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# MEASUREMENTS IN THE ENGINEERING SCIENCES: AN EPISTEMOLOGY OF PRODUCING KNOWLEDGE OF PHYSICAL PHENOMENA

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## 1. INTRODUCTION

One of the earliest uses of measurements was their well-known role in trade, where the ability to use rudimentary measures of weight not only made it possible to barter with food and raw materials but also enabled things to be built and manufactured. The simple ability to measure the length of things by means of specific units, combined with some elementary arithmetic and geometry, enabled craftsmen to design and construct things such as cathedrals, castles, bridges, houses, musical instruments, furniture, tools and clothes. Reflecting further upon this observation, we come to realise that it is the ability of humans to measure and apply basic mathematics that *makes it possible to design things at all*. Designers can work out on paper or by means of computer simulations how to build something that does not yet exist – how to construct, say, a building or a ship whose size matches our needs and is stable and strong enough while also satisfying our aesthetic ideals. More than this, though, our ability to measure and calculate makes subsequent *epistemic uses* of the design possible. In the actual process of construction the epistemic uses of a design include, for instance, calculating the quantity of materials to be used and the dimensions of the component parts.

This perspective on the role of measurements and mathematics in the design of artefacts can be extended to the design of more advanced technologies, such as those found in chemical engineering, biomedical engineering and nanotechnology. These differ from the examples of technological artefacts just mentioned in that the latter are considered primarily in terms of having a function suitable for certain uses by humans[i], whereas more advanced technologies usually 'do something' themselves: they produce something, they generate changes and transformations and they perform technological activities (or have the capacity to do so). This kind of technological functioning is often described in terms of physical-technological processes (e.g. the conversion of chemical compounds or the conversion of light into an electric current) and capacities (e.g. the capacity of a material to resist an electric current or the capacity of a chemical catalyst to accelerate a chemical reaction).

As a consequence of this difference, the 'naïve' picture sketched above, in which the ability to measure properties of objects such as size, shape and weight enables the design of, say, a house, is insufficient for understanding how measurements enable the design of advanced technologies.[ii] This is because such design additionally involves the measurement of physical properties that manifest only in specific physical-technological circumstances. Crucial to the argument developed in this article is the fact that these kinds of properties can be measured only when they manifest, i.e. when they become apparent as a result of specific physical-technological circumstances; these properties are 'capacities', so to speak. Strictly speaking, then, physical properties are actually measured by means of the measurement of *physical phenomena*.[iii] [iv]

The key idea being proposed here is that the ability to measure the physical properties of materials and technological devices is the very thing that makes the design of a technology possible in the first place and enables the epistemic uses of a design in the actual manufacture of a technology.[v] The reasoning behind this idea is as follows: physical phenomena produce the technological functioning (and malfunctioning) of technological devices.[vi] Therefore, designing a technological device requires knowledge of physical phenomena, and this knowledge is acquired by means of measurements and mathematization. The aim of this article is to outline *an epistemology of producing knowledge of physical phenomena* and to highlight, in particular, the way such knowledge of physical phenomena is produced using measurements and mathematization.

The structure of this chapter is as follows. Section 2 briefly explains what 'knowledge of a physical phenomenon' must consist of in order to enable design to occur. It also addresses the presuppositions that are involved in using this knowledge and explores how knowledge of phenomena is used in scientific modelling as a crucial part of designing a technology. The question then is how such knowledge of phenomena is produced. First and foremost, how do we come to know that there *is* a phenomenon *at all*? Surely we do so by means of measurements – yet measurements produce data, not a picture of the 'unobservable' phenomenon. Bogen and Woodward (1988)[vii] have proposed that phenomena are inferred from data. Their view will be discussed in Section 3. As an alternative to this view I propose that in scientific practices, predictions of the occurrence of an 'unobservable' phenomenon are inferred by combining measured and observed data describing the specific physical-technological circumstances with conjectured knowledge of the phenomenon. However, this still leaves unanswered the question of how researchers come to infer to yet unknown phenomena. In Section 4, I follow Feest (2010)[viii] in arguing that a scientific concept of 'unobservable' physical phenomena is formed by describing relevant aspects of the experimental set-up (including the experimental data). This implies that the concept of a phenomenon is inextricably entangled with aspects of the experimental set-up held responsible for its occurrence. In turn, the experimental set-up and the use of all kinds of measurement techniques enable further investigation of the phenomenon, thereby producing different kinds of data. In Section 5, it is explained how the data thus produced in measurements are organized by means of two important epistemic strategies: by mathematization – thus generating (phenomenological) laws – and by determining quantities that are characteristic of the materials, substances and objects involved.

## 2. KNOWLEDGE OF PHYSICAL PHENOMENA USED FOR DESIGN

In the course of explaining 'how it is possible that scientific knowledge of physical phenomena enables designing,' Boon[ix] addresses the question 'what scientific knowledge of phenomena is,' focusing on those aspects of knowledge of phenomena that enable this epistemic function. This section summarizes those aspects of this account that are relevant to the topic of the current chapter.

