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Abstract

This article explores the role of ‘robustness-notions’ in an account of the engineering sciences. The engineering sciences aim at technological production of, and intervention with phenomena relevant to the (dis-)functioning of materials and technological devices, by means of scientific understanding thereof. It is proposed that different kinds of robustness-notions enable and guide scientific research: (1) *Robustness* is as a metaphysical belief that we have about the physical world – i.e., we believe that the world is robust in the sense that the same physical conditions will always produce the same effects. (2) ‘*Same conditions – same effects*’ functions as a regulative principle that enables and guides scientific research because it points to, and justifies methodological notions. (3) *Repetition*, *variance* and *multiple-determination* function as methodological criteria for scientific methods that justify the acceptance of epistemological and ontological results. (4) *Reproducibility* and *stability* function as ontological criteria for the acceptance of phenomena described by A→B. (5) *Reliability* functions as an epistemological criterion for the acceptance of epistemological results, in particular law□like knowledge of a conditional form: “A→B, provided C_{device}, and unless other known and/or unknown causally relevant conditions.” The crucial question is how different kinds of robustness□notions are related and how they play their part in the production and acceptance of scientific results. Focus is on production and acceptance of physical phenomena and the rule-like knowledge thereof. Based on an analysis of how philosoophy of science tradtionally justified scientific knowledge, I propose a general schema that specifies how inferences to the claim that a scientific result has a certain epistemological property (such as truth) are justified by scientific methods that meet specific methodological criteria. It is proposed that ‘same conditions – same effects’ as a regulative criterion justifies ‘repetition, variation and multiple□determination’ as methodological criteria for the production and acceptance of (ontological and epistemological) scientific results.

Chapter 12

Understanding Scientific Practices: The Role of Robustness Notions

Mieke Boon

12.1 Introduction

The rationale for considering robustness as an important notion for understanding scientific practices is directly related to key issues in the philosophy of science such as: why science is so successful; why theories are accepted; how scientific knowledge can be justified; and how scientific theories are related to the real world. Within this scope, which focuses on theories as the aim of science, the issue is whether robustness functions as a 'truth-maker' of theories or as an alternative to their truth.

The perspective from which robustness will be considered in this article is for understanding scientific research in the context of practical applications, such as technological, (bio-) medical and agricultural research, and the forecasting of natural processes. Scientific research in these fields interprets practical problems or technological functions in terms of *phenomena* that determine the cause of technological (dys)functioning. Scientific research aims at intervening with these phenomena (e.g. their artificial production or prevention) by developing scientific understanding about them (cf. Boon 2009; Boon and Knuuttila 2009). Therefore, the epistemic aim of these practices differs from the ultimate aim that the philosophy of science usually ascribes to science. The epistemic aim of scientific research in the context of such things as practical applications is the reliability and relevance of theoretical knowledge regarding these applications, rather than the truth of theories. From this practice-oriented perspective, accounting for the *truth of conclusions* drawn from scientific theories is more important than accounting for the *truth of scientific theories*. Clearly, someone may object that the distinction between true

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theories and true conclusions is already accounted for in the relationship between fundamental and applied sciences, according to which drawing conclusions from true knowledge produced in the fundamental sciences produces true conclusions in the applied sciences. However, it is an empirical fact of scientific practices that the conclusions drawn from supposedly (approximately) true theories are often false (cf. Cartwright 1983) or irrelevant. Usually a significant amount of additional experimental research is required to produce scientific models that fit the real world (see also Morrison and Morgan 1999).

Given this situation, scientific practices in the context of practical applications require a philosophical account that explains what science can and cannot do, rather than an account of how the truth of scientific results is justified. Therefore, understanding the character and justification of the reliability and relevance of scientific knowledge used in practical applications is an issue that matters. Within this context, the principle question of this article is: *What part can robustness notions play in understanding scientific practices aimed at producing reliable and relevant scientific results (such as scientific theories, models and concepts, but also phenomena and physical systems) for practical application*? My thesis comprises four statements: (a) different kinds of robustness notions must be distinguished (i.e. metaphysical, regulative, methodological, ontological and epistemological), each pointing at different aspects and presuppositions of scientific research; (b) they have to be viewed as complementary to each other; (c) they are ultimately held together by the regulative principle ‘same conditions – same effects’; and (d) robustness as an epistemological notion functions as an alternative to truth.

The structure of this article is as follows. Section 12.2 explains some philosophical presuppositions about scientific practices that provide the foundation for my argument. Section 12.3 presents a conceptual analysis of robustness. There appear to be different kinds of robustness notions. By utilizing traditional philosophical accounts of the justification of scientific knowledge, it also analyses how robustness is related to truth. This analysis seeks to examine whether robustness can be an alternative to truth. Section 12.4 explains why methodological robustness notions justify the attribution of epistemological (and ontological) robustness notions to scientific results, and why the role of ‘same conditions – same effects’ as a regulative principle is crucial.

My argument is divided into two parts, each of which takes a different approach. The first part (Section 12.3) uses traditional analytical approaches in the philosophy of science. It employs Van Fraassen’s (1980) notion of empirical adequacy as a philosophical guide for articulating the role of epistemological criteria in accepting epistemological results. The second part (Section 12.4) focuses on the idea that scientific practices seek a variety of scientific results. It takes Hacking’s (1992, 1999) notion of a mutual fit between different elements that constitute a laboratory practice (‘ideas, matériel, and marks’) as a preliminary philosophical account in which ‘true theories’ are no longer regarded as crucial for explaining the success of science.

12.2 Traditional Philosophy of Science Versus Philosophy of Scientific Practices

My approach in Part I (Section 12.3) of the argument aims to tie in with a traditional approach in the philosophy of science because this tradition contributes to the conceptual clarification of robustness. At the same time, traditional philosophical approaches involve several assumptions about science that are unproductive for understanding concrete scientific practices. In this section, I will compare some of the important presuppositions of traditional philosophy of science with those I consider as more appropriate for a philosophy of scientific practices. The proposed alternatives will be taken as the philosophical foundation to Part II (Section 12.4) of my argument.

As an alternative to the assumption that the aim of science is true theories, I propose that the epistemic aim of science is to produce epistemic means that allow for scientific reasoning about the (natural or laboratory) world (see also Rouse 2009, forthcoming), and as a consequence, that the task of the philosophy of science is to account for the acceptance of scientific results that facilitate the performance of this epistemological function. This alternative assumption does not necessarily exclude the role that truth could play. Rather, this proposal is made because accounting for the truth of theories is extremely problematic and may not even be necessary in accounting for the success of science and understanding actual scientific practices.

The second assumption of traditional approaches is the idea that science can be reduced to two basic elements: facts and theoretical knowledge. Observations and data are considered as the objective basis of facts, meaning that facts are philosophically unproblematic. The role that facts are supposed to play is in proving theories. The divide between the two elements is crucial to accounts of methodologies that justify (or falsify) the truth of theoretical knowledge, such as induction or verification (confirmation or falsification) by hypothetical-deductive approaches.

The so-called 'New experimentalists'[1] have criticized the idea that facts result from observations and data in an unproblematic manner. They have emphasized that observations and data of the independent real world are gathered by means of experiments, technological instruments and data-processing. Therefore, facts result from constructive activities in the physical world, while these constructive activities go together with practical and theoretical reasoning about technological instruments, data and physical phenomena. What is more, data, facts (i.e. descriptions of observable physical phenomena), data-processing, experiments, instruments and theoretical interpretations develop in a mutual interplay, and eventually 'vindicate' one another. Hacking (1992), therefore, proposed a much richer taxonomy of laboratory sciences, which he cleaved into three basic elements: marks (including observations, data and data-processing), matériel (including instruments and

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[1] Some of the key figures of this movement in the 1980s and early 1990s are Ian Hacking, Nancy Cartwright, Allan Franklin, Peter Galison, Ronald Giere and Robert Ackermann. More recent important contributions have come from Deborah Mayo and Hasok Chang.

experimental procedures, and the substances or objects investigated) and ideas (including theories and models of instruments). He thereby rejects the idea that data can prove theories. Instead, Hacking argues that the elements that constitute laboratory practices are mutually adjusted. Laboratory practices eventually become stable because a proper fit has been established between these elements.

