized, i.e., with or without human intervention. Because of the relational structure of experiments, special relations derived from the general relations may be confronted with experiments, leading to their confirmation or disconfirmation. This holds only if the technological means are available to indeed fix the values of the independent variables and measure the values of the dependent variables. In the case of confirmation, this result may travel upwards to the general relation, providing them with (hypothetical and partial) confirmation. Because this is, according the epistemic ideal of modern science, all that can be achieved at the most general level, this confirmation is seen as scientifically sufficient though in a strict sense hypothetical and thus provisional.

6. Technological Exploitability

Now I want to argue that the general relations that are confirmed by the experimental procedures just described are necessarily technologically exploitable. "Technological exploitability" of an X means that X can be used for the performance of technological actions. What is a technological action? Roughly speaking, in a technological action some action A is performed with the help of a technological device in order to realize a certain goal G. Unscrewing a screw with a screwdriver is a simple example of a technological action: one turns the screwdriver after putting it into the recess of the screw (action A) in order to remove the screw from its hole (goal G).

Let us now assume that we have a general relation R that has been confirmed experimentally. This means that a number of special relations R_1, … R_n were derived from the general relation R and subjected to experimental testing. Let us assume for simplicity that each R_i claims a functional dependence of variable y_i from an independent variable x_i, i.e., $y_i = f_i (x_i)$. Experimentally testing the relations $y_i = f_i (x_i)$ means experimentally realizing a number of

[27] This is the simplest case. More can be found, for instance, in Steinle (1997) and Franklin (2005).

[28] For a more general discussion of knowledge (dis-)confirmation, there called "the defense of knowledge claims" and knowledge generation, see Hoyningen-Huene (2013), Sections 3.4 and 3.8.

values of x_i and then measuring the ensuing values of y_i. The confirmation of f_i means that over a range of experimentally realized values of x_i, the *measured* values of y_i are in reasonable agreement with the values of y_i *predicted* by the equation $y_i = f_i (x_i)$, and that the experiment is reproducible.

Note that the goal of performing the above experiment was purely epistemic. Because the intended object of modern natural science is general relations, they are tried to be confirmed by experimental tests. However, any reproducible experiment can be repeated with a different aim in view, namely the creation of certain values of y_i by realizing the appropriate values of x_i. Thus, by using the experimental setup, I can achieve a goal G, namely certain values of y_i, by doing an action A, namely realizing the appropriate values of x_i. It is now obvious that this is technological action as described above, using the experimental setup as a technological device. Thus, every successful, i.e. reproducible experiment with positive results can be used for technological action.

To illustrate with a highly simplified example, let us assume that a certain new drug is tested on a group of patients with a certain disease. The researchers want to find out whether the drug leads to an improvement of the health condition of the patients.[29] Let us assume that the result of the experiment is positive and reproducible, i.e., that the health condition of the patients improves significantly due to the drug. Then, the drug may be used for treatment. The actions aiming at treatment are exactly the same as the actions in the experiment: administering the drug to the patients. However, the purpose of these action is significantly different; in the former case, treatment of patients, in the latter case, knowledge of the potential therapeutic effect of the drug.

However, the technological exploitability of experimentally confirmed knowledge goes further than the simple literal repetition of particular experiments as technological actions. So far, I have only shown that every single reproducible experiment that confirms the equation $y_i = f_i (x_i)$ for a *particular* value of x_i can be repeated as a technological action aiming at the production of the corresponding particular value of y_i. However, the experiment led to a confirmation of the equation $y_i = f_i (x_i)$ for *all* values of x_i within a certain range.[30] By this confirmation we are licensed to assume that the realization of *any* value of x_i in the allowed range will produce the value

[29] Note that this is a gross simplification of a clinical investigation because of the omission of controls, side effects, dosage, etc. However, for the given purpose of the example these omissions are not detrimental.

[30] How that confirmation exactly works is an extremely thorny question that I am not going to tackle in the paper; it implicates the problem of induction. I presuppose that this sort of confirmation indeed works in the natural sciences.

of y_i as it is given in the equation $y_i = f_i (x_i)$. Thus, we get a continuum of possible technological actions allowing us to produce all values of y_i within range of the validity of the equation $y_i = f_i (x_i)$.