A key part of the idea that scientific knowledge of phenomena are epistemic building-blocks for designing a technology, is recognizing that physical phenomena should not be considered as independent physical entities. Instead, physical phenomena (such as electrical conductivity, magnetic resonance or a chemical reaction) manifest at, or are produced by means of specific physical conditions and technological circumstances. This implies that a conceptual distinction is needed between 'physical phenomena' and the 'physical-technological environment' responsible for their occurrence.

Crucially, the design process depends on the presupposition that *given the same conditions, the same effects will occur*. This presupposition implies that, when we design something, we assume first that a phenomenon can be produced by creating (relevant aspects of) the physical-technological circumstances held responsible for its occurrence and, conversely, that given specific physical-technological circumstances the actual occurrence of specific phenomena can be predicted. Accordingly, in the engineering sciences – and, more generally, in the experimental sciences – this presupposition functions as a *regulative principle* for producing and applying scientific knowledge of physical phenomena. An important feature of this epistemology is that, in the process of design the occurrence of all kinds of 'unobservable' phenomena – such as chemical reactions, electrical conduction, or transfer of compounds between different phases – is assumed based on established scientific knowledge of these phenomena, often without checking whether these phenomena actually occur.

Scientific knowledge of phenomena that can be used in the process of design, therefore, consists of more than a description of something that can be directly observed. It consists first of the scientific concept of the phenomenon. Additionally, though, it entails knowledge of physical conditions and (if relevant) the technological circumstance at which the phenomenon manifests. It also consists of mathematical equations (i.e. laws) that represent the phenomenon as a function of (some of the known) causally relevant conditions of its physical-technological environment, by means of which the quantitative effects of physical conditions and technological circumstances can be calculated.

The aim of the design process is to work out how a technological function (e.g. removing toxic compounds from an industrial waste gas[x]) can be constructed in terms of the physical phenomena and the physical-technological circumstances that produce this function. This usually involves the construction of scientific models that are based on knowledge of potentially relevant physical phenomena ($P_1$, .. $P_n$) and physical-technological circumstances (including knowledge about their mutual interactions) by means of which a physical phenomenon ($P_T$) that is held to be responsible for the technological function is generated. In this brief example, the technological function 'waste gas cleaning' is generated by a physical phenomenon ($P_T$) that is called 'reactive-absorption of toxic compounds in a gas into a fluid.' The scientific model eventually represents how the desired physical-phenomenon ($P_T$) is generated in terms of all kinds of interacting phenomena ($P_1$, .. $P_n$) and physical-technological circumstances, such as different kinds of transfer and dissolution processes of toxic compounds in the gas- and liquid-phase, and different kinds of chemical reactions.

Constructing these scientific models is an inherent part of technological design. The models enable further investigation of how the technology can be built and of the technological production of the technological function. For example, scientific models make it possible to create computer programmes capable of performing simulations by means of which the technology can be investigated. They also enable the design of experimental set-ups in which contributing physical phenomena ($P_1$, .. $P_i$) can be investigated in isolation.

## 3. DATA AND PHENOMENA

What are phenomena, and how are they identified if they are not directly observable? Bogen and Woodward (1988)[xi] developed an account of phenomena that seeks to do justice to scientific practice by distinguishing between data and phenomena .[xii] Loosely speaking, data are the observations reported by experimental scientists, while phenomena are objective, stable features of the world whose existence scientists infer on the basis of reliable data. According to Bogen and Woodward, the melting point of lead is *inferred* or *estimated* from patterns in observed data; it is not *determined* by observing the result of a single thermometer reading.[xiii] Hence, their argument for distinguishing between data and phenomena is that *data*, for the most part, can be straightforwardly and uncontroversially observed (e.g. the thermometer readings and the observation that a solid is melting) whereas most *phenomena* are not observable. This distinction is relevant because, according to them, data, although observable, are idiosyncratic to particular experimental contexts and typically cannot occur outside of those contexts. At the same time, data play the role of evidence for the existence of phenomena:

> '[D]ata are far more idiosyncratic than phenomena, and furthermore, [...] their production depends upon highly irregular coincidences involving a great number of different factors. It follows that explanations of data, when they can be given at all, will be highly complex and closely tied to the details of particular experimental arrangements. As we vary the method used to detect some phenomenon, and other details of the experimental design, the explanation we must give of the data will also vary, often in rather fundamental ways.'[xiv]

I agree with Bogen and Woodward that a distinction must be made between data and phenomena. The question is, however, how are phenomena inferred from data? Bogen and Woodward discuss two possibilities: phenomena are inferred (1) from patterns of data (e.g. by means of statistical inference) or (2) by means of 'inference to the best explanation'. The second option implies that descriptions of phenomena are theories, an implication they seek to avoid for obvious reasons. Concerning the first option, however, the two co-authors leave open the question of how scientists infer phenomena from data. It is a question which has been debated by several authors.
One of their critics is James McAllister.[xv] He summarizes their view as the claim that the function of scientific theories is to account for phenomena, which Bogen and Woodward describe as both investigator-independent constituents of the world and as corresponding to patterns in data sets. Yet according to McAllister this view is incoherent. He proposes instead that phenomena are investigator-relative entities. Each one of the countless patterns exhibited by data sets has an equally valid claim to the status of phenomenon: each investigator may stipulate which patterns correspond to phenomena for him or her. Below, it will become clear that I agree with McAllister on the first point. However, I also note that the epistemic uses of observed and measured data suggest that scientific researchers agree on epistemic strategies for their organization (Section 5).
Bruce Glymour (2000) also points out that Bogen and Woodward fail to state how scientists discern or discover phenomena in the first place.[xvi] Bogen and Woodward claim that phenomena do not explain data. But if this is so, then we are bound to ask whether phenomena are merely summaries of data. Or is there something more to phenomena than just patterns, summaries of data, or statistical features? If so, what could this be? Glymour argues that there is not. According to him, scientists infer patterns from data by means of statistical analysis. If we accept this argument, then McAllister[xvii] is mistaken in thinking that the choice about 'which patterns to recognize as phenomena' can only be made by the investigator on subjective grounds. Furthermore, Glymour

