Introduction to the edited volume "Scientific Understanding and Representation: Modeling in the Physical Sciences"

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Note

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Successful science, it would seem, is an effective means of both understanding and representing the empirical world. Although important antecedents can be found all the way back to the ancients, it is somewhat surprising that these themes have gained prominence in the philosophy of science only recently, with most monograph-length books on either scientific understanding or scientific representation being published in the past decade.[1] More surprising still is the sparse interplay between the literature on these two topics. Clearly, how a phenomenon is represented has far-reaching ramifications for how it is understood. Consider, for instance, idealizations, such as frictionless planes, infinite populations, ideal gases, and rational actors. Idealizations misrepresent their target systems, yet they frequently provide a deeper understanding than more accurate representations. However, to develop this idea, more detailed accounts of representation and of understanding must engage each other. Otherwise, it remains mysterious as to how a misrepresentation can provide a genuine understanding.

It was concerns such as these that animated a lively brainstorming session between Kareem Khalifa and Daniel Kostić in a Parisian café in March 2018: we would bring together leading scholars working on understanding and representation in the philosophy of science in the hopes of encouraging greater crosstalk between these two research areas. The fruits of those discussions led to the first annual Scientific Understanding and Representation (SURe) workshop held at the University of Bordeaux in February 2019, with subsequent meetings in Atlanta at Emory University (2020), in Nijmegen at Radboud University (2021), and in New York at Fordham University (2022).

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[1] See Frigg and Nguyen (2020) and Grimm (2021) for reviews of the scientific representation and understanding literatures, respectively.

The goal of this edited volume is to give readers a sense of the productive discussions that have emerged from the SURe workshops, with the hopes of advancing discussions concerning scientific understanding, scientific representation, and their delicate interplay. We also hope that readers get a sense of the intellectual energy and synergy that have characterized our workshops since their founding. To that end, this work includes both standalone chapters and "critical conversations" between pairs of contributors. In the critical conversation format, the contributors each write an original target article on a related theme, and they then provide commentary on each other's work. What frequently emerges are unexpected rapprochements, deeper clarifications of earlier debates, and discoveries of new intellectual niches that were previously overlooked.

We have found it useful to group the contributions into four parts: (I) Understanding, Knowledge, and Explanation, (II) Understanding and Scientific Realism, (III) Understanding, Representation, and Inference, and (IV) Understanding and Scientific Progress. We discuss each in turn.

1. Understanding, Knowledge, and Explanation

Several interrelated debates concern the relationship between understanding, explanation, and knowledge. A longstanding position, which Khalifa (2017b) calls the "received view" of understanding, holds that understanding is knowledge of a correct explanation. Such a view is expressed, with varying degrees of explicitness, by philosophers working on scientific explanation (e.g., Hempel 1965, Kitcher 1989, Woodward 2003). However, the received view has faced several probing objections. Chief among these is that understanding requires skills or cognitive abilities that knowledge does not (de Regt 2017), and that understanding, unlike knowledge, can be achieved through what Elgin (2017) dubs "felicitous falsehoods." Both of these challenges to the received view concern scientific representation. Models are the paradigmatic kind scientific representation. The skills involved in the construction and interpretation of models are frequently associated with understanding. Similarly, scientific models frequently involve idealizations, approximations, and other departures from the truth that exemplify the kinds of felicitous falsehoods that yield understanding.

Part I, "Understanding, Knowledge, and Explanation," advances several of these discussions. It begins with an exchange between Henk de Regt and Kareem Khalifa that explores some of their longstanding disagreements in greater depth and with fresh perspectives. In earlier work, Khalifa (2012, 2017a, 2017b, 2020) criticized de Regt's contextual theory of understanding and advertised the advantages of his own, knowledge-based account. In Chapter 2, de Regt turns the tables, criticizing Khalifa's knowledge-based account of understanding and advertising the advantages of his contextual theory. De Regt's core arguments are twofold. First, understanding involves skills that are not required of knowledge. Second, knowledge is factive, whereas understanding is not. In Chapter 3, in the hope of reorienting his exchanges with de Regt, Khalifa considers the benefits of unifying their two accounts of understanding. He argues that de Regt's account substantially improves his own account of how considering different explanations contributes to understanding. Conversely, Khalifa argues that his account of understanding substantially improves upon de Regt's account of how explanatory evaluation contributes to understanding. Khalifa attempts to dissolve his apparent disagreement with de Regt about the so-called factivity of understanding through a voluntaristic approach to the scientific realism debates, in which theorists of understanding have considerable flexibility in how accurate an explanation must be in order to provide understanding.