Siding with Hacking, I propose that different kinds of elements are mutually dependent and adjusted; they are stabilized in constructive activities by means of practical and theoretical reasoning, along with interventions that seek to explore and adjust their mutual interplay – which is an alternative to the traditional assumption that facts are unproblematic and serve to prove theories.

There is a third assumption related to the first and second traditional one: the idea that theories are science's most important results. However, if we accept the idea that the elements that constitute scientific practices, such as the ones distinguished in Hacking's taxonomy, are developed in a mutual interplay of interventions with the physical world (i.e. the natural world and technological devices and procedures) together with practical and theoretical reasoning, then these other elements must also be regarded as scientific results. In other words, it is not only theories that are the results of scientific research, but also data and data-processing, physical phenomena and their descriptions, instruments and their uses, experimental set-ups and technological procedures, scientific laws and models of data and phenomena, scientific methods, etc.

This suggestion is particularly significant for understanding scientific research in the context of application. Often, the purpose of these practices is to produce phenomena for practical uses, including the technological devices or procedures that bring them into being, and in tandem with practical and theoretical understanding of how these phenomena are produced (or prevented, controlled, improved, etc.). Moreover, in many cases the aim of these research practices is to create *artificial phenomena*. These phenomena are created by technological manipulation, for instance, in order to meet a certain technological function (cf. Boon and Knuuttila 2009). Engineering sciences, which is scientific research in the context of technological applications, is an example of a science in the context of application. Its purpose is scientific research that contributes to the development of technological devices, processes and materials. Usually, the proper (or improper) functioning of devices, processes and materials is understood in terms of phenomena that produce (or are detrimental to) their desired behaviour. By experimentation and scientific modelling, the engineering sciences strive to respectively understand and produce the specific behaviour of devices and processes and/or the properties of materials. In working towards this purpose, scientific practices develop three things in a mutual interplay: (1) experimental techniques and scientific instruments that enable the creation of and intervention with phenomena relevant to the functioning of technological applications; and (2) 'rule-like knowledge' and scientific models about (a) these phenomena and (b) how scientific instruments and experimental techniques produce the desired and undesirable phenomena.

To summarise, the third assumption, which holds that science is only interested in theories, is inadequate. Scientific practices, in particular those that work in the context of applications, produce different kinds of scientific results, which include data, physical phenomena, instruments, scientific methods and different kinds of scientific knowledge. In this dynamic, the fit between different kinds of scientific results is an important criterion for their acceptance. In this article I will focus on three aspects: the production and acceptance of physical phenomena as ontological entities; the role of instruments and experiments in their production; and the rule-like knowledge that is produced simultaneously.

Finally, a fourth (often implicit) assumption of traditional accounts is that theoretical knowledge somehow *represents* some kind of 'mind-independent' structure in the real world.[2] As an alternative position that entirely avoids accounts that involve the need for a representational relationship between epistemological results and the world, one might adopt Hacking's (1992) assumption that the stability of scientific results consists of a proper fit between different elements that constitute laboratory practices. This position circumvents the idea that our theories somehow represent a cognizable structure that exists in the world, independent of human ways of knowing. However, Hacking's notion of stability is not entirely satisfactory because it does not explain *why* a proper fit between these different elements leads to the *success* of science. In particular, part of the success of laboratory practices comprises an exchange of these elements among different practices. The fact that these elements seem capable of travelling independently of the laboratory context in which they were produced (also see Howlett and Morgan 2010) cannot be explained by 'the self-vindication of a laboratory practice'. As an alternative, I will propose (in Section 12.4), as a minimal metaphysical belief, the idea that the world is real (or *robust*) in the sense that it is external to us and stably sets limits to our interventions with it. This position is a kind of realism since it assumes that an independent real world sets limits to what we can *do* with it and to the regularities, causal relations, phenomena and objects that can possibly be determined. Yet, this kind of realism is minimal because it avoids the idea of a cognizable independent order or structure in the real world.

12.3 Part I: Conceptual Analysis of Robustness

12.3.1 Metaphysical, Regulative, Ontological, Methodological and Epistemological Robustness Notions

William C. Wimsatt (1981, 2007) suggests that all the variants and uses of robustness share a common theme in distinguishing the *real* from the *illusory*; the *reliable* from the *unreliable*; the *objective* from the *subjective*; the *object* of focus from

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[2] Knuuttila and Boon (forthcoming) present a critical analysis of how and why scientific models (and theoretical knowledge) give us knowledge. They argue that most philosophical accounts eventually draw on a representational relationship between scientific models and how the real world is.

artefacts of perspective; and, in general, that which is regarded as ontologically and epistemologically *trustworthy* and *valuable* from that which is *unreliable*, *ungeneralizable*, *worthless* and *fleeting*. In this context, *robustness analysis* is of key importance to scientific methodology. Things or scientific results such as processes, laws and structures are reliable and valuable (or "robust") to their degree of invariance or stability under a robustness analysis, which involves the following procedures: analyzing a *variety* of *independent* derivation, identification or measurement processes; looking for and analyzing things which are *invariant* over or *identical* in the conclusions or results of these processes; determining the scope of the processes across which they are invariant and the *conditions* on which their invariance depends; and analyzing and explaining any relevant *failures of invariance*. Wimsatt calls these procedures *multiple determination* or *robustness* (Wimsatt 2007, pp. 43–44).

Several other authors have also used 'robustness' and related notions to account for the epistemological or ontological character of scientific results, as well as for the way in which these results are accepted or justified. Pickering (1987, 1989) argues that scientific results are accepted, not because they correspond to something in the world, but because scientists bring so-called plastic resources in relations of mutual support, thus producing a "robust-fit" (cf. Hacking 1999). The resources are: the material procedure (including the experimental apparatus itself along with setting it up, running it and monitoring its operation); the theoretical model of that apparatus; and the theoretical model of the phenomena under investigation. As already mentioned, Hacking (1992) suggests that the results of mature laboratory science ('ideas, matériel and marks') achieve stability when the elements of laboratory science are brought into mutual consistency and support. Woodward AQ1 (2001) seeks an account of the robustness of explanatory generalizations. He proposes that a generalization in biology is explanatory only if it is *invariant*, which means that it continues to hold under a relevant class of changes. Weisberg (2006) and Weisberg and Reisman (2008) argue that the *robustness* of theorems, such as the Lotka-Volterra principle that describes ecological processes, can be identified and confirmed by means of a robustness analysis (or stability analysis) of heorems.

