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Focusing on Scientific Understanding

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■ In the eyes of most scientists, and of educated laypeople, understanding is a central goal of science. In the past centuries scientific research has enormously increased our understanding of the world. Indeed, it seems a commonplace to state that the desire for understanding is a chief motivation for doing science. But despite the prima facie plausibility of these claims, it is not so clear what their precise content is. What do we mean when we say that scientists understand, for example, global climate change? What is involved in achieving scientific understanding of phenomena, be they the origin of the universe, the structure of matter, the behavior of organisms, or economic and social developments? These are fundamental philosophical questions, yet they have received little philosophical attention. This volume constitutes the first concerted effort by philosophers of science to explore these questions and provide a variety of possible answers.

Lord Kelvin famously declared, "It seems to me that the test of 'Do we or not understand a particular subject in physics?' is, 'Can we make a mechanical model of it?'" (Kargon and Achinstein 1987, 3). What is expressed here is not only the idea that understanding is an aim of science (in this case, physics) but also the view that there is a preferred way of achieving that aim, namely, devising mechanical models of physical phenomena. Yet, while Kelvin's approach had strong appeal and was widely supported in the mid-nineteenth century, it has proved to be untenable in the light of later developments in physics. In particular, the advent of quantum theory refuted the universal applicability of mechanical modeling as a road to understanding. The failure of such models led to a discussion among physicists about what kind of understanding physics could and should achieve. Thus, Erwin Schrödinger criticized the abstract mathematical theory of matrix mechanics for its lack of *Anschaulichkeit* (intelligibility, visualizability). Schrödinger (1928, 27) argued that "we cannot really alter our manner of thinking in space and time, and what we cannot comprehend within it we cannot understand at all." Werner Heisenberg (1927, 172), by contrast, believed that nonvisualizable theories also could provide understanding (*anschauliches Verstehen*) of quantum phenomena. These examples show that ideas about what it takes to understand phenomena can change. Moreover, they reveal that it is important to distinguish between understanding phenomena and understanding the theories or models used to represent and/or explain phenomena. While scientists' ultimate goal is to understand phenomena, achieving that goal often involves the development and understanding of appropriate theories or models.

A look at sciences other than physics confirms that there are many ways to achieve understanding of phenomena and, consequently, that there are many forms of understanding that play a role in scientific practice. Within experimental biology, for instance, there is a strong emphasis on understanding phenomena through the manipulation of biological entities such as organisms or their components. Biologists have developed several forms of experimental intervention ranging from the unobtrusive observation of animals in the field to the dissection of specimens in a laboratory. Psychologists, who cannot resort to the latter type of intervention on human subjects, rely on models and empathy to acquire understanding of the human mind. Similarly, but on a very different scale, economists favor the use of mathematical models and simulations to capture the behavior of the market under changing conditions.

Given this diversity, it is not surprising that there is no satisfactory, generally accepted answer to the question of what precisely scientific understanding consists in, and how it is achieved. It seems to be impossible to give a single, universally valid definition of the notion of scientific understanding. But this impossibility should not drive philosophers away from the study of understanding. On the contrary, the multifaceted nature of understanding testifies to its central importance for practicing science and to the need for a philosophical analysis of its many aspects and forms. The essays in this book constitute a wide-ranging and in-depth investigation of the nature of scientific understanding. While a general account of understanding may prove to be unattainable, much can be said, as this book shows, about the ways it becomes manifest and about the specific tools and conditions that can promote understanding of a typically scientific kind. In this introductory chapter we will introduce the topic by reflecting on the most important features of scientific understanding, by reviewing what philosophers of science have said about it, and by outlining the main themes of the book. Rather than defending specific claims in detail, a task that we leave to individual chapters, we focus on what we perceive to be the overall position emerging from this collection.

A key feature of understanding is the fact that it involves a cognizing subject. In the case of scientific understanding this subject is typically a scientist who tries to understand a phenomenon, for example by developing a theory. There is an important difference between understanding and explanation: while one may legitimately say that theory *T* explains phenomenon *P*, one can only speak about understanding *P* by means of *T* if one invokes a subject (in the case above, the scientist). In other words, while explanation may be viewed as a two-term relation between an *explanans* (for example, a theory) and an *explanandum* (the phenomenon), understanding is always a three-term relation involving *explanans, explanandum,* and a subject. This feature of understanding has important implications.