In their replies, both de Regt (in Chapter 4) and Khalifa (in Chapter 5) explore the implications of this proposed "friendship" or synthesis of their respective views. Though broadly sympathetic to this synthesis, de Regt raises some questions about Khalifa's proposal that explanatory comparisons proceed by way of "empirical fitness," the requirement that good explanations perform at least as well as any rival in saving the phenomena. De Regt contends that this can be too restrictive, in no small part because scientists can reasonably disagree about the standards of empirical adequacy. By contrast, Khalifa shows how de Regt's objections to his view—concerning skills and factivity—can be answered using the hybrid of their two views developed in Chapter 3. Specifically, Khalifa argues that because the hybrid position includes all of the skills that de Regt underscores, it can meet de Regt's challenge in terms that the latter should accept. Further, Khalifa shows how voluntarism allows both realists and antirealists to accommodate the intuition that Newtonian mechanics provides understanding despite its inaccuracies.

While de Regt and Khalifa aim at dissolving debates concerning the factivity of understanding through their newfound commitment to voluntarism, Sorin Bangu and Mazviita Chirimuuta take different angles on this issue in Chapters 6 and 7, respectively. Bangu considers the question of whether past, false scientific theories such as the Newtonian gravitational theory provide some understanding of physical phenomena in our present times. Specifically, he asks whether de Regt's (2017) contextual theory of scientific understanding can support a non-factivist approach to understanding the gravitational deflection of light. Bangu argues that depending on how precisely we characterize gravitational light bending, de Regt's theory delivers two answers. Namely, characterized qualitatively, the Newtonian theory affords an understanding of the light bending phenomenon on de Regt's account. However, if this phenomenon is characterized quantitatively, then this account is shown to entail that no understanding is provided by the Newtonian theory. Hence, Bangu concludes that de Regt's account can only support a weak sense of non-factivism.

Chirimuuta's contribution, in Chapter 7, also broaches on the issue of understanding and truth, but she begins with the observation of a trade-off in models of complex occurrences. Specifically, increasing the predictive accuracy of the model often decreases intelligibility (the capacity of the model to provide scientific understanding). She argues that this trade-off lends support to non-factivist accounts of scientific understanding. However, non-factivism faces an important objection, concerning the hypothetical availability of de-idealized models that afford factive understanding. Chirimuuta replies to this objection by arguing that Potochnik's (2017) non-factivist account of understanding is overburdened by an ontological commitment to "real causal patterns." Chirimuuta shows that the account can be strengthened by replacing this commitment with the notion of an "ideal pattern," where the targets of model building are not patterns that are simply "out there" in nature, but they are, to some extent, dependent on the methods of data collection and processing chosen by the researcher. This proposal is then related to earlier accounts of scientific phenomena.

While de Regt, Khalifa, Bangu, and Chirimuuta all discuss the relationship between understanding and truth, Daniel Kostić focuses more squarely on explanation in Chapter 8. Rather than broaching larger debates about whether understanding requires explanation (Khalifa 2017b, Ch. 4) or not (Lipton 2009), Kostić discusses a particular kind of explanation: those that are driven by the resources of graph theory—so-called topological explanations. These more focused discussions provide the basis for seeing how different kinds of explanations produce understanding in different ways (Kostić 2019). To that end, Kostić provides a systematic and critical overview of topological explanations in the philosophy of science. Kostić's overview proceeds by presenting his account of topological explanation (presented in, e.g., Kostić 2020), and then comparing this account with some of its most prominent rivals. In the process, he highlights some problems with these alternatives and outlines his responses to some of the main criticisms raised by the so-called new mechanists.

Many of the threads in Part I come together in Juha Saatsi's contribution (Chapter 9). Saatsi identifies two dimensions of explanatory power. The first, "factive" dimension of explanatory power concerns how explanations relate to mind-independent reality. The second, "pragmatic" dimension of explanatory power concerns the relationship between explanations and us as epistemic agents who use explanations to gain understanding. Saatsi argues that keeping these two dimensions in mind helps us to better understand three key issues. First, the factive dimension of explanatory power immediately accords a role to truth and thereby provides yet another way of conceiving the relationship between understanding and truth, in addition to de Regt, Khalifa, Bangu, and Chirimuuta's accounts. Second, Saatsi argues that the distinction clarifies the explanatory role of mathematics in a manner that contrasts with Kostić's treatment of topological explanation. Kostić argues that topological properties are explanatory in themselves, whereas Saatsi argues that mathematics enhances the pragmatic dimension of explanatory power in a manner that is consistent with denying the explanatory power of mathematical properties along the factive dimension. Third, Saatsi argues that scientific understanding may advance along either the factive or pragmatic dimensions of explanatory power, yet it is only when there is progress along the former that understanding amounts to an epistemic achievement. Pragmatic advances in explanatory power merely provide "cognitive scaffolding" for these epistemic achievements.