Hence, robustness is used in the sense of reality, invariance, stability and reliability – other notions with a similar meaning are reproducibility, empirical adequacy and a notion that will be newly introduced in this context: 'same-conditions – same effects'. I will call them *robustness notions*. Interestingly, these robustness notions apply to different categories of things, such as physical processes and properties, scientific laws, theorems and models, methodological procedures and even the physical world or scientific practice as a whole. Indeed, despite their apparent synonymy, these robustness notions have distinct roles in the philosophical analysis of scientific practices. In order to account for these roles, I propose a conceptual distinction between *metaphysical*, *regulative*, *ontological*, *epistemological* and *methodological* robustness notions:

i. *Reality and stability* are properties of the physical world. We believe that the physical world is robust in the sense that it is external to us and stably sets limits to our interventions with it. In this context, reality and stability function as metaphysical robustness notions.

ii. *'Same conditions – same effects'* is a robustness notion that functions as a regulative principle of scientific practices. This principle says that under exactly the same physical conditions (in the natural world or in the laboratory or in technological devices) exactly the same physical effects will occur, which is an elementary assumption, the metaphysical or empirical truth of which cannot be proven. A regulative principle, therefore, is a fundamental presupposition or a 'condition of possibility' that facilitates scientific research: experimental sciences would not be possible without this presupposition. I will propose that 'same conditions – same effects' as a regulative principle is the philosophical basis of the other robustness notions and that it plays a crucial part in understanding the workings of these notions. This principle provides the condition for the possibility of metaphysical and/or logical principles that aim to justify inferences in scientific practices, such as induction, falsification and the ceteris paribus clause.

iii. *Reproducibility* denotes a property of measured data and observable or quantifiable physical occurrences that are produced by means of natural, experimental and/or technological conditions. Data and physical occurrences are considered as being reproducible if they are repeatable under the same technological and/or experimental conditions.

iv. *Stability* and *invariance* are ontological robustness notions because they are criteria for what can be accepted as *real* objects and phenomena. Importantly, scientists usually regard phenomena or objects as stable or invariant if they can intervene with them, for instance in experiments, or if they assume that they could intervene with them if they had better (or practically possible or ethically acceptable) procedures and technological means (cf. Woodward 2003) at their disposal. Additionally, scientists accept that an object is real *because* it is invariant or stable when transferred to other circumstances, while they also accept that a phenomenon is real *because* it is invariant or stable in the sense that they can experimentally or technologically create, produce, control or even prevent its occurrence.

v. *Reliability* denotes a property of theoretical knowledge, such as phenomenological laws (or "rule-like" knowledge) and scientific models, in their epistemic use to create explanations and predictions about real-world situations. Reliability is an epistemological robustness notion because it is a criterion for accepting theoretical knowledge.

vi. *Empirical adequacy* denotes a property of fundamental theories such as Newton's or Maxwell's. It is an epistemological robustness notion because it applies to theoretical knowledge.

vii. *Repetition* and *multiple determination* denote properties of scientific methods. They are methodological robustness notions that function as criteria for how scientific results such as reproducible data, stable phenomena and technological devices, reliable phenomenological laws and scientific models, empirically adequate fundamental theories, etc., are produced and justified. These notions guide the development of scientific methodologies that warrant the production of ‘robust’ scientific results. Important aspects of multiple determination are the above-mentioned aspects of a robustness analysis, e.g. variation, independence, invariance and failure of invariance (cf. Wimsatt 1981). The role of this methodological robustness notion is in the design and use of various technological instruments for producing measurements of the target system; the development of various technological devices and experimental procedures for the production of and intervention with phenomena; and the invention of methods for examining the proper and stable workings of these instruments and devices.

Hence, robustness notions function in different ways: Firstly, as a fundamental belief that we have about the (physical) world; secondly, as a regulative principle of scientific practices that justifies the functioning of other robustness notions and explains how these notions are related; thirdly, as a criterion for the actual existence of objects and phenomena; fourthly, as a criterion for the acceptance of epistemic results; and fifthly, as a criterion for methods that produce and justify the ‘robustness’ of measurements, phenomena and (theoretical) knowledge, i.e. methods that produce these scientific results and justify the attribution of epistemological and ontological properties. The proposed conceptual distinction between these robustness notions is summarized in Table 12.1.

Table 12.1 Conceptual distinctions of robustness notions

Category	Object	Robustness notion
Metaphysical	i. Reality→	i. Stable, deterministic, independent physical world
Regulative	ii. Scientific practice→	ii. ‘Same conditions – same effects’ as a presupposition or ‘condition of possibility’ for knowledge production
Ontological	iii. Measured data and physical occurrences→	iii. Reproducibility
	iv. Observable and theoretical objects, phenomena and causal relations→	iv. Stability and invariance
Epistemological	v. Phenomenological laws (or rule-like knowledge) and scientific models→	v. Reliability
	vi. Fundamental theories→	vi. Empirical adequacy
Methodological	vii. Scientific methods that ‘widen the span of phenomena, and the refinement of rule-like knowledge’	vii. Repetition and multiple-determination

12.3.2 Robustness as Truth-Maker or as an Alternative to Truth?

How do robustness notions relate to truth? Does ‘multi-determination’ taken as a methodological notion function as a ‘truth-maker’ or does reliability as an epistemological notion function as an alternative to truth? The two possibilities differ in the following way:

1. ‘Robustness’ functions as a *truth-maker*: Multi-determination functions as an alternative *methodological notion* that justifies the truth of scientific knowledge. It explains – or accounts for – *why* scientific knowledge is true. Scientific knowledge is true *if* it is the result of multiple-determination. This is how ‘robustness’ seems to function in Wimsatt (1981), Woodward (2001), Weisberg (2006) and Weisberg and Reisman (2008). ‘Robustness’ as a truth-maker is an alternative to how methodological notions such as ‘induction’, ‘hypothetical-deduction’ or ‘inference to the best explanation’, etc., are supposed to justify the truth of scientific knowledge.
2. ‘Robustness’ functions as an *alternative to ‘truth’*: Reliability functions as an alternative *epistemological notion*. In other words, truth as the central property of scientific knowledge is substituted by reliability. In this account, multiple determination may function as a methodological notion to justify the reliability of scientific knowledge but not its truth.

I will defend the second option and argue against the first. The questions to be answered then are: why and how robustness (in the sense of reliability) can function as an epistemological criterion, i.e. why and how it can function as an alternative to truth, and why robustness, in the sense of multi-determination, cannot function as a truth-maker.

Truth is an epistemological criterion. An epistemological criterion is the property that theoretical knowledge must have in order to be accepted or believed. This implies that the use of ‘reliability’ as an epistemological criterion must be similar to how ‘truth’ or other epistemological criteria, such as ‘empirical adequacy’, are used in statements such as: ‘a theory is accepted *if* it is true’ or ‘a theory is accepted *if* it is empirically adequate’. Similarly, ‘a theory is accepted *if* it is reliable’.

The crucial question is then how we know that a theory is true or empirically adequate or reliable. In other words, how do we justify that a theory has this epistemological property? In order to clarify this further, I will use Van Fraassen’s (1980) well-known approach to the meaning and justification of the truth of scientific theories. First, I will outline his approach. Then, I will apply the resulting analytical schema to the analysis of ‘reliability’ as an alternative epistemological criterion.

Van Fraassen’s point of departure is Tarski’s semantic definition of truth, according to which, truth is a property of a sentence, which tells us something about the relationship between the sentence and the real world. Van Fraassen’s *definition* of the truth of a sentence or theory “T” is (slightly rephrased for my purpose): The truth of “T” means that what T says is literally the case – that is, “T” literally tells what the real world is like. Subsequently, a methodological criterion is needed that determines whether "T" literally says what the world is like. Van Fraassen's much-debated criterion is that the truth of statements or 'stories' can only be determined for the directly observable state of affairs and occurrences. In other words, the story told by "T" must be observable.