First of all, it entails that understanding belongs, at least partly, to the domain of pragmatics: when we want to analyze how scientific understanding of a phenomenon is achieved, we cannot restrict ourselves to analyzing the syntactic structure and semantic content of the statements (for example, theories, explanations) involved in this activity. In addition, we should consider the purpose and effects of these statements for the particular persons who use them. This applies to understanding as the end-product of explanatory activity (the cognitive state achieved, the goal of explanation), because it is the state of a cognizing subject. And it applies even more to understanding the theories and models used in these explanatory activities: such an understanding concerns the usefulness and tractability of the theories and models as evaluated by a specific group of peers.

Philosophers in the logical empiricist tradition, most notably Carl Hempel, claim that for this reason the notion of understanding falls outside the scope of the philosophy of science. Their argument is that a philosophical account of science should be objectivist and steer clear of pragmatic elements. According to this viewpoint, understanding is nothing but a subjective feeling evoked by explanations, which is irrelevant for philosophy of science for it can have no epistemic import. Nowadays, however, many philosophers of science have more liberal viewpoints regarding the relevance of pragmatics for philosophy of science and see no reason to reject the notion of understanding out of hand. Obviously, the authors in this volume are among this group: they agree that understanding is a philosophically interesting and relevant notion, despite or by virtue of its pragmatic aspects.

Another implication of viewing understanding as a three-term relation is accepting that it may be context-dependent. Whether a particular explanation makes scientists understand a phenomenon may depend on the context (both social and material) in which those scientists find themselves. Among many others, the case of Kelvin cited above suggests that criteria for understanding vary in history and across disciplines. In other words, the historical and disciplinary context determines at least in part when and how understanding is achieved. This offers a new perspective on the well-known thesis that there is a fundamental distinction between the natural sciences, which aim at explaining natural phenomena (*Erklären*), and the social sciences and humanities, which aim at understanding human actions and cultural products (*Verstehen*). That thesis hinges on an opposition between explanation and understanding that we think should be abandoned. On the one hand, understanding plays a role in the natural sciences, too. On the other hand, the understanding provided in the social sciences and humanities may be the product of explanatory activities. Of course, it might be that the conditions for achieving understanding are fundamentally different among the various sciences; this is just one example of the contextuality of scientific understanding. This contextuality implies, in turn, that it is difficult, if not impossible, to give a universal definition of (the essence of) scientific understanding.

Understanding in the Philosophy of Science

Until quite recently philosophers of science have paid relatively little attention to the topic of scientific understanding because, as noted above, understanding necessarily involves a subject. Many philosophers of science, especially those raised in the objectivist tradition of logical empiricism, took this to imply that understanding is thereby also subjective. They concluded that it can be nothing more than a psychological by-product of scientific activity. In Hempel's words, "such expressions as 'realm of understanding' and 'comprehensible' do not belong to the vocabulary of logic, for they refer to the psychological and pragmatic aspects of explanation" (Hempel 1965, 413).

According to Hempel, every good scientific explanation is a logically valid argument in which the *explanandum* is deduced from an *explanans* containing at least one universal law and relevant initial and background conditions. This is the well-known deductive-nomological (D-N) model, which was first proposed by Hempel and Oppenheim in 1948.[1] In this pioneering paper (reprinted in Hempel 1965), the authors distinguished between "understanding in the psychological sense of a feeling of empathic familiarity" and "understanding in the theoretical, or cognitive, sense of exhibiting the phenomenon to be explained as a special case of some general regularity" (Hempel 1965, 257). They criticized the former as being neither a necessary nor a sufficient requirement for scientific explanations, and argued that explanations can only be said to provide understanding in the latter sense. Note, however, that it is unclear whether the understanding lies in the objective relation of subsumption under laws itself, or in the ability of "exhibiting" those relations. In his 1965 "Aspects of Scientific Explanation," Hempel added that a deductive-nomological explanation can provide understanding because "the argument shows that, given the particular circumstances and the laws in question, the occurrence of the phenomenon *was to be expected;* and it is in this sense that the explanation enables us to *understand why* the phenomenon occurred" (337). If Hempel wants to speak about understanding at all, it is only in a sense that is closely tied to the objective (deductive) relation between *explanans* and *explanandum*.