However, the full force of the technological exploitability of experimentally confirmed knowledge comes to the fore only when we observe that technological actions can be concatenated. The reason is simple. If I have, for a certain range of values of x, an experimentally confirmed equation y = f (x), it is unimportant how the values of x are realized, by a human experimentalist or by *another experiment*. Thus, if I have another experiment confirming the equation x = g (z) for a certain values of z, I can use this equation in order to technologically producing values of x by realizing certain values of z. Then I can feed these values of x into the technological action (or more precisely now: technological *process*) based on the equation y = f (x), thus producing certain values of y. Machines are artifacts that use the concatenation of technological processes in this way, and these technological processes may be based on regularities coming from very different domains. For instance, a combustion engine exploits regularities from mechanics, thermodynamics, chemistry, electrodynamics, material science, etc., concatenating them in such a way as to produce the intended performance.

I am closing this section by three remarks concerning the technological exploitability of experimentally confirmed scientific regularities. First, it should be noted that historically, the technological exploitation of experimentally confirmed scientific knowledge started comparatively late. In the 17th up to the mid 19th century, experimentally gained scientific knowledge had few, if any, technological applications. Either there simply was no possible technological application, or the knowledge had already been produced by the technological tradition that was, over millennia, independent of the scientific tradition.[31] The onset of the systematic exploitation of scientific knowledge for technological purposes took place in the mid 19th century, beginning perhaps with agricultural chemistry: In 1840, chemist Justus von Liebig begun a systematic investigation of the conditions of plant growth, which was an application of organic chemistry. This was triggered by the (world-wide) famine of 1816, the "year without a summer". He discovered the phosphor was taken up by plants much faster if delivered by so-called superphosphate. In 1846, the first firm was founded to produce superphosphate for fertilization. It improved the nutrition in the second half of the 19th century tremendously and is still used today. Later examples for the systematic exploitation of scientific knowledge for technological

[31] For this and the rest of this paragraph see Kuhn (1977 [1971]), pp. 141-147.

purposes include organic-chemical dyeing, which was discovered 1856 and which very quickly led to the development of the synthetic dyestuff industry.

Second, it is important to see what role the epistemic ideal plays in the technological exploitability of modern science. Suppose we were capable of proving, without recourse to experiment, the truth of natural laws (or similar general relations), and could in this way achieve epistemic progress. Such epistemic progress would not, despite the relational structure of natural laws, necessarily entail any technological progress. For though insight into natural laws alone permits us to derive the relations between independent and dependent variables, nothing in this hypothetical situation ensures that we are able to either indeed realize any values for the independent variables, nor measure those of the dependent variables. Such knowledge would be, in principle, technologically exploitable, but not by us, since we would still lack the technological prerequisites for such exploitation. However, when theoretical progress is, by virtue of its guiding epistemic ideal, linked to experimental testing, then at least some consequences of confirmed general relations will prove technologically exploitable.

Third, it should be noted that the necessary connection between experimental confirmation and the ensuing technological exploitability of scientific knowledge is a prime factor for science's astonishing growth over centuries. This is due to the feedback mechanism built into science. Experiments involve technological devices, often of a staggering complexity. Since the late 19^{th} century, the development of technological devices has massively profited from progress of the experimentally supported natural sciences. Thus, the results of science at one stage feed into the progress of science at the next stage, and the necessarily technological exploitability of experimental science's results play a pre-eminent role in this process.

7. Summary

As we have seen, the modern concept of nature has been shaped by the notion of a natural law, conceived as a universal relation. Because the epistemic ideal of modern natural science does not demand the rigorous proof of natural laws, experiment becomes the central process in the (dis-) confirmation of natural laws and other general relations. Experimentally confirmed relations can necessarily be turned into technological actions. In the view of this essay, the most fundamental element in the transformation to modern science is the concept of natural law, or more generally of general *relations* in nature. Given the foundational role of general relations in nature, three other elements characteristic of modern science can enter: the *mathematization* of the relations involving calculus, the *experimental* (dis-)

confirmation of these relations, but the latter only if at the same time the *epistemic ideal is weakened* from absolute certainty to confirmation due to inductive support. It is this package of four elements which leads necessarily to the sort of quantitative technology that now, for more than a century, has so strongly influenced our world.

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