Following these ideas, I propose to explicate the use and meaning of epistemological criteria and how they relate to methodological criteria in five systematic steps:

1. *The epistemological criterion*. An epistemological criterion, E, (e.g. truth) accounts for the *acceptance* of theoretical knowledge "T". This criterion is used as follows: An expression "T" is accepted *if* "T" is E. In other words, an expression (e.g. a sentence or a scientific theory) called "T" and saying T is accepted if and only if the epistemological property (e.g. truth) has been attributed to the expression "T". For instance, a theory or law "T" (e.g. Newton's theory or the ideal gas law) is accepted *if* "T" is E (e.g. true).[3]
2. *A semantic conception of the epistemological criterion*. In this account, epistemological properties are regarded as semantic concepts. Semantic concepts deal with certain relations between expressions of a language and the object referred to by that expression (cf. Tarski 1944). This means that epistemological concepts are regarded as properties of expressions in a language, and not as properties of objects in the world to which these expressions refer. Accordingly, an epistemological property (e.g. truth) is a property of "T" (e.g. theoretical knowledge) that specifies a certain relationship between expression "T" and the real world.[4]
3. *A semantic definition of the epistemological criterion*. One of the characteristics of semantic concepts is that their meaning must be given by definition and not, for instance, by designation. Hence, a semantic definition of the epistemological property E must be given. The form of this definition is: An expression "T" is E means or is defined as that what T says relates such and such to the empirical world. For instance, that a theory or law "T" is true means that what T says is actually the case.
4. *An operational definition of the epistemological criterion*. One of the characteristics of concepts introduced by means of a definition rather than by means of

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[3] Note that epistemological criterion E is a necessary property for scientific knowledge to be accepted, but may not be a sufficient criterion for acceptance, since other criteria, such as *relevance* or *explanatory power*, may play a role as well. Van Fraassen (1980, pp. 12–13) calls these additional criteria pragmatic values.

[4] In this manner, a distinction is made between properties of the world, e.g. material entities in the real world, and properties of expressions of a language, including theories. For example, red is regarded as a property of material or physical objects (e.g. the apple is red), whereas truth is regarded as a property of an expression (e.g. 'the apple is red' is true). Importantly, the way in which we learn their meaning is different. Usually, we learn the meaning of the properties of material objects by designation (e.g. by pointing at a red apple and saying 'Look! The apple is red.'), not by definition. The meaning of semantic concepts cannot be learned by designation (e.g. by pointing at something and saying 'Look! Newton's theory is true.'). Instead, the meaning of semantic concepts must be given by definition.

designation is that the use of that concept must also be defined.[5] This can be called an operational definition of the concept. The semantic definition of E (i.e. "T" is E means that what T says relates such and such to the empirical world) already includes the operational definition: "T" is E *if* what T says relates such and such to the empirical world. This latter version of the definition presents a criterion Q (e.g. is actually the case) for attributing the epistemological property E to a sentence "T". Namely, a sentence or scientific theory called "T" (and saying T about the empirical world) is E (e.g. true) if and only if what T says relates such and such to the empirical world. In short, the operational definition of the epistemological criterion reads: "T" is E (e.g. "T" is true) *if* T is Q (e.g. what T says about the empirical world is actually the case).

5. *The methodological criterion*. Hence, the problem of how to justify that the epistemic property for accepting theoretical knowledge applies (i.e. whether "T" is E) has been transferred to the problem of how to determine that T is Q (i.e. whether T relates such and such to the world). This is where methodology comes into play. Methodology involves a methodological criterion M (e.g. an observation), which is the quality a method must have in order to be accepted as a method by which it can be determined that T is Q. The use of this criterion is summarized as follows: "T is Q is justified *if* the question of whether T is indeed Q is determined by a methodology that meets methodological criterion M." For instance, the claim that 'what T says is actually the case' is justified *if* what T says can be directly observed in the real world. In short, observation counts as a methodological criterion: A method justifies the (approximate) truth of a sentence, a theory or a law *if* what the sentence, theory or law says is actually or literally the case. What the sentence, theory or laws says is literally the case must be determined by observation.

In the case of truth as an epistemological property of theoretical knowledge and direct observation as the methodological criterion for attributing this property to theoretical knowledge, this schema results in:

1. (1^T) *Epistemological criterion for the acceptance of theoretical knowledge*: "T" is accepted *if* "T" is true.
2. (2^T) *Semantic conception of the epistemological criterion*: Truth is an epistemological property of theoretical knowledge "T", which specifies a certain relationship between "T" and the real world, i.e. a relationship between what the theory says about the real world and how the world really or literally is.

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[5] For instance, knowing how to use the term 'bachelor' (e.g. in saying, 'this man is a bachelor') requires an explication of how we determine whether this man is a bachelor. Similarly, in order to use a semantic concept such as truth in saying 'this theory or law is true', it needs to be explicated how we determine whether the theory is true. Importantly, a definition of a term (e.g. a definition of being a bachelor) not only states its meaning (e.g. a man is a bachelor means that a man is not married), it also presents a criterion for whether the term applies (e.g. a man is a bachelor *if* a man is not married).

3. (3^T) *Semantic definition of the epistemological criterion*: "T" is true means or is defined as that what T says is actually the case.
4. (4^T) *Operational definition of the epistemological criterion*: "T" is true *if* what T says is actually the case.
5. (5^T) *Methodological criterion*: Direct observation is a methodological criterion for methods that determine whether what T says is actually the case. The use of this methodological criterion is summarized as follows: What T says is actually the case *if* 'what T says is actually the case' is determined by a methodology that is based on direct observation.

Clearly, if what our knowledge says about the world is observable in an unproblematic manner, we would not call it theoretical or scientific knowledge. Yet, the character of theoretical knowledge, "T", is that what T says is not observable in an unproblematic manner. According to Van Fraassen (1980), if T says something that is not observable in principle, we should refrain from attributing (approximate) truth to "T". In that case, this epistemological property does not apply and we need another property to account for, e.g. the acceptance or the success of "T". Van Fraassen proposed 'empirical adequacy' as an alternative notion, which is defined as: A theory "T" is empirically adequate *if* what it says about *observable* things in the world is true. Using this same line of reasoning, a methodological criterion is required to determine whether what the theory says about observable things is true. Van Fraassen (1980) and Suppe (1989) introduced the criterion of (partial) *isomorphism* between models that satisfy the axioms of the theory, on the one hand, and data models produced in experiments and data processing, on the other. In the case of empirical adequacy as an epistemological property of theoretical knowledge and (partial) isomorphism as the methodological criterion for attributing this property to theoretical knowledge, the former schema results in the following:

1. (1^{EA}) *Epistemological criterion for the acceptance of theoretical knowledge*: 'T' is accepted *if* 'T' is empirically adequate.
2. (2^{EA}) *Semantic conception of the epistemological criterion*: Empirical adequacy is an epistemological property of theoretical knowledge 'T', which specifies a certain relationship between 'T' and the real world, i.e. a relationship between what the theory predicts about the observable world and what can be directly observed of the real world).
3. (3^{EA}) *Semantic definition of the epistemological criterion*: 'T' is empirically adequate means or is defined as that what T predicts about the observable world is actually the case.
4. (4^{EA}) *Operational definition of the epistemological criterion*: 'T' is empirically adequate *if* what T predicts about the observable world is actually the case.
5. (5^{EA}) *Methodological criterion*: (Partial) isomorphism is a methodological criterion for methods that determine whether what T predicts about the observable world is actually the case. The use of this criterion is summarized as follows: What T predicts about the observable world is actually the case *if* 'what T predicts about the observable world is actually the case' is determined by a

methodology that is based on (partial) isomorphism, i.e. partial isomorphism between models that satisfy the axioms of the theory and data models of real-world systems (cf. Suppe 1989).

In summary, methodological criteria (i.e. direct observation of a state of affairs in the case of truth, and isomorphism between theoretical models and data models of a system in the case of empirical adequacy) are needed to justify the attribution of epistemological properties (i.e. truth and empirical adequacy) to theoretical knowledge.