The D-N model dominated the scene until the 1970s, even though it had been criticized in earlier years. One influential early critic was Michael Scriven, who argued for giving understanding a more prominent role in the analysis of explanation than Hempel did: "Whatever an explanation *actually* does, in order to be called an explanation at all it must be *capable* of making clear something not previously clear, that is, of increasing or producing understanding of something" (Scriven 1962, 175). Scriven added that it depends on the context whether a particular piece of information appropriately fulfills this role, and hence qualifies as an explanation. He emphasized, however, that "understanding is *not* a subjectively appraised state anymore than knowing is; both are objectively testable and are, in fact, tested in examinations" (176), and he concluded that Hempel's theory is unsatisfactory for several reasons, among which, "It leaves out of account three notions that are in fact essential for an account of scientific explanation: context, judgment and understanding" (196).

A decade later, in 1974, Michael Friedman took another step toward a rehabilitation of understanding. In his seminal paper, "Explanation and Scientific understanding," he argued that one of the requirements for a good philosophical theory of explanation is that it "should somehow connect explanation and Understanding—it should tell us what kind of understanding scientific explanations provide and how they provide it" (Friedman 1974, 14). Like Scriven, Friedman criticized Hempel for not living up to this demand, but he followed Hempel in insisting that a philosophical account of explanation (and accordingly, of understanding) should be objective and noncontextual: "what counts as an explanation should not depend on the idiosyncrasies and changing tastes of scientists and historical periods. It should not depend on such nonrational factors as which phenomena one finds somehow more natural, intelligible, or self-explanatory than others" (14).

Since Friedman's paper, philosophers of science, including those in the objectivist tradition, have paid more attention to the topic of understanding. They have in different ways tried to specify the (objective) kind of understanding that science provides, and employed this specification as a requirement for good scientific explanations. There have been two major approaches in the objectivist tradition: the unificationist approach, advanced by Friedman, Philip Kitcher, and others, and the causal-mechanistic approach, developed by Wesley Salmon and others. In addition, more in line with Scriven's position is a pragmatic approach to explanation advanced by Bas van Fraassen and Peter Achinstein.

Friedman's idea was that objective understanding is provided by explanations that unify the phenomena: "science increases our understanding of the world by reducing the total number of independent phenomena that we have to accept as ultimate or given" (Friedman 1974, 15). Because of technical problems with Friedman's account, Philip Kitcher (1981, 1989) developed an alternative approach to unification in which argument patterns are central. An argument pattern consists of a schematic argument with filling instructions and a classification of the inferential structure of the argument. According to Kitcher, "Science advances our understanding of nature by showing us how to derive descriptions of many phenomena, using the same patterns of derivation again and again" (1989, 432). Since Friedman's and Kitcher's essays, much more work has been done on unification. A notable account that refers especially to the understanding-providing power of unification is that of Gerhard Schurz and Karel Lambert (1994).

Meanwhile, following the severe critiques launched against the D-N model, causal approaches to explanation were developed that offered an alternative conception of explanatory understanding. The most important proponent of this view is Wesley Salmon, who presented an elaborate theory of causal-mechanistic explanation in his 1984 *Scientific Explanation and the Causal Structure of the World*. This theory was later refined and elaborated in discussion with others (see Salmon 1998, esp. chaps. 8 and 16). According to Salmon, we need a causal theory of explanation because "underlying causal mechanisms hold the key to our *understanding* of the world" (Salmon 1984, 260; italics added). This is because "causal processes, causal interactions, and causal laws provide the mechanisms by which the world works; to understand why certain things happen, we need to see how they are produced by these mechanisms" (132). In his later work, Salmon has put even stronger emphasis on the importance of achieving understanding in science (see Salmon 1998, 3, 9, 387, and chap. 5). Notable alternative causal approaches are defended by Paul Humphreys (1989) and James Woodward (2003). Mechanistic explanation is nowadays very popular in the philosophy of biology (Machamer, Darden, and Craver 2000; Bechtel and Abrahamsen 2005).