2. Understanding and Scientific Realism

In discussing the factive dimension of explanatory power and its implications for understanding, Saatsi also broaches upon the relationship between understanding and debates about realism and instrumentalism. In particular, scientific realism is, roughly, the position that what our best theories say about the world is approximately true (see Chakravartty (2017) for a discussion of the various dimensions of realist commitment). The realist holds that entities and structures posited by our best theories, including unobservable ones, exist and behave more or less as our theories say they do. Non-factivists about understanding, such as Potochnik (2017), hold that science aims at understanding instead of truth. So, on the face of it, non-factivism about understanding stands in tension with scientific realism. Part II, titled "Understanding and Scientific Realism," focuses on such issues. It begins with an exchange between Angela Potochnik and Christopher Pincock, who each offer a new defense of scientific realism. In Chapter 10, Pincock defends scientific realism while drawing on the requirements for successful scientific understanding and knowledge based on it. Whenever a scientist conducts a successful experiment that relies in part on theoretical beliefs about unobservables, grasps that this success is obtained independently of their actions and their scientific community, and understands the phenomenon in question well, then it is highly likely that they know that the unobservables exist. Pincock argues that no form of realism that involves context-dependent understanding or knowledge is feasible (such as Giere's (2006) perspectival realism or Potochnik's (2017) account of understanding), because they cannot explain how scientists extrapolate context-independent knowledge from their experimental findings. In Chapter 11, Potochnik defends a variant of selective realism. She argues that we can be realists, although scientists frequently work with models and idealizations that do not purport to be true. Her selective realism is based on the hypothesis that scientists do not aim at developing true theories. Instead, they aim at discovering causal patterns, that is, partial, simplified accounts of complex reality. These causal patterns exist in a mind-independent way. So, knowledge of causal patterns is knowledge about mind-independent reality. However, which patterns we detect depends partially on the research interests and the aims of the scientists who seek the explanations.

In his response in Chapter 12, Pincock insists that any form of selective scientific realism that construes the knowledge, explanation, or understanding involved as being context-dependent is not defensible. Knowledge of unobservables requires independence from the agent's situation, including their research interests. For instance, it requires us to know when an observable feature genuinely depends on something unobserved rather than being an artifact of the experiment. In her response in Chapter 13, Potochnik first argues that scientific realism should be about the truthmakers of theoretical claims (rather than the existence of unobservables or their character). Then, she addresses Pincock's concerns. She points out that the context-dependency of scientific knowledge only means that knowledge of some causal pattern could be unenlightening in a different research context, because it does not matter for the research goals in that context. The objects of scientific knowledge are selected based on context. The existence of the causal patterns is not context-dependent.

Writing also on the scientific realism debate in Chapter 14, Amanda Nichols and Myron Penner look at the evidence supporting the accuracy of current molecular models based on the data collected via infrared spectroscopy and high-magnitude microscopes. They argue that the

best explanation for the correspondence between the observed data and that predicted by molecular models is that these models are correct with respect to the number and kind of atoms, bond connections, and orientation in three-dimensional space. This suggests that realism about molecular structures is justified. However, Nichols and Penner consider the possibility of withholding ontological commitment by reframing their abductive argument, such that the best explanation of correspondence between observed and predicted data is simply that molecular models are empirically adequate. Nichols and Penner discuss how the satisfactoriness of such reinterpretation depends on one's account of explanation and on how one characterizes the observable/unobservable distinction in light of technologically assisted observations such as infrared spectroscopy and high-magnitude microscopes.

Commitments to scientific realism and reductionism may suggest that in representing and modeling the world, we privilege those entities and structures that are the most fundamental. In Chapter 15, Julia Bursten looks at and expands on the work of Waters (2017, 2018) and Batterman (2021) as examples challenging reductive scientific metaphysics. Specifically, these are accounts that challenge the idea that the best guide to ontology is found in the so-called fundamental physical theory. She notes how these accounts highlight the important role that scale plays in defining ontological categories in scientific theories, thereby rejecting the reductionist perspective that the smallest scale is the most fundamental, general, or real. Consequently, Bursten urges philosophers to seek alternatives to the dominant part–whole approach to scientific metaphysics. She identifies Massimi's (2022) perspectival realism and her own "conceptual strategies" (Bursten 2018) as such accounts, and in doing so brings into fruitful dialogue various anti-fundamentalist approaches to scientific metaphysics.