This approach is similar to how Van Fraassen proposed empirical adequacy as the epistemological property that a theory must have in order to be accepted – which includes that empirical adequacy is proposed as an alternative to truth – as it aims to explore 'reliability' as an alternative epistemological criterion that accounts for the acceptance of theoretical knowledge in the scientific practices mentioned, instead of being a route to the truth of theoretical knowledge. Following this line of approach, the proposed schema results in the following:

1. (1^R) *Epistemological criterion for the acceptance of theoretical knowledge*: 'T' is accepted *if* 'T' is reliable.
2. (2^R) *Semantic conception of the epistemological criterion*: Reliability is an epistemological property of theoretical knowledge 'T', which specifies a certain relationship between 'T' and the real world, i.e. a relationship between what the theory predicts about the observable or measurable world and what can be observed or measured of the real world.
3. (3^R) *Semantic definition of the epistemological criterion*: 'T' is reliable means or is defined as that what T predicts about the empirical (observable or measurable) world is actually the case.
4. (4^R) *Operational definition of the epistemological criterion*: 'T' is reliable *if* what T predicts about the empirical world is actually the case.
5. (5^R) *Methodological criterion*: Repetition and multiple determination (cf. Wimsatt 1981) are methodological criteria for methods that determine whether 'what T predicts about the empirical world is actually the case'. The use of these criteria is summarized as follows: What T predicts is actually the case *if* 'what T predicts is actually the case' is determined by a methodology that is based on repetition and multiple-determination.

In summary, this analysis (in schema 1^R–5^R) proposes reliability as an alternative epistemological criterion for the *acceptance* of theoretical knowledge. Repetition and Wimsatt's (1981) notion of multiple determination are proposed as criteria for methods that justify the attribution of reliability to theoretical knowledge. Multiple means of determination, according to Wimsatt, consists of using different sensory modalities to detect properties or entities; using different experimental procedures to verify empirical relationships or the existence of phenomena; using different assumptions, models or axiomatizations to derive theoretical results, etc. As a result, the schema draws a relationship between two different kinds of robustness notions: reliability (an epistemological criterion) is related to repetition and multiple-determination, which are methodological properties that a method must have in order to justify the reliability of theoretical knowledge.

At face value, the semantic definition of reliability as an epistemological criterion is the same as that of Van Fraassen's notion of empirical adequacy (compare 3^{EA} and 4^{EA} with 3^{R} and 4^{R}). I propose to distinguish between 'empirical adequacy' and 'reliability' as distinct epistemological criteria for different kinds of theoretical knowledge. In Van Fraassen's analysis, Newton's theory or Maxwell's theory, which have an axiomatic form, are used as examples. 'What the theory says' is understood as the scientific model that satisfies the axioms of the theory, such as the model of a harmonic oscillator and its theoretical data structures, e.g. curves in an x-t diagram. The theory is empirically adequate if these curves are (partially) isomorphic with the data structures produced by a real, but ideally behaving harmonic oscillator (cf., Suppe 1989). However, in many cases there is no abstract theory from which a model of the phenomenon can be deduced in a straightforward manner. In those cases, scientific models are theoretical interpretations of phenomena using different 'ingredients' (cf. Boon and Knuuttila 2009; Bailer-Jones 2009). In this case, 'what the theory says' is a theoretical interpretation of the phenomenon, which is accepted *if* it is reliable in explaining or predicting 'rule-like knowledge' produced by means of a variety of sufficiently independent experimental procedures and measurements (i.e. multiple-determination), for example.

Additionally, the difference between the two notions is related to different concepts of the epistemic aim of science, i.e. producing theories or producing epistemic results for specific epistemic purposes. Reliability as an epistemological property must account for the *use* of theoretical knowledge in performing epistemic tasks, such as in explaining or predicting specific phenomena in technologically produced circumstances. In other words, theoretical knowledge is reliable if it can perform the kind of epistemic tasks for which the knowledge is produced.

Provisionally, I propose to use empirical adequacy as an epistemological criterion for theories that have an axiomatic form – and which are usually called 'fundamental theories' –where reliability applies to theoretical knowledge that has as its primary aim the reliable (mathematical or verbal) description, explanation or prediction of phenomena (see also Table 12.1).

Based on this analysis, I will conclude that the acceptance of theoretical knowledge does not necessarily run via truth. I will also adopt Van Fraassen's critical point that truth only applies to descriptions of a state of affairs that can be directly observed in an unproblematic manner, where truth is inappropriate as an epistemological property of theoretical knowledge.[6]

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[6] In accepting Van Fraassen's claim, I deliberately ignore the well-known critique with regard to his notion of observability. The important point of Van Fraassen's suggestion is, in my view, that we have a more or less intuitively clear understanding of the meaning of truth in every day situations. In those situations, we know how to use this notion and how it functions in distinguishing

However, it still needs to be explained *why* a methodological criterion justifies the attribution of an epistemological criterion, i.e. why theoretical knowledge produced by means of repetition and multiple determination is reliable or, in line with the proposed conceptual structure, why do scientific methods with this methodological criterion as a property justify that theoretical knowledge is reliable? This question will be addressed in Section 12.4 of my argument.

12.4 Part II. How Robustness Notions Work Together as Criteria for Producing Scientific Results

12.4.1 'Same Conditions – Same Effects' as a Regulative Principle

The physical world is real or robust in the sense that an independent world stably sets limits to what we can do with it and to the regularities, causal relations, phenomena and objects that can possibly be determined. This metaphysical idea functions in scientific practices by way of the assumption that with exactly the same physical conditions exactly the same physical effects will occur. This belief involves a metaphysical principle about 'how the physical world is', which reads: There is one stable, deterministic physical world in which the same physical conditions will always produce the same physical effects.[7] The philosophical problem of metaphysical principles is that there is no method to prove them, e.g. to find out whether the same conditions will always produce the same effects.[8] At the same time, the belief that the world is structured, regular or stable inescapably 'regulates' our interactions with and our thinking about the world. It is a belief without which thinking about the world and producing knowledge that guides our thinking and acting would be impossible. Therefore, I propose to regard 'same conditions – same

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between claims that are true and those that are not. The use of this notion with regard to theoretical knowledge, on the other hand, is not intuitively clear.

[7] Stochastic behaviour in quantum physical experiments does not violate the idea of 'same conditions – same effects' given that under the same conditions the same stochastic behaviour will occur. Hence, physicists still work with the presupposition that the same experimental set-up in quantum physics will produce the same patterns.

[8] This problem resembles David Hume's problem of causal relations: How can we know that causes and effects will be related in the future as they were in the past if we cannot find out empirically which *power, force, energy* or *necessary connexion* keeps them together? (Hume, D. (1777 (1975)). *On the Idea of Necessary Connexion*, Part I in**:** *Enquiry concerning Human Understanding.*) Accordingly, Hume framed the problem of inferring a stable relationship between cause and effect as a fundamental problem of empiricism: we cannot *observe* the connection in an unproblematic manner – as a consequence, inductive inference to a stable relationship between cause and effect cannot be empirically verified. To this fundamental problem of empiricism, Popper (1963) added that inductive inference cannot be logically justified either. In order to avoid such metaphysical problems, Popper framed it as the problem of induction, i.e. as a problem of the logic of science. The underlying philosophical problem is that the metaphysical belief that the world is structured, regular or robust cannot be proven.

effects' as a *regulative principle* that 'guides and enables' the production and justification of knowledge about the world, by means of which we think about and act in it.[9] A regulative principle is one that scientists must adopt in order to enable scientific and practical reasoning about the world, while at the same time they must acknowledge that it is not possible to find out whether this principle is an empirical or metaphysical truth.

In my view, 'same conditions – same effects' as a regulative principle that 'guides and enables' scientific inferences is more appropriate as an account of how and why 'robust' knowledge about the real world is possible than logical principles, e.g. the principle of induction or falsification or the ceteris paribus clause, or metaphysical principles, e.g. the principle that there must be a conceivable independent order or structure in the world (see also note 8). It is more appropriate in the sense that it accounts for the refined way in which scientific practices actually produce, justify and use knowledge.