A different approach to explanation and understanding, which falls outside the objectivist camp, is provided by van Fraassen (1980) and Achinstein (1983). In van Fraassen's account of science, explanation is a pragmatic virtue and does not constitute an epistemic aim of science. Van Fraassen analyzes explanations as answers to why-questions, and argues that explanation is context dependent. Although the issue of the character of scientific understanding is not mentioned explicitly by van Fraassen, one may safely conclude that his analysis of the nature of explanation as extrascientific holds a fortiori for understanding. Achinstein (1983) focuses more directly on understanding by providing a critique of noncontextual approaches to explanation. In his view, the act of explaining is an illocutionary act characterized by the intention to make something understandable. Whether an explanation is "good" depends on the values and interests of the audience to which it is directed. Achinstein emphasizes that, due to this context dependency, there is a variety of different forms of good explanation in science.

Aspects of Scientific Understanding

The above overview shows that understanding has typically been viewed as a by-product of scientific explanation. This volume provides a radically different approach: the study of understanding is not only worthy of philosophical attention, but actually contributes new insights to a number of traditional debates within the philosophy of science. The most important themes emerging from this collection of papers are the following: the relation between understanding and explanation; the feeling of understanding; the role of models and theories as tools to achieve understanding; the notion of intelligibility; understanding as tacit knowledge; and pluralism of understanding. This list highlights some key results obtained through our philosophical investigation of scientific understanding; it also serves to guide the reader toward the specific chapters where reflections on these themes are most thoroughly developed.

Understanding and Explanation

The objectivist position reduces understanding to an automatic consequence of having a good explanation, where "good" indicates its unifying power or causal-mechanistic nature. As discussed above, this view does not resolve the issue of what understanding actually involves. We take issue with the facile equation between possessing an explanation and possessing understanding of a phenomenon. Gaining understanding through explanations is not an automatic process, but rather a *cognitive achievement* in its own right—a point that is stressed, in various contexts, by all contributors to this collection.

Once it is granted that deriving understanding from an explanation is a matter of ability, the question arises of how that actually works. What are the mechanisms through which scientists extract understanding from explanations that they already possess? Confronting this question in the case of historiography, Edwin Koster emphasizes the role of *personal judgment* in determining which ideas and events are selected as part of an explanation. Henk de Regt and Sabina Leonelli both note how judgment in the natural sciences involves the exercise of *epistemic skills* of various kinds, which help scientists to make sense of the conceptual as well as the empirical significance of explanations for the phenomena to which they refer. Peter Lipton strengthens the point by challenging the very idea that explanations are needed to acquire understanding: he discusses cases where individuals acquire understanding without recourse to explanations. Further, Lipton distinguishes four types of cognitive benefits that derive specifically from understanding a phenomenon: *causal information,* as acquired through activities such as observation, experimentation, manipulation, and inference; a *sense of necessity* deriving from the knowledge that, in given conditions, an event, object, or process could not have been otherwise; a *sense of what is possible,* which can spring even from potential or false explanations; and the *unification* obtained by comparing phenomena through mechanisms such as analogies and classifications, as in the case of Kuhnian exemplars. Lipton shows that each of these cognitive benefits can be obtained in the absence of explanations, indicating that "understanding is more extensive and more varied in its sources than those who would equate explanation and understanding allow."

The Feeling of Understanding

Petri Ylikoski explores cases where the acquisition of scientific understanding is at least partly illusory, insofar as it springs from a feeling of understanding ("Aha!") that has no relation to whether that understanding is reliable or truth-conducive. This cognitive phenomenon is recognized by several authors in the volume, who all agree on the necessity to distinguish the feeling of understanding and understanding itself, but who disagree quite radically on whether the feeling of understanding has any epistemic value. De Regt does not think that this is the case. In his view, "the phenomenology of understanding has no epistemic function": what counts, rather, are the epistemic skills and values used to construct tools for understanding, such as intelligible theories and models. Ylikoski goes even further by characterizing this feeling, which he dubs "illusion of depth of understanding," as having a downright pernicious effect on various aspects of scientific research. He notes how several features of contemporary science have evolved as measures against illusory understanding felt (and promoted) by individuals. For instance, the peer review system exposes personal insights to critique, while the development of external representations makes it possible to express individual intuitions so that they can be discussed and tested. According to Ylikoski, scientists can improve their ability to discern reliable from illusory understanding by adopting strict standards for what constitutes an adequate explanation—and philosophers of science are ideally placed to contribute to this effort.