argues that, according to Bogen and Woodward, phenomena are nothing more than summaries of data, which can be taken to imply that phenomena coincide with patterns in data. Therefore, Bogen and Woodward are mistaken in thinking that a distinction between phenomena and data is necessary. Instead, according to Glymour, talk of phenomena is superfluous. Certainly Glymour makes a powerful argument to contest Bogen and Woodward's position. However, the argument I seek to render plausible here is that a conceptual distinction between 'data' and 'phenomena' (as well as some other conceptual distinctions proposed in this chapter) is crucial for pragmatic reasons – namely, to facilitate epistemic uses of measured and observed data.

At this point, it should be recognized that the distinction between data and phenomena proposed by Bogen and Woodward must be understood in the context of efforts to solve two related issues in the philosophy of science: how can observations generated by means of experiments constitute evidence for theories, and how can the theory-ladenness of observation be circumvented. Against this background, Bogen and Woodward propose that facts about phenomena – rather than data – are explained by theories:

> 'In undertaking to explain phenomena rather than data, a scientist can avoid having to tell an enormous number of independent, highly local, and idiosyncratic causal stories involving the (often inaccessible and intractable) details of specific experimental and observational contexts. He can focus instead on what is constant and stable across different contexts.'[xviii]

Rather than focus on philosophical issues concerning the justification of theories by means of measurements, my aim here is to understand how the design process is enabled by scientific knowledge of physical phenomena. As a consequence, my account of physical phenomena contradicts Bogen and Woodward on two important points. First, Bogen and Woodward seek to avoid portraying phenomena to be some kind of low level theories, whereas in my account, 'unobservable' phenomena are conceptualized, a process involving both empirical and theoretical content.[xix] Second, while I agree with Bogen and Woodward's claim that physical phenomena exist independently of us, I also argue that phenomena are not independent of their physical and (where relevant) technological environment. Phenomena are not independent, 'self-enclosed', 'free-floating' physical entities, so to speak. In order to account for this ontological point of view, I have proposed a conceptual distinction between physical phenomena and the physical-technological environment causally relevant to their manifestation.[xx] As a consequence, scientific knowledge of physical phenomena involves knowledge of the causal influences exerted by their physical-technological environment. Accordingly and contrary to Bogen and Woodward, I claim that the 'highly complex details of experimental arrangements producing the data' are a relevant part of knowledge of the phenomenon. Researchers need to figure out which of these physical and technological details are causally relevant to the phenomenon and which are not. This latter aspect of my account is supported by the *regulative principle* that the same physical-technological circumstances will bring about the same effects.

Accordingly, one way in which phenomena are inferred from data is based on this principle. If researchers possess scientific knowledge of phenomena $P_1, ..., P_n$, and also know the physical-technological circumstances of a specific 'data-producing experimental set-up,' this knowledge enables them to infer the occurrence of physical phenomena $P_i$ in that system, even if the system is very different from the experimental set-ups by means of which the individual phenomena $P_i$ were discovered and/or investigated. If this account is correct then it serves to explain, contrary to Glymour[xxi], why a conceptual distinction between descriptions of patterns of data and descriptions of physical phenomena is crucial for pragmatic reasons. Without such a distinction, it would be unclear how to apply knowledge (i.e. knowledge of mere data patterns gained by means of a specific experimental set-up, rather than knowledge of phenomena occurring in specific physical-technological conditions) to another system, let alone how to apply it in designing another system – for, as Bogen and Woodward put it, the data are idiosyncratic to the system that produced them, to which I would add that physical phenomena are idiosyncratic to the specific physical-technological conditions that produced them.

## 4. FORMATION OF SCIENTIFIC CONCEPTS OF PHENOMENA IN EXPERIMENTAL PRACTICE

The broader aim of this article is to explain 'how it is possible that scientific knowledge of physical phenomena enables designing.' In order to answer this question, I contend that the trick is precisely *not* to split it into two apparently obvious, separate questions: how scientific knowledge of physical phenomena is possible and, next, how it is possible that this knowledge enables design. The crux lies in recognizing that researchers involved in experimental practices produce knowledge of phenomena *in such a manner that it enables epistemic uses*. For instance, knowledge produced by means of experiments must be such that it enables new experiments to be designed and their outcomes (i.e. the physical phenomena produced by these experiments) to be predicted. In the philosophy of science, designing new experiments that are aimed at generating phenomena that are predicted by tentative knowledge hypothesized in earlier experiments is commonly interpreted as a methodology initially intended to test the hypothesis (e.g. to test whether the purported phenomenon really does exist). Yet in actual experimental practice this approach may also be interpreted differently: preliminary knowledge hypothesized in earlier experiments (e.g. a hypothesized physical phenomenon or property) can be seen as enabling the design of new experiments which in turn facilitate further investigation of the purported object of research (i.e. the phenomenon or property), thereby generating new knowledge of it – notably, this may also involve its rejection. The hypothesis that describes the purported physical phenomenon or property is a scientific concept. Uljana Feest[xxii] proposes an account of scientific concepts that explains this further. She proposes that we