Importantly, in scientific practices, we do not know what exactly belongs to the conditions nor do we have complete knowledge of what belongs to the effects. Scientists usually have to find out what the (causally relevant) conditions are and what the relevant effects are. Accordingly, this principle guides what scientists should look for (to wit, phenomena and the conditions that are causally relevant to their occurrence or existence or deterioration) and it justifies inference to general rules of the form: 'If A then B provided C, unless other causally relevant conditions K (known) and/or X (unknown)', rather than, 'If A then B'. Hence, the general rules that are justified by 'same conditions – same effects' are conditional. They enable and justify predictions in new situations, while simultaneously stating that new situations may involve other (known or unknown) causally relevant conditions that affect the phenomenon.[10]

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[9] Understanding metaphysical presuppositions as regulative ideas was Kant's solution to the problems of empiricism raised by Hume. I do not claim that 'same conditions – same effects' is the only kind of basic belief that enables and guides scientific research. I largely agree with Chang (2009), who, with a similar Kantian approach, aimed to explain the functioning of these kinds of principles. He proposed calling basic beliefs about the world 'ontological principles', which – similar to what I claim about the function of 'same conditions – same effects' as a regulative principle – enable epistemic activities such as observation, experimentation, counting, logical reasoning, etc.

[10] 'Same conditions – same effects' differs from the ceteris paribus clause in the sense that the latter does not count 'all other conditions' as part of the rule-like knowledge, whereas the former counts any addition to knowledge of them as an extension of the rule-like knowledge. In scientific practice, this difference is crucial because explicit knowledge of these conditions (C_{device} and K) enables us to predict under which circumstances the phenomenon described as $A \rightarrow B$ can or cannot be expected. Ceteris paribus laws only apply to what Cartwright calls a nomological machine: the law applies only with 'all other conditions being equal,' which would only allow for a very limited use.

12.4.2 Reproducibility and Stability as an Ontological Criterion for the Acceptance of Phenomena

'Same conditions – same effects' as a regulative principle points to a different idea about the nature of phenomena than the commonly accepted ideas, such as those articulated by Hacking (1983), Bogen and Woodward (1988) and Bailer-Jones (2009).[11] Contrary to what philosophers often suggest, phenomena are usually not the point of departure of scientific research. Identification and reproducible technological (or experimental) production of physical phenomena is a central activity of scientific practices, in particular of those practices that are conducting research in the context of application. What is essential to my account of 'same conditions – same effects' is that phenomena themselves must be recognized as technological achievements, as well as ontological and epistemological achievements.

In order to appreciate these claims, the nature of phenomena needs to be explained a bit further. Common language suggests that phenomena must be regarded as independent, 'freely floating' physical entities. Sentences such as 'we observe a phenomenon' or 'we isolate a phenomenon by means of a technological device' suggest that phenomena are very much like the grains of sand on a beach or heavenly bodies in an empty space. However, phenomena do not exist as isolated objects (see also Trizio 2008). They exist, emerge or disappear under specific physical conditions. In other words, phenomena are usually determined by and are dependent on physical conditions and, in principle, they can interact with or be affected by any other physical condition, thereby producing a different phenomenon. For this reason, and as explained above, an infinite number of physical phenomena can, in principle, be identified (see also McAllister 1997 and forthcoming).

As a consequence, 'simple' phenomena must be regarded as ontological entities that are physically 'carved-out' by us. A 'simple' phenomenon is constrained by how the physical world is, but shaped into something by experimental interventions and/or technological devices and (formally) described as A→B; for instance, the phenomenon described that if gas is heated (A), it expands (B).[12, 13] Usually, identifying and describing them also involves pragmatic considerations. To be considered as an ontological entity requires that a phenomenon is regarded as (qualitatively)

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[11] Hacking (1983, p. 221) is canonical: 'A phenomenon is noteworthy. A phenomenon is discernible. A phenomenon is commonly an event of process of a certain type that occurs regularly under definite circumstances'.

[12] The understanding of phenomena I propose can loosely be explained by an analogy with Aristotle's notion of four causes of an object: the physical world is the material cause of a phenomenon, whereas our technological devices and experimental set-up are their formal cause. Additionally, the scientist is the efficient cause for describing the phenomenon as A→B, while the scientific or practical purpose for which the phenomena described as A→B is 'carved out' is its final cause.

[13] Clearly, some phenomena are observable in principle, e.g. the orbits of planets, the tides, an apple falling. However, as Kant has already argued, we are already actively involved even in 'simple' observations of phenomena, i.e. we actively 'carve them out' even in 'simple' observations. Massimi's article (2008) on this matter is insightful.

relevant and/or (quantitatively) significant for one purpose or another, such as for understanding the behaviour of a specific physical system or for being used in technological applications. Only then does a phenomenon acquire ontological status, and as such becomes an ontological achievement. Furthermore, the phenomenon described as A→B is an epistemological achievement. In order to express this entangled ontological and epistemological understanding of physical phenomena, I propose to use the expression 'the phenomenon described by A→B', rather than, 'the phenomenon P' or 'the phenomenon A→B'.

Experimental interventions with technological devices will also produce knowledge of conditions that are causally relevant to the reproducible production of a phenomenon described by A→B, which is presented in 'rule-like' knowledge in the form: $A + C_{\text{device}} \rightarrow B$, unless (K and/or X). For instance, in experimental interventions with a particular device, e.g. heating a gas in a gas-tight cylinder with a freely moving piston, it has been found that 'if A then B', e.g. if gas is heated, then it expands. Additionally, it has been examined how the working of the device contributes to this phenomenon, resulting in a description of the causally relevant conditions of the device, C_{device}, e.g. the device contains the gas and allows for its free movement of it. In this manner, rule-like knowledge has been produced in the form 'if A then B, provided C_{device}, unless other known (K) and/or yet unknown (X) causally relevant conditions'.

The question that still has to be answered is how the acceptance of a phenomenon described as A→B works: how does a phenomenon acquire ontological status?

In scientific practices, *reproducibility* applies to measured data and observed physical occurrences, which are either naturally or technologically produced. Subsequently, reproducible physical occurrences may acquire ontological status and thus be referred to as phenomenon described as A→B. It will usually acquire ontological status only if a physical occurrence that reproducibly appears in a specific set-up also occurs at other (technologically produced) circumstances. If not, we merely have an occurrence and/or a measured data set that is reproducibly produced by that specific device. In other words, in order to acquire ontological status, the physical occurrence must be *stable or invariant* in the sense that it occurs when the same conditions occur at other (technologically produced) circumstances, e.g. another kind of technological device or experimental set-up.

In analyzing how phenomena described as A→B are produced and justified, I propose that this also involves ontological and methodological robustness notions playing a role, similar to how these notions play a role in the acceptance of epistemic results. I will take *reproducibility and stability or invariance* as a combined ontological robustness notion, although a more refined analysis should separate them. Accordingly, the formerly proposed analytical schema results in the following:

1. (1^{O}) *Ontological criterion for the acceptance of a phenomenon*: A phenomenon described as A→B is accepted as real *if* it occurs reproducibly and is stable or invariant.
2. (2^{O}) *Semantic conception of the ontological criterion*: Reproducibility and stability or invariance is a property of a phenomenon described as A→B, which

specifies a certain relationship between the description, A→B, and an occurrence in the real world, i.e. a relationship between what this description A→B says about the real world and an occurrence that happens in the real world.