By contrast, Lipton and Stephen Grimm share a belief in the epistemic value of the “aha” experience, which they both characterize as helpful rather than detrimental to the search for scientific understanding. After illustrating the differences between the feeling of understanding and other pleasant feelings involved in research, such as surprise and expectation, Lipton notes how the “aha” experience might plausibly work not only as an incentive, but also as a guide to the human search for understanding. Lipton proposes that scientists use their feelings of understanding as ground for their choice of the “loveliest” explanation. This does not imply that understanding itself is hopelessly subjective, as Lipton makes clear by distinguishing the feeling of understanding from actual understanding (as he states, “understanding is a form of knowledge; the feeling of understanding is not”). Rather, it points to the unarticulated, and yet epistemically relevant, grounds on which scientists judge their results. Grimm complements this argument by pointing to the “conditional reliability” of the feeling of understanding, which depends chiefly on the accuracy of the background beliefs of whoever experiences it. Scientists are most likely to feel that they understand something when that bit of information coheres with the rest of their beliefs about the world. This by no means guarantees the reliability of the feeling of understanding, but it does imply that it can be checked by reviewing one’s background knowledge (or, as Johannes Lenhard proposes, by employing simulations to check the empirical consequences of one’s assumptions).

Models, Theories, and Understanding

A crucial question raised in this volume concerns the relation between models and theories as aids toward acquiring understanding. Models are the subjects of part 2 and their role toward the acquisition of understanding is highlighted by virtually all contributors. There are, however, various interpretations of the relation between models and theories and of how scientists might use either or both of them as tools to understand phenomena.

Some authors support the view that theories are only useful for understanding when they are represented through models. Lenhard argues along these lines in his discussion of understanding through computer simulations. In his view, simulations constitute surrogates for theories: they allow scientists to explore the implications of adopting specific theoretical assumptions, yet at the same time the development of simulations requires scientists to blackbox several aspects of the underlying modeling and theories so as to enable technical implementation (for example, programming and display). Thus, simulations provide information on how to construct and use models to understand phenomena by allowing scientists to compare the implications and advantages of models based on different theoretical assumptions. Tarja Knuuttila and Martina Merz explore the implications of such an account: "the understanding-providing features of models exist due to the interplay between their materially embedded medium-specific and technological features, and their multiple uses." By pointing to models and their uses as the main locus for scientific understanding, they limit the role of theories to their usefulness as instructions for building models.

Other authors are instead interested in exploring the extent to which theories might play an independent role as tools for understanding. In his chapter on understanding in physics, Dennis Dieks emphasizes the role of fundamental theory in developing different understandings of relativistic effects. Mieke Boon also illustrates how, even in the supposedly "applied" engineering sciences, theories may be seen to play a crucial role in fostering understanding. She presents the notion of "interpretative structures" as involving the use of fundamental theories to make sense of one's experience of phenomena. These structures serve the function assigned by Koster to personal judgment: that is, they help scientists to determine which types of objects (and relations among objects) to use when constructing an explanation of a phenomenon. Notably, Boon leaves open the possibility that fundamental theories, causal explanations, and models may all play the role of interpretative structures, depending on the scientific context in which they are used.

Another take on the relation between theories and models derives from studying the mechanisms, rather than the tools, through which understanding is acquired. This is the task undertaken by Margaret Morrison in the case of mathematical abstraction in physics and biology. As she notes, mathematical abstraction is an important mechanism through which understanding is developed, especially in highly formalized fields such as quantum physics or population genetics. Indeed, abstraction blurs the boundaries between what is considered to be a model and what is considered to be theory—as in the case of the Hardy-Weinberg equation, a model so abstract and general so as to be regarded as a fundamental law in population genetics. Morrison argues that mathematical abstraction can and often does generate understanding of concrete systems that could not have been obtained otherwise: it allows scientists to model those systems through assumptions that could never hold in the physical world (such as the idea of infinite populations), and yet are necessary to obtain new information about the potential behavior of those systems. Morrison shares with several other contributors a willingness to shift philosophical focus from the structural components of scientific research (such as theories, models, instruments, and phenomena) to the ways in which these components are *used* to carry our research. What "used" actually implies is made clear when reflecting on intelligibility and tacit knowledge.