> 'think of the descriptive features of a concept not in terms of whether they can adequately represent the object under investigation, but how they enable experimental interventions in the process of investigating the purported or ill-understood object. The basic idea here is that concepts figure as tools for the investigation of such objects. As such they can contribute to experimental knowledge generation, but they can also be refined and discarded in the process.'[xxiii]

She continues:

> 'The basic point here is that we cannot even begin to study the purported object of research ... unless we work with a preliminary understanding of how to empirically individuate the objects that possess it. Operational definitions function as tools to this end by providing paradigmatic conditions of application for the concepts in question.'[xxiv] [xxv]

In brief, Feest[xxvi] argues that concepts of (in my case) phenomena are formed by creating operational definitions of them; these definitions are cast in terms of a description of a typical, paradigmatic experimental set-up believed to generate data that are indicative of the phenomenon specified by the concept. Furthermore, as a consequence of this account, the descriptive features of these concepts do not initially constitute an adequate representation of the phenomenon. Instead, according to Feest, concepts are tools which enable experimental intervention in the domain of study, thereby generating knowledge about the phenomenon.

If this account is correct, it implies that: (1) the actual conception of a phenomenon is enabled by the description of aspects of an experimental set-up and (2) the resulting scientific concept is entangled with that description. This account explains how it is possible that scientific knowledge of physical phenomena enables design. When designing advanced technologies, researchers do not need knowledge of phenomena independent of the physical-technological environment responsible for their occurrence or manifestation. On the contrary, they need knowledge of the physical effects produced by a physical-technological environment (e.g. as generated by means of the experimental set-up) and, more specifically, they need to know which features of this environment are crucial for the occurrence of that effect. This is exactly what an operational definition of a phenomenon such as the one proposed by Feest[xxvii] seems to provide. In other words, this account explains how scientific concepts of phenomena (e.g. objects, processes, properties) are formed so that these concepts can be put to epistemic use in design processes.

In Boon (2012)[xxviii], I elaborate on the account of scientific concepts proposed by Feest[xxix], arguing that the process of inferring from the description of aspects of an experimental set-up an operational definition of a phenomenon, which, in turn can be used as a scientific concept involves subsuming this description under more abstract concepts, such as naming it as an 'object', a 'property', or a 'causal relationship', and under theoretical concepts, such as 'force', 'energy', 'fluid', etc. I argue that subsuming an empirical description under such abstract and theoretical concepts makes them theoretical rather than strictly empirical, as it introduces new epistemic content that expands on what is empirically known and is therefore also hypothetical. It is exactly this additional epistemic content that enables asking new questions by means of which the investigation of the phenomenon moves forward. Furthermore, the additional abstract and theoretical content enables epistemic uses of these concepts in new circumstances, as will be shown below.

Examples of phenomena – also called properties – in the engineering sciences that have been conceptualized by means of paradigmatic experiments include material properties such as 'elasticity', 'viscosity', 'heat content', 'melting point', 'electrical resistance', 'thermal conductivity', 'magnetic permeability', 'physical hysteresis', 'crystallinity', 'refractivity', 'chemical affinity', 'wavelength', 'chemical diffusivity', 'solubility', 'electrical field strength', 'super-conductivity', and 'atomic force'. The concept of each of these properties is related to experiments by means of which they were initially defined. Hooke's experimental set-up, for instance, in which the extension of a spring was measured as a function of its weight, can be regarded as a paradigmatic experiment by means of which the property 'elasticity' was operationally defined. The description of the paradigmatic experiment might be formulated as follows: 'to measure the reversible (and proportional) extension of a spring by a weight,' which is the observable phenomenon. The preliminary operational definition of 'elasticity' derived from it could be rendered as 'the property of a spring to reverse its stretch when extended by a weight.' Accordingly, the description of the paradigmatic experiment is subsumed under a more abstract concept (e.g. the concept 'property') and also – as elasticity is conceived of as a kind of force – under the theoretical concept 'force', which results in the scientific concept 'elasticity' being defined as 'the measurable *property* of an object to reverse a deformation imposed by a *force*.'

In other words, researchers infer an operational definition of a phenomenon from a description of a paradigmatic experiment: the definition is cast in terms of a description of the paradigmatic experimental set-up. In a subsequent step the operational definition, by being interpreted as a definition of a *property* and by interpreting the observed phenomenon in terms of theoretical concepts, is turned into a scientific concept which can be applied to situations that differ from the paradigmatic experimental set-up: wherever the reversible deformation of an object occurs, we attribute the property 'elasticity' to the object and assume that it is a quantifiable property, independent of the kind of object, the kind of matter and the kind of force involved. Therefore, the concept 'elasticity' refers to a qualitative and quantifiable *property* of materials or substances while at the same time expressing aspects of the paradigmatic experiment significant for the occurrence of elasticity.