3. (3^{O}) *Semantic definition of being reproducible and stable*: a phenomenon described as A→B is reproducible and stable means (or is defined as) that the same conditions, $A+C_{device}$, will produce the same effects, B, unless (K and/or X).
4. (4^{O}) *Operational definition of* being reproducible and stable: a phenomenon described by A→B is reproducible and stable *if* the same conditions, $A+C_{device}$, will produce the same effects, B, unless (K and/or X).
5. (5^{O}) *Methodological criterion*: Repetition and multiple determination are methodological criteria for methods that justify the reproducibility and stability of phenomena described by A→B, as well as the reliability of rule-like knowledge of the form: 'same conditions $A+C_{device}$, will produce the same effect B, unless (K and/or X)'. Hence, a phenomenon described by A→B is reproducible, stable and invariant (for use in practical applications) *if* the rule '$A + C_{device} \rightarrow B$, unless (K and/or X)' has been produced and justified by multiple-determination. Conditions $K_1 \ldots K_n$ that are causally relevant for the phenomenon described as A→B under other relevant circumstances must be determined by repetition and multiple-determination.

To summarize, the proposed schema relates reproducibility, stability and invariance as ontological criteria for the acceptance of a phenomenon described as A→B to multiple determination as a methodological criterion for justifying this attribution of ontological status. This schema also shows that referring to a phenomenon as an ontological entity is intertwined with the experimentally produced rule-like knowledge about it.

Finally, it needs to be explained *why* repetition and multiple determination justify the acceptance of a phenomenon described as A→B and of the rule-like knowledge about it or, in line with the proposed conceptual structure, why do scientific methods that have these methodological criteria as a property justify that a phenomena described as A→B is *reproducible* and *stable*, and that rule-like knowledge in the form '$A + C_{device} \rightarrow B$, unless (K and/or X)' is *reliable*?

12.4.3 Repetition and Multiple Determination as Methodological Criteria for Justifying the Acceptance of Scientific Results

A central idea of my analysis is that epistemological and/or ontological properties can only be attributed to a scientific result by methodological criteria that justify this inference. Thus, in traditional philosophical accounts, induction or hypothetical-deduction or 'severe tests' are supposed to function as methodological criteria that justify inference to the truth or empirical adequacy of a scientific theory. One of the tasks of the philosophy of science is to give an account of *why* a methodological criterion justifies this inference.

Wimsatt (1981) proposed that robustness *is* multiple-determination. However, he is not fully clear about what is achieved by robustness as a methodological criterion (in my terminology). One can argue that multiple determination functions as an alternative methodological criterion that justifies inference to the (approximate) *truth* of epistemic results and the *reality* of ontological results. Alternatively, Wimsatt may have meant that multiple determination functions as a methodological criterion for producing 'robust' (rather than true or real) results, which is in line with my own proposal in this article. In both cases, an account is needed of why multiple determination as a methodological criterion justifies that a scientific result is (approximately) true, real or 'robust'.

I will argue that multiple determination cannot justify the attribution of (approximate) truth to theoretical knowledge nor independent reality to phenomena described as A→B. Instead, I propose that in scientific practice the character of accepted phenomena and scientific knowledge is much more moderate and refined. In my proposal, these kinds of scientific results are accepted *because* ontological or epistemological robustness notions apply to them. Three aspects of 'same conditions – same effects' are important for understanding what exactly has been achieved (if not 'truth') by attributing these properties.

Firstly, 'same conditions – same effects' as a regulative idea may incorrectly suggest that *repetition* is sufficient as a methodological criterion for justifying the acceptance of phenomena. Repetition as a methodological criterion would work as follows: Data and physical occurrences are reproducible and stable *if* they are the same in every repetition. More specifically, according to the proposed conceptual schema, the fifth statement would then read:

5. ($5^{\text{O-false}}$) Repetition is a methodological criterion for methods that justify the reproducibility and stability of phenomena described as A→B, together with reliable rule-like knowledge in the form 'same conditions $A+C_{\text{device}}$ will produce the same effect B, unless (K and/or X).'

Indeed, in scientific practices the reproducibility of data and physical occurrences produced in measurements and experimental procedures is (partly) justified by repetition.[14] Yet, repetition is insufficient as a methodological criterion for justifying the stability of phenomena described as A→B because repetition does not present us with knowledge of causally relevant conditions, C_{device} and K, that must be created or prevented to produce the phenomenon described as A→B.

Multiple determination is a methodological criterion that goes beyond mere repetition. In experiments, the variable conditions (e.g. temperature, pressure,

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[14] In scientific practices, repetition is often too limited as a methodological criterion for reproducibility because repetition (or replication) often does not produce the same results. This is because not all relevant causal conditions are known. If repetition shows anomalous behaviour, a possible but not entirely essential explanation is that the previously measured data or phenomena are not reproducible and were, therefore, artefacts. Usually, scientists will search for 'hidden' causally relevant conditions.

speed, size, chemical concentrations, fluidic movements and electro-magnetic field strength) of the natural environment, the technological means, and/or the experimental procedure are varied in order to see what happens to the phenomena described as A→B produced by these systems. Using this approach, scientists find out whether phenomena described as A→B are causally influenced by these conditions and how sensitive they are to them (see also Woodward 2003). This methodological approach is also called a *sensitivity analysis*.

Multiple determination also involves other instruments or procedures being employed either to examine the proper functioning of the equipment or to expand on the conditions under which measurements or experiments are performed. This can be done, for instance, by enhancing the sensitivity (e.g. the sensitivity of measuring a variable parameter by using other types of instruments) or in range (e.g. the range of values of a variable condition is enlarged in order to see the effects at the limits) or in complexity (e.g. other kinds of phenomena are simultaneously produced in order to see whether they affect the phenomenon described as A→B). Wimsatt (1981, 2007) and Franklin (1986, 2009) have listed a wide variety of strategies that illustrate ways in which scientific practices employ 'multiple determination' to examine the robustness of scientific results (including technological devices and experimental procedures).

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Secondly, the point of repetition as a methodological criterion is to produce the *same* results (thus, strictly, the same data and the same physical occurrences), whereas the point of multiple-means of determination is that it usually does not produce the same results, at least not at the level of our observations or measurements. Yet, in his examples of multiple determination Wimsatt suggests that the point of it is producing the *same* results: '…to detect the *same* property or entity', '…to verify the *same* empirical relationships or generate the *same* phenomenon', etc. (Wimsatt 2007, p. 45, my italics). This way of phrasing how multiple determination works suggests, again, that phenomena are like grains of sand on the beach. They are clearly identifiable objects in whatever circumstances: they remain as exactly the same identifiable entities whether on the beach, at the bottom of the sea, in the belly of a fish or in my shoes. As I have explained, this is often not the case for phenomenon described as A→B under new circumstances. The point of 'same conditions – same effects' as a regulative principle is that scientists must seek to discover conditions that occur under other circumstances, and whether these conditions are causally relevant to the phenomenon described as A→B, and also how these conditions account for results that deviate from the phenomenon described as A→B. As a consequence, multiple determination is a methodological criterion for determining conditions that are causally relevant to phenomena described as A→B and for determining how sensitive phenomena are to the causally relevant conditions.

Thirdly, a related aspect of 'same conditions – same effects' is that a phenomenon described as A→B is stable – and the rule-like knowledge about it is reliable – to 'some extent' or 'conditionally'. The extent to which these results are stable or reliable, respectively, is given by the extent to which they have been put to experimental tests. This conditional character of scientific results has been made operational in the following manner. The regulative principle ‘same conditions – same effects’ guides and enables scientists to carve out phenomena described as A→B, accompanied by the production of rule-like knowledge in the form: ‘$A + C_{device} \rightarrow B$, unless (K and/or X).’ Repetition and multiple determination characterize the methodological approach by which K has been found, and by which scientists continue to search for X. Accordingly, repetition and multiple determination are methodological criteria that account for the fact that the reliability of scientific knowledge lies in the *span* of simple phenomena described as A→B, and the *refinement* of rule-like knowledge about these phenomena, which can only be acquired by experimental interventions with the natural world and with technological instruments, devices and procedures.