Intelligibility

One well-known case of "using" instruments to understand phenomena is Galileo's use of the balance to understand principles of equilibrium. As argued by Machamer and Woody (1994), using the balance crucially improved the intelligibility of Galileo's views on motion to other scientists. Indeed, understanding unavoidably involves making something intelligible. Yet what determines intelligibility and how can intelligibility be improved? Premodern rationalist philosophers held that knowledge must be based on self-evident "intelligible principles." Modern science has rejected this methodology, and empiricist philosophy leaves no room for intelligibility in this sense. Kant's philosophy revived the idea of intelligibility in a different form, namely via the forms of intuition (*Anschauungsformen*) that structure sensory input and the categories that transform it into knowledge. However, in the early twentieth century the alleged refutation of the Kantian system by relativity and quantum physics led again to a rejection of intelligibility as a philosophically reputable concept, especially by logical-positivist and logical-empiricist philosophers (Frank 1957 provides a nice example of this tendency—this semipopular introduction to the philosophy of science turns out to be one long attempt to debunk intelligibility).

In his chapter, Hasok Chang gives new vitality to the Kantian insights by viewing intelligibility as an epistemic virtue whose function is to harmonize our actions with our basic beliefs about the world. An unintelligible action is an action that cannot be performed because it betrays one of the principles guiding all human epistemic activity—for instance, the principle that "a real physical property can have no more than one definite value in a given situation," which Chang calls the ontological principle of single value. The betrayal of an ontological principle does not represent a mistake or a falsehood; rather, it involves taking up a belief that makes no sense to us (such as the belief that a physical property can have two different values in the same situation), because we would not know how to act on its basis. Ontological principles constitute the platform of common sense on which the whole scientific enterprise is built through its various activities, including testing, experimentation, observation, and the like. In a pragmatist fashion, intelligibility is thus defined as the performability of an epistemic activity—and understanding as the ability to actually perform such an activity.[2]

Another take on intelligibility as an epistemic virtue is defended by Kai Eigner. On the basis of his analysis of the behaviorist movement in psychology, Eigner argues that intelligibility has epistemic relevance as an essential virtue of the models used to apply theoretical principles to the study of phenomena. As he shows, using theoretical models to describe phenomena involves making judgments about similarity and relevance that cannot be based on objective methodological rules. To make these skillful judgments, scientists need to give "surplus meaning" to the theoretical terms in the models such that these models are rendered intelligible to them. Due to the surplus meaning of the theoretical terms, the models acquire virtues that allow a match with the skills of scientist, which in turn enables them to establish the connection between models and phenomena. De Regt generalizes this position by characterizing intelligibility as "the value that scientists attribute to the cluster of virtues (of a theory in one or more of its representations) that facilitate the use of the theory for the construction of models."

Understanding as Tacit Knowledge

Objectivist objections to viewing understanding as a reliable source of knowledge might perhaps seem plausible if one focuses only on theoretical knowledge. However, a precious lesson taught by the philosophical literature on models concerns the importance of tacit (or embodied) knowledge for obtaining and interpreting theoretical knowledge. It is only through the *use* of models, or indeed any other kind of object or representation, that scientists acquire understanding of the world. The unarticulated knowledge required for successful interaction with models, phenomena, and experimental settings constitutes not only an important source of knowledge in itself, but also a strong constraint to the types of understanding that are actually developed in science.