Note that, from a theory-oriented perspective, the epistemological approach in Hooke's experiment is interpreted differently. Van Fraassen (2012)[xxx], for instance, may critically ask: '*what* quantity does Hooke's measurement measure?', going on to argue that this involves a theory-dependent answer: 'Whether a procedure is a measurement and, if so, what it measures are questions that have, in general, answers only relative to a theory.' Van Fraassen refers to Galileo's design of an apparatus to measure the force of a vacuum (in his *Dialogues Concerning Two New Sciences*) and argues that, from Galileo's point of view, this apparatus measures the magnitude of the force of the vacuum, although from a later point of view it is measuring a parameter absent from Galileo's theory, namely, atmospheric pressure. However, in many cases, experimental findings precede theory. Furthermore, whether experimental findings are interpreted as measuring 'something' also depends on aspects of the experiment itself, such as its stability and reproducibility. Hence, although I am not in disagreement with Van Fraassen[xxxi], one of the consequences of shifting the focus to the role of experiments in producing and investigating physical phenomena, as proposed in this article, is that experimental practices may also give rise to a different epistemology. The proposal made here is that the interpretation of experimental findings involves formulating a scientific concept in terms of an operational definition and subsuming this empirical description under abstract and theoretical concepts. The covering concepts, such as 'property' and 'force', are not initially derived from theories, as Van Fraassen suggests, but have first and foremost an everyday meaning; applying them in contexts beyond their everyday uses in the ways just mentioned makes them theoretical.[xxxii]

Does this account indeed provide an understanding of how researchers produce scientific knowledge of phenomena such that it enables epistemic uses in the design process? In line with Feest[xxxiii], I suggest that the scientific concept thus formed enables additional experimental investigation of the purported phenomenon *because* it is phrased in terms of a description of a paradigmatic experimental set-up. In sum, the scientific concept together (and entangled) with knowledge of the paradigmatic experimental set-up make it possible to investigate the phenomenon or property in varying physical conditions and technological circumstances. In such experimental research, the space of causally relevant technological and physical variables is explored, wherein the original physical-technological conditions of the experimental set-up will be varied and extended using all kinds of often newly developed measurement techniques.

## 5. PHENOMENA AND PROPERTIES – THEIR MEASUREMENT AND MATHEMATIZATION

Authors in the philosophy of science such as Bogen and Woodward, do not usually distinguish between properties and phenomena, whereas scientific practices do. It was suggested above that in the distinct uses of these terms, a phenomenon is the actual manifestation of a property and that, conversely, a property is a capacity that manifests under specific conditions. Yet scientific practices employ an additional distinction, that is, between phenomena and measurable quantities that are characteristic of a material or object (such as a technological device). Measurable quantities are also called characteristic or specific properties but are often referred to as just 'properties of a material or object'.[xxxiv] In this section, I seek to elucidate how the determination of characteristic quantities of materials and objects is important as an epistemic strategy for producing knowledge of physical phenomena.

Experimental investigations of a purported phenomenon, such as those as outlined in the previous section, produce different kinds of large amounts of data. In order to be useful for performing epistemic functions, these data must be efficiently organized. One of the well-known strategies in scientific research for doing so is to establish mathematical relationships (e.g. proportionality) between measured data.[xxxv] Hooke's law, for instance, describes the extension of a spring, X, as a function of the exerted force, F, and a constant factor, *k*, the elasticity coefficient of a spring. Stated more generally, these kinds of equations describe the phenomenon (e.g. 'deformation of an elastic object by means of exerting a force') as a function of variable quantities (i.e. causally relevant technological circumstances such as length and width of the spring, and physical conditions such as temperature and pressure) and some more stable quantities that characterize the substance, material, object, or system under study (e.g. the elasticity coefficient of a material or object). Accordingly, in constructing these kinds of mathematical equations for describing measured data (i.e. phenomenological laws), a conceptual distinction is made for pragmatic reasons between (1) variable quantities typical of the phenomenon, (2) variable physical and technological quantities affecting or determining the phenomenon and (3) more stable quantities characteristic of the substances, materials, objects and systems involved.

Generally speaking, the aim of experimental practices is to characterize substances, materials, objects and systems in terms of stable, quantifiable physical properties, that is, stable quantities called *characteristic properties*. These stable quantities are derived from measurements by converting measured data to a quantity *per* characteristic unit of the substance, material, object or systems, such as per unit of mass, molecules, electrons, length, surface, volume, time, or temperature. For instance, the density of a material is the measured weight of this material *per* characteristic unit of volume (e.g. cubic meter) of this material; the elasticity coefficient of a spring is its extension *per* unit of length of the spring and per unit of mass causing its extension; the heat transfer coefficient of a material is the measured Joules transferred *per* unit of time, per unit of surface, per unit of length (thickness), and per unit of temperature difference between the two surfaces of the material. Note that the inference from measured data to characteristic stable quantities is only justified if the proportionality has been experimentally tested. Also note that the values of these stable quantities are usually still dependent on causally relevant conditions. The density and the elasticity coefficient of a specific material, for instance, are affected by its temperature. Similarly, in the case of such causal influences on 'stable' quantities, researchers will deal with this using the same epistemic strategy, namely, constructing mathematical equations that describe the property (such as the elasticity coefficient) as a function of *variable quantities* (i.e. causally relevant physical conditions and technological circumstances). The latter equations may entail yet other stable quantities that characterize the substance, material, object, or system under study (e.g. its molar weight, its specific heat constant). Hence, again and again, the same epistemic strategies of experimentation and mathematization are used in producing scientific knowledge of phenomena and properties.