Based on this analysis, the crux of the role that robustness notions play in scientific practices can be summarized. A central aim of traditional philosophical accounts was to justify methodologies by which we could possibly infer the truth of theoretical knowledge and/or the real and independent existence of theoretical objects. Based on the analyses by means of the proposed conceptual schema, I suggest that attributing these highly desired epistemological and ontological properties to scientific results *transcends* the methodological and regulative criteria that are the leading factor in producing and accepting them. Robustness as a truth-maker would work as follows: theories are true *because* we found that they are robust, i.e. reliable. Similarly, phenomena described as A→B exist independently *because* we found that they are robust, i.e. stable or invariant. The point of my argument against ‘robustness’ as a truth-maker is that attributing epistemological and ontological properties that transcend what has been attained by means of the methodological and regulative criteria is philosophically problematic.

As an alternative, I propose that robustness notions work together in a manner that avoids this kind of transcendence. Regulative, methodological and epistemological or ontological criteria are used in a mutual interplay, thereby guiding and enabling the production and acceptance of scientific results. ‘Same conditions – same effects’ is a regulative principle that justifies repetition and multiple determination as methodological criteria for producing results that are defined as epistemologically or ontologically robust. Accordingly, it is justified to accept that: ‘the phenomena are reproducible and stable *if* they have been determined by repetition and multiple determination’, while it is unjustified to conclude that, ‘the phenomena are reproducible and stable, and therefore they exist independently.’ Similarly, the following inference is justified: ‘rule-like knowledge is reliable *if* it has been determined by repetition and multiple determination’, whereas, ‘rule-like knowledge is reliable (or robust, cf. Weisberg and Reisman 2008), and therefore it is true,’ is unjustified. In brief, transcendence to the highly desired epistemological and ontological properties by means of methodology cannot be justified. By using methodological robustness notions, robust (stable and reliable) scientific results are produced – nothing more and nothing less. As a consequence, the idea that ‘robustness’ is a ‘truth-maker’ must be rejected.

This restriction of scientific inferences is important to gain a better understanding of what science can do and what not. Science is much more limited than philosophers of science tend to believe. It must be kept in mind that the stability of a phenomenon described as A→B, and the reliability of the rule-like knowledge that accompanies it, is only justified to the extent that it has been put to the test. This account has been made operational by stating that the rule-like knowledge is conditional in the form: '$A + C_{device} \rightarrow B$, unless (K and/or X).' Hence, the proposed account of robustness notions is more appropriate for scientific practices than common traditional accounts of the justification of scientific results. Unjustified transcendence is avoided because the regulative principle and methodological criteria for producing and accepting a scientific result *define* the meaning of the epistemological or ontological property that is attributed to scientific results, which implies that scientific results are accepted *because* they have this epistemological or ontological property.[15]

12.5 Conclusions

The general scope of my interest in robustness notions is to understand scientific practices that work in the context of practical and technological applications. How can we explain their successes and limits? What can these practices do and what can they not do? Do we have to explain the applicability of scientific results using their truth? In this article, I have developed an account of robustness notions that may provide us with a more appropriate understanding of these practices. My argument aims to make plausible that explaining the success of scientific practices does not necessarily happen via the truth of scientific theories and/or the independent existence of theoretical entities, since 'robustness', as it is interpreted here, can sufficiently explain what science can do, while it also explains why science is limited. Here, I will summarize the structure of my argument.

In order to create a philosophical space within which the issues mentioned can be analysed, I have proposed four philosophical presuppositions as alternatives to some of the dominant traditional ones that tend to make important aspects of these scientific practices invisible or turn them into 'non-issues'. These alternative presuppositions were used as the philosophical foundation for understanding the different kinds of roles of robustness notions in scientific practices that produce, justify and use scientific results. They can be summarized as follows: (a) The *epistemic* aim of science is to produce epistemological results that allow for scientific reasoning about the world; (b) Scientific practices employ a methodology in which different kinds of elements are mutually adjusted and stabilized; (c) These different kinds of elements must each be recognized as different kinds of scientific results; (d) 'Same conditions – same effects' is an essential presupposition without which experimental practices cannot function or, in other words, it is a regulative principle that makes these practices possible since it guides the production and justification of empirical results.

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[15] Which resonates with one of the central ideas of logical positivism that the meaning of a synthetic statement is the method of its empirical verification.

My focus is on scientific research in the context of practical and technological applications. In that context, epistemic results, such as scientific theories, models and concepts, but also rule-like knowledge about phenomena described as A→B, are *accepted* not necessarily because they are true, but because they enable and guide our thinking about the world and/or about intervening with it, in a relevant and reliable manner. As a consequence, a philosophical account is needed of how scientific results that meet this epistemic function are justified.

I have proposed a conceptual schema for analyzing the acceptance of epistemological results. The development of this schema was motivated by Van Fraassen's (1980) analysis of true scientific knowledge, which is founded on the following ideas: (i) Truth is an epistemological property of knowledge, not of the world; (ii) Knowledge is accepted *because* it has this epistemological property; (iii) The attribution of an epistemological property must be justified by a methodological criterion. I adopt Van Fraassen's idea that truth is inappropriate as an epistemological property because theoretical knowledge cannot be observed in a straightforward manner. Epistemological properties other than truth, e.g. empirical adequacy or robustness, may justify the acceptance of theoretical knowledge.

Based on an analysis of how several authors in the philosophy of science have used robustness in accounting for the success of science, I have proposed a conceptual distinction between *metaphysical, regulative, methodological, ontological and epistemological* robustness notions. These notions *function* as properties and criteria for different kinds of things. Reality and stability function as a metaphysical robustness notion about how the world is. Reproducibility and stability function as an ontological criterion for the acceptance of data and phenomena. Reliability functions as an epistemological criterion for the acceptance of scientific knowledge, while repetition and multiple determination function as methodological criteria for the production and justification of epistemological and ontological results. The notion 'same conditions-same effects' is introduced as a regulative robustness notion. Next, the proposed conceptual schema is utilized to explain how these different robustness notions are related in the production and acceptance of scientific results.

Following Hacking's view that the stability of experimental sciences results from the mutual adjustment of different kinds of elements, thereby producing a self-vindicating structure, I have suggested that in order to explain why scientific results can travel to other scientific fields or technological applications, some kind of realism is needed. As a minimal metaphysical belief, I proposed that the real world is stable and independent in the sense that it puts real constraints on what we can *do* with it – what we can *think* about the real world, on the other hand, is constrained but *not* determined by it.[16] This metaphysical belief claims that the same physical conditions will always produce the same physical effects, but does not claim that there is an independent *cognizable* order or structure in the world.

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[16] This realism is close to Hacking's realism, which emphasizes the materiality of the world.

What is crucial to my argument is that the regulative principle ‘same conditions – same effects’ explains and justifies *why* methodological criteria (multiple determination) justify the acceptance of epistemological and ontological results. This argument, which expands on Wimsatt’s account of the methodological role of multiple determination, explains the appropriateness of the methodological criteria of repetition and multiple determination for producing and justifying reliable rule-like knowledge that is also conditional. Multiple determination also accounts for the fact that the reliability and relevance of scientific results lies in the *span* of simple phenomena described as A→B, and the *refinement* of rule-like knowledge about these phenomena, which can only be acquired by varying (mutually independent) experimental interventions with the natural world or with technological instruments, devices and procedures. This account also implies that the regulative principle ‘same conditions – same effects’ is more appropriate as scientific inference than logical principles such as induction, falsification or the ceteris paribus clause.

Finally, this account leads to the conclusion that robustness is not a truth-maker, i.e. multiple determination cannot function as a methodological criterion for justifying that theoretical knowledge is true. The crucial point of the latter argument is that epistemological and ontological properties of scientific results cannot transcend the methodological criteria that led to their production and acceptance. AQ4

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Chapter 12

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