As Knuuttila and Merz make clear in their chapter, scientists typically seek to extract evidence from objects with very specific characteristics. Models provide understanding insofar as they constitute "concrete constructed objects with which one can interact in various ways." In their view, understanding springs from the scientists' interaction with these objects of knowledge. Leonelli defines tacit knowledge more broadly as "the awareness of how to act and reason as required to pursue scientific research." Such awareness is expressed not only through the handling of objects as models, but also through the implementation of experimental procedures and protocols, the calibration of instruments, and the ability to work in specific research environments such as the lab or the field. As Leonelli notes, in the life sciences the development of explanations and interventions is inextricably intertwined—a result that is not surprising in the light of the link proposed here between understanding and the ability to apply theories and models.

Pluralism of Understanding

As we noted, the history of science shows great variation in what is and what is not deemed understandable. Even at one particular moment in history opinions about what is understandable often diverge. For example, in 1926 physicists in the Copenhagen-Göttingen circle believed that atomic phenomena could be understood with the theory of matrix mechanics, while most other physicists—notably Schrödinger—disagreed (Beller 1999; de Regt 2001). Authors in this volume have several ways to account for scientific pluralism among ways of understanding. One option is to distinguish between embodied and theoretical knowledge as sources for the skills and commitments used by scientists to understand phenomena. *Theoretical* skills and commitments are the ones involved in reasoning through available concepts, theories, and explanations, while *performative* skills and commitments are developed through physical interaction with research objects and settings. Leonelli uses this distinction to argue for the coexistence of three types of understanding in biology: one prioritizing recourse to theoretical commitments and skills, one where performative skills are of primary importance, and one deriving from a balanced coordination of theoretical and embodied knowledge. A second form of pluralism concerns the diversity of understandings that can be acquired from using the same tools. This point is supported by Knuuttila and Merz, who stress the *multiplexity* of models as tools for acquiring understanding: the same model can be interpreted in a variety of ways depending on the background skills and knowledge of their users.

Yet another form of pluralism concerns the *epistemic interests and purposes* guiding the search for understanding. Jeroen Van Bouwel shows how "the plurality of epistemic interests is better served by a plurality of theoretical perspectives than by a unified one." In Van Bouwel's view, understanding derives from explanations that are both empirically adequate and adequate to the epistemic interests of whoever acquires it. Given the existing diversity of epistemic interests among scientists, understanding is therefore acquired from several explanations that cannot be reduced to one another. Unification is thus seen as limiting, rather than aiding in, our understanding of the world.

This view is shared by Dieks in his analysis of physical explanations of relativistic effects. As he shows, the same physical theory may be used to construct different arguments, depending on "exactly *what* one wishes to know, and *from which point of view*"—that is, on which kind of understanding one wishes to acquire. Dieks's work dispels any suspicion that Van Bouwel's claims might be uniquely related to the area he studies, that is, political science. As these two chapters jointly demonstrate, both in the natural and in the social sciences epistemic interests vary considerably depending on the context and group adopting them.

The last, and possibly most obvious, form of pluralism in understanding emerges from the discipline-specific analyses provided in part 3 of this volume. Different disciplines focus on understanding diverse entities and processes. The attempt to find methods perfectly suited to each subject matter has generated a vast array of tools to acquire understanding, which in turn signals great variation in the types of understanding that can be obtained in each field. For instance, Koster shows how historians acquire understanding through recourse to empathy. Understanding a historical event involves judging the actions of the people involved so as to select relevant factors and evaluate their relative weight in the explanation of an event. The ability to make such judgments benefits from the capacity of the historian to put himself or herself in the shoes of the subjects in question.

Eigner also highlights the role of empathy in his analysis of understanding in psychology. As he demonstrates, even behaviorist psychologists, notoriously staunch believers in the experimental method and advocates of objective psychology, rely on an empathic ("prescientific") understanding of their research subjects to construct intelligible models of their behavior. As argued by Marcel Boumans, understanding in economics has very different features. Here the favored tools are modular representations (or, in Boumans's words, "gray-box models"), which are efficient in capturing several features characterizing economic practices: for instance, the recourse to "passive observations" as data in the absence of other types of evidence; the calibration of models via mimicking of actual economics; and the need to describe and predict the behavior of extremely complex systems, which can only be fulfilled through partitioning them into manageable subsystems.