The values of characteristic properties of materials etc. are most reliably measured by standardized measurement methods.[xxxvi] These values are summarized in handbooks such as the classic *CRC Handbook of Chemistry and Physics*.[xxxvii] Significantly, any one kind of property can be determined of many different kinds of materials (e.g. the elasticity coefficient of different kinds of materials or the melting point of different kinds of metals and fluids). Conversely, any one kind of material (e.g. gold) allows for determining many different kinds of properties (e.g. its density, melting point, electrical conductivity coefficient and elasticity coefficient). Besides being convenient for constructing mathematical equations to describe phenomena, the values of characteristic properties of materials etc. are also useful for comparing differences between materials (or substances, objects and systems), which is important for design.

Similarly, specific physical properties of types of technological processes and systems can be determined using standardized measurement methods. Mathematical equations and values describing these quantities are summarized in engineering handbooks.[xxxviii]

Although the qualitative and quantitative measurements used to establish physical properties are reproducible, there is nothing 'essential' about them. The point being made here is that physical quantities are reproducibly and stably *produced* by means of *contingent* technological instruments and measurement procedures, which reproducibly and stably *determine* the measurement outcomes.[xxxix] In other words, given the regulative principle stating that *under the same physical conditions the same quantitative and qualitative effects will occur*, the manifestation of these quantities is inevitable, that is, their occurrence is produced and determined by the physical-technological system and procedure used.[xl] However, this also implies that there is no point in claiming that materials have properties that are in some way essential. Conversely, as soon as a technologically produced property (such as 'elasticity,' 'electrical resistance,' and 'melting point') has been conceptualized, this property can often be determined (in principle, although not always in practice) of many other materials as well. In other words, these properties are made manifest in other materials by means of new measurement techniques together with the concept of that new property.

Another consequence of the observation that many properties manifest only through the technological and physical conditions produced in an experimental set-up is that there is not an essential or limited set of physical properties. On the contrary, the number of different kinds of properties of substances, materials and systems increases with technological instrumentation and experimentation and with the theoretical interpretation of their outcomes. A sign of this increase can be witnessed in the *CRC Handbook* mentioned above, which contains new properties in every new edition: in the first edition of 1914, for example, all the measured physical properties covered some 100 pages while in the 94th edition of 2014 they covered more than 2600 pages.

Expanding on the point just made, many material properties and phenomena result only from technological interventions and interactions, that is to say, their existence and/or their manifestation depends on specific causally relevant conditions brought about by means of the physical conditions of technological instruments and procedures. Why would researchers be interested in investigating them? We only have to skim through the *CRC Handbook of Chemistry and Physics* to begin guessing at the answer to this question. Why, for example, would they be interested in physical phenomena such as diffusion, heat transfer and electrical conduction in different types of material? And why should they measure for different types of materials' characteristic properties such as the melting point, specific heat content, diffusion coefficient, electrical resistance coefficient and so on and so forth, other than for their technological relevance? Indeed, it can be said of many of the properties and phenomena that have been investigated that the researchers involved were not so much interested in them in order to test theories; instead, most properties and phenomena are studied out of an interest in potential technological applications.

## 6. CONCLUSIONS

Traditionally, the philosophy of science has assumed that theories are the ultimate aim of science and has therefore considered the role of experiments and measurements in discovering and testing scientific theories. In this article, the role of measurements and experiments has been considered in a different context, namely, in relation to the question of how it is possible that scientific knowledge of physical properties and phenomena enables designing – or, should we say, *inventing* – advanced technologies. The pragmatic approach taken to articulate an epistemology that accounts for the production of scientific knowledge through measurement and mathematization such that this knowledge enables design additionally gives rise to a novel pragmatic position on the character of scientific knowledge that is significant for the philosophy of science more generally: One of the points resulting from this analysis is that the explanation of successful uses of scientific knowledge, such as their uses in technology, seems not to be in need of the kind of justification which philosophers of science often seek to provide. The crucial point in developing an explanation of *how it is possible that scientific knowledge of physical phenomena enables designing* is that this question should not be analyzed in terms of two separate questions, *how is scientific knowledge of physical phenomena possible?* and *how does this knowledge make design possible?* The crux lies in recognizing that researchers engaging in experimental practices produce scientific knowledge of phenomena *such that* it enables epistemic uses in epistemic activities such as designing. Further, from an epistemological perspective some aspects of the process of design appear to be very similar to the scientific methodology of deriving verifiable predictions that are tested in experiments, thus enabling the hypothesis in question to be tested and improved (i.e. the hypothetical-deductive method). However, focusing on the epistemic uses of scientific knowledge produced by experimental set-ups reveals that these epistemic uses are actually inextricably linked with measurable and observable aspects of the technical and physical world.

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[i] See also W. Houkes and P. E. Vermaas, 'Technical Functions: On the Use and Design of Artefacts', in *Philosophy of Engineering and Technology* Vol. 1 (Dordrecht: Springer 2010).

[ii] It is worth noting that nowadays the design of, say, a house can also be advanced. Given that this is the case, the distinction identified is an intuitive one.

[iii] Note, however, that the notions of 'property' and 'phenomenon' are conceptually entangled and are often used interchangeably. Bogen and Woodward (1988), for instance, use the sentence 'Lead melts at 327 $^{0}$C' as an example of a *phenomenon* that is inferred from measurements: See J. Bogen and J. Woodward, 'Saving the Phenomena', *The Philosophical Review*, 97:2 (1988), pp. 303-52. This suggests that we could equally describe the measured *property* as follows: 'The melting-point of lead is 327 $^{0}$C.' Nevertheless, as pointed out in section 5 below, a conceptual distinction between 'phenomena' and 'properties' is relevant in terms of how experimental set-ups and measurement results are produced, organized and utilized in scientific practices.

[iv] In this article, 'physical' is meant in the broad sense, including chemical, biological, biochemical, electrical, mechanical, thermo-dynamic, hydro-dynamic (and so forth) properties. Furthermore, different kinds of things can have physical properties, including substances, materials, phenomena, objects, and technological systems. In this article, this set of meanings is abbreviated by referring to the 'physical properties of materials and systems.'

[v] Examples of measurable characteristic or specific physical properties of *materials* include the elasticity coefficient, refraction index, viscosity coefficient, diffusion coefficients, heat conductivity, electrical conductivity or resistance coefficient, magnetic permeability, specific solubility (e.g. of salts or gases in a fluid), melting and freezing temperature, critical temperature, volumetric heat capacity, chemical affinity, reaction-rate coefficient and dissociation constant. Similarly, specific properties of *technological devices* such as industrial chemical plants play a role in design. Examples of measurable physical properties in these systems include the specific mass-transfer coefficients (e.g. for the transfer of a compound from the gas phase to the liquid phase in a mechanically stirred fluid), the specific mixing time (e.g. of a mechanically stirred fluid), and specific heat transfer coefficients. In these latter examples, 'specific' means 'per unit significant to the system', i.e. per unit of time, length, volume, mass, temperature, energy input etc.

[vi] My account of 'technological function' can be found in E. Weber, T. A. C. Reydon, M. Boon, W. Houkes and P. E. Vermaas, 'The ICE-theory of Technical Functions', *Metascience,* 22:1 (2013), pp. 23-44., on p. 33.

[vii] See Bogen and Woodward, 'Saving the Phenomena'.

[viii] See U. Feest, 'Concepts as Tools in the Experimental Generation of Knowledge in Cognitive Neuropsychology', *Spontaneous Generations: A Journal for the History and Philosophy of Science*, 4:1 (2010), pp. 173-90.

[ix] See M. Boon, 'An Epistemology of Designing', (forthcoming).

[x] See E. Y. Kenig, R. Schneider and A. Górak, 'Reactive Absorption: Optimal Process Design via Optimal Modelling', *Chemical Engineering Science,* 56:2 (2001), pp. 343-50.

[xi] See Bogen and Woodward, 'Saving the Phenomena'.

[xii] See J. F. Woodward, 'Data and Phenomena: a Restatement and Defense', *Synthese*, 182:1 (2011), pp. 165-79.

[xiii] See Bogen and Woodward, 'Saving the Phenomena', p. 308.

[xiv] Bogen and Woodward, 'Saving the Phenomena', p. 326.

[xv] See J. W. McAllister, 'Phenomena and Patterns in Data Sets', *Erkenntnis,* 47:2 (1997), pp. 217-28; J. W. McAllister, 'What Do Patterns in Empirical Data Tell Us About the Structure of the World?', *Synthese*, 182:1 (2011), pp. 73-87.

[xvi] See B. Glymour, 'Data and Phenomena: A Distinctions Reconsidered', *Erkenntnis*, 52:1 (2000), pp. 29-37.

[xvii] See McAllister, 'Phenomena and Patterns in Data Sets'.

[xviii] Bogen and Woodward, 'Saving the Phenomena', p. 326.

[xix] See M. Boon, 'Scientific Concepts in the Engineering Sciences: Epistemic Tools for Creating and Intervening with Phenomena', in U. Feest and F. Steinle (eds.), *Scientific Concepts and Investigative Practice* (Berlin, New York: Walter De Gruyter, Series: Berlin Studies in Knowledge Research, 2012), pp. 219-43.

[xx] See Boon, 'An Epistemology of Designing'.

[xxi] See Glymour, 'Data and Phenomena: A Distinctions Reconsidered'.

[xxii] See U. Feest, 'Concepts as Tools in the Experimental Generation of Knowledge in Psychology', in U. Feest, G. Hon, H.-J. Rheinberger, J. Schickore and F. Steinle (eds.), *Generating Experimental Knowledge* (MPI-Preprint

340, 2008), pp. 19-26; Feest, 'Concepts as Tools in the Experimental Generation of Knowledge in Cognitive Neuropsychology'.

[xxiii] Feest, 'Concepts as Tools in the Experimental Generation of Knowledge in Cognitive Neuropsychology', p. 177.