The Philosophical Future of Scientific Understanding

The arguments presented in this volume bear wide implications for the philosophy of science. All chapters in this volume firmly agree on linking understanding to cognition. Understanding is defined as a cognitive achievement, or as an ability acquired through appropriate training and as the bearer of cognitive benefits (such as, in Lipton's words, "knowledge of causes, of necessity, of possibility and of unification") that scientists could not acquire solely from explanations. This emphasis on the cognizant individual involves a reevaluation of the epistemic role of human agency in producing, disseminating, and using scientific knowledge. To understand scientific understanding, philosophers must find ways to study and analyze scientific agency. This means taking scientific practices seriously, for arguably a study of agency in science needs to be based on knowledge of how scientists across various fields actually act. The study of experimentation, the iconic scientific activity, has already yielded relevant insights, as demonstrated by the pioneering work on this topic by Ian Hacking (1983), David Gooding (1990), and Hans Radder (1996), among others.[3] Research on scientific understanding can help to integrate these insights into the philosophy of science and assess their impact on traditional notions of inference, explanation, modeling, and theory-making.

Reflecting on scientific practices can also help to tackle another question touched upon in this volume, yet deserving more explicit attention: the relation between scientific understanding and other forms of understanding (technical, humanistic, and so on). Any human being has the ability to engage in several forms of understanding. One way to differentiate between scientific and nonscientific understanding might be to analyze the social conditions under which understanding is achieved in science. All scientific disciplines have developed sophisticated ways to establish and communicate knowledge about nature, including specific terminologies, representations, methods, and instruments. Knowing how to use these tools usually requires years of training and professionalization within the relevant communities. An individual who lacks familiarity with the social and material environment in which research is conducted will not be able to use scientific tools and skills to understand phenomena—nor to communicate to his or her peers what he or she understands. This makes scientific understanding an intrinsically social, rather than individual, achievement, thus opening a potentially fruitful avenue for research in the social epistemology of science.

As we already suggested, defining understanding as pragmatic and contextual goes hand in hand with emphasizing the pluralism in understandings of phenomena that might be acquired by depending on the skills and commitments of the individual(s) involved. The normative question then arises: Which type of understanding is best suited for which type of research? In particular, are there types of understanding (and thus specific combinations of tools and mechanisms to understand) that are more valuable than others in specific research contexts? One way to investigate this issue could be to construct a classification of scientific understandings and find criteria to establish how each of them fulfills different goals and interests (where these goals and interests can be scientific as well as economic, social, or ethical, as for instance when acquiring a scientific understanding of stem cell research in order to evaluate its ethical status). This research path could help to develop normative frameworks to evaluate the quality of scientific understanding achieved in any given case, a result of great interest to philosophers and scientists alike.

Finding ways to assess the quality of scientific understanding might also help to assess the relation between scientific understanding and scientific knowledge. Concerns about this relation are bound to remain the most fascinating and contentious aspect of the approach proposed in this volume. Scientific understanding is the result of the tools, commitments, and skills available to scientists at a particular point in time and space. Such tools are honed through constant negotiation with the material world and are thus not simply the fruit of cultural trends or social settings (as radical constructivists would like to believe). However, precisely because of the specificity of their context and of the motivations and interests guiding their use, these tools and commitments are fallible: they might lead to achieving an understanding of the world, but they do not guarantee that such an understanding will be truthful. This volume sets no sure path toward establishing what might work as a guarantee of truth-value in this context. What we hope to offer is a framework to articulate further the notion of understanding, with the aim of outlining a conception of scientific understanding that is not entirely dependent on the truth-value of the knowledge used to understand, but rather incorporates the values, experiences, and skills of the individuals and communities attempting to carve nature at its joints.

Notes

1. Hempel later added inductive-statistical explanation to cope with explanations in which the *explanandum* cannot be deduced with absolute certainty from the *explanans,* but only with a high degree of probability.

2. An important outcome of Chang's analysis is a strong argument for disconnecting intelligibility from truthfulness (or one of its measures, such as empirical adequacy). This is a step that several other authors are reluctant to take.

3. Paying attention to scientific practices such as experimentation also involves collaboration with historians and sociologists of science, whose work has already illuminated several characteristics of experimental practice (for example, Shapin and Schaffer 1989 and Bruno Latour 1987).

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