[xxiv] Feest, 'Concepts as Tools in the Experimental Generation of Knowledge in Cognitive Neuropsychology', p. 177.

[xxv] Chang presents an overview of 'Operationalism' in H. Chang, 'Operationalism', in E. N. Zalta (ed.), *The Stanford Encyclopedia of Philosophy* (Fall 2009 Edition), URL = <http://plato.stanford.edu/archives/fall2009/entries/operationalism/>.

[xxvi] See Feest, 'Concepts as Tools in the Experimental Generation of Knowledge in Cognitive Neuropsychology'.

[xxvii] See Feest, 'Concepts as Tools in the Experimental Generation of Knowledge in Cognitive Neuropsychology'.

[xxviii] See Boon, 'Scientific Concepts in the Engineering Sciences: Epistemic Tools for Creating and Intervening with Phenomena'.

[xxix] See Feest, 'Concepts as Tools in the Experimental Generation of Knowledge in Psychology'; Feest, 'Concepts as Tools in the Experimental Generation of Knowledge in Cognitive Neuropsychology'; U. Feest, 'What Exactly is Stabilized When Phenomena are Stabilized?', *Synthese*, 182:1 (2011), pp. 57-71.

[xxx] See B. C. Van Fraassen, 'Modeling and Measurement: The Criterion of Empirical Grounding', *Philosophy of Science*, 79:5 (2012), pp. 773-84.

[xxxi] See Van Fraassen, 'Modeling and Measurement: The Criterion of Empirical Grounding'.

[xxxii] See also H. Chang, 'Acidity: The Persistence of the Everyday in the Scientific', *Philosophy of Science,* 79:5 (2012), pp. 690-700.

[xxxiii] See Feest, 'Concepts as Tools in the Experimental Generation of Knowledge in Cognitive Neuropsychology'.

[xxxiv] The two terms, 'property' and 'quantity' are often used interchangeably. How are they related? The *Joint Committee for Guides in Metrology* (VIM 2012) defines 'quantity' as 'a property of a phenomenon, body, or substance, where the property has a magnitude that can be expressed as a number and a reference.' VIM (2012). 'International Vocabulary of Metrology – Basic and General Concepts and Associated Terms (VIM)', Document produced by Working Group 2 of the Joint Committee for Guides in Metrology (JCGM/WG 2), at http://www.bipm.org/utils/common/documents/jcgm/JCGM_200_2012.pdf.

[xxxv] In Boon (2011), I argue that data produced in experiments can be interpreted in two different ways: causal-mechanistically and mathematically. See M. Boon, 'Two Styles of Reasoning in Scientific Practices: Experimental and Mathematical Traditions', *International Studies in the Philosophy of Science*, 25:3 (2011), pp. 255-78. These two perspectives produce distinct scientific results, which are connected by means of the target system (the experimental set-up), but cannot be reduced to each other. Conversely, they enable distinct kinds of epistemic uses. In the current article, it is argued that scientific knowledge of a phenomenon required for designing involves both types of knowledge: the scientific concept presenting a causal or causal mechanistic description that is partially phrased in terms of the experimental set-up, and the mathematical formula describing the phenomenon as a function of relevant other physical and technical circumstances.

[xxxvi] E.g., test methods as have been documented and published through the *American Society for Testing and Materials, ASTM International*.

[xxxvii] The website of this handbook http://www.crcpress.com/product/isbn/9781466571143 states: 'Celebrating the 100th anniversary of the *CRC Handbook of Chemistry and Physics*, the 94th edition is an update of a classic reference, mirroring the growth and direction of science for a century. The Handbook continues to be the most accessed and respected scientific reference in the science, technical, and medical communities. An authoritative resource consisting of tables of data, its usefulness spans every discipline.'

[xxxviii] For instance, *Perry's Chemical Engineer's Handbook* http://accessengineeringlibrary.com/browse/perrys-chemical-engineers-handbook-eighth-edition and *The Handbook of Chemical Engineering Calculations* http://accessengineeringlibrary.com/browse/handbook-of-chemical-engineering-calculations-fourth-edition.

[xxxix] See also Cartwright's notion of nomological machines, which are considered as stably and reproducibly functioning experimental set-ups producing stable, repeatable patterns of data. See N. Cartwright, *How the Laws of Physics Lie* (Oxford: Clarendon Press, Oxford University Press, 1983); N. Cartwright, *Nature's Capacities and their Measurement* (Oxford: Clarendon Press, Oxford University Press, 1989). For an expanded explanation of Cartwright's notion see Boon, 'Scientific Concepts in the Engineering Sciences: Epistemic Tools for Creating and Intervening with Phenomena'.

[xl] Note that this situation is contingently dependent on the physical, practical and technological possibility of constructing physical systems and procedures that act stable and reproducible. This holds for many physical-technological systems. However, from a pragmatic point of view, the situation is very different for systems studied in social sciences, and also when studying more complex physical systems such as those under study in medical or climate research. Concerning these kinds of systems, the regulative principle that 'at the same conditions the same quantitative and qualitative effects will happen' may still be held true by scientific researchers in these practices. Yet, it is of much lesser use as a *guiding* principle, that is, as a principle that guides (*regulates*) scientific approaches.