3. Understanding, Representation, and Inference

Scientific representations such as models afford understanding and facilitate surrogative reasoning and inference. Questions arise regarding how models represent, to what extent they are analogous to maps, and how they provide understanding and warrant inference. Part III, titled "Understanding, Representation, and Inference," includes essays that focus on such issues. In their contributions, Collin Rice and Jaakko Kuorikoski shed light on the social dimensions involved in scientific representations and the understanding that they produce. In Chapter 16, Kuorikoski defends a pragmatist concept of understanding; (explanatory) understanding is the ability to draw correct counterfactual what-if inferences about the object of understanding (rather than the possession of relevant correct mental representations). This inferentialist account of understanding is driven by the social epistemological function of attributions of understanding (drawing on Brandom 1994, Craig 1990). This ability-focused account of understanding can explain controversies within the sciences (which are concerned with what can be achieved with a given theory), it helps to defend the factivity of understanding (because it only matters whether the correct inferences are drawn), and it supports a moderate explanatory pluralism (because it allows for different kinds of counterfactual dependency). In Chapter 17, Rice argues that scientific representations and the understanding that they produce are a fundamentally social and dynamic enterprise and communal achievement. For instance, what scientific theories or idealized models represent can only be determined by how communities of scientists use these representations over time. Likewise, scientific understanding is gained by scientific communities using conflicting models, interests, and values over long periods of time. Rice uses a teleosemantic theory of mental representation to flesh out the historical components involved.

In his commentary in Chapter 18, Kuorikoski agrees that scientific representation and understanding are inherently communal and dynamic achievements. However, he is not convinced that the historical roots are decisive and points out, among other things, that grasping mature scientific representations does not require knowledge of their genesis. Kuorikoski offers an inferentialist analysis of communal and dynamic representation (based on Brandom 1994) as an alternative philosophical framework. In his commentary in Chapter 19, Rice acknowledges the virtues of an ability-focused account of understanding, but he raises various objections against Kuorikoski's analysis of counterfactual what-if inferences and the factivity of understanding. In addition, he argues against a purely pragmatist analysis of understanding. The possession of relevant correct mental representations seems to be necessary for having the abilities in question. As an alternative, Rice suggests that a proper account of the various social and epistemic functions of understanding involves both representationalist and pragmatist components.

In their exchange, James Nguyen, Roman Frigg, Jared Millson, and Mark Risjord discuss the nature of scientific representation and modeling, and that of cartographic representation. Specifically, in various publications (e.g., Frigg and Nguyen 2020), Frigg and Nguyen have explicated and argued for their preferred account of scientific representation, the "DEKI account," which consists of four main elements: denotation, exemplification, keying-up, and imputation. In Chapter 20, Nguyen and Frigg utilize the DEKI account to offer an account of how maps represent and facilitate surrogative reasoning. In doing so, they suggest that issues such as the nature of representational accuracy, the purpose relativity and historically situatedness of representations, and the possibility of total science, are further illuminated. For instance, they hold that the models-as-maps analogy, which entails that all scientific representations are partial, purpose relative, and historically situated, "pours cold water" on the dream of a complete, final scientific theory. In Chapter 21, Millson and Risjord criticize the DEKI account for not distinguishing between justified and unjustified surrogative inferences based on scientific representations. Specifically, they identify what they call "the fortuitous misuse of a map," where unjustified surrogative inferences from maps can sometimes accidentally result in true conclusions. The DEKI account's ability to distinguish use from misuse depends on what a representation denotes. However, looking at the methodology of archaeological site mapping, Millson and Risjord hold none of the common accounts of denotation enable DEKI to avoid fortuitous misuse.

In response in Chapter 22, Frigg and Nguyen distinguish between two different aspects of inferences from representations that might need to be justified, which they call derivational correctness and factual correctness. They then argue that although it is fair to demand that an account of representation provides justification of inferences having to do with derivational correctness, they maintain that factual correctness is beyond the scope of an account of representation (including DEKI). Moreover, Frigg and Nguyen explain that DEKI provides the needed justification in the context of derivational correctness via the notion of keying-up. However, in their reply in Chapter 23, Millson and Risjord argue that keying-up does not save DEKI from the problem of fortuitous misuse. They identify three general characteristics of mapping conventions and conditions of production, namely, relevance, measurement, and derivation, and hold that such characteristics are not circumscribed by the DEKI account in a way that accounts for derivational correctness. In so doing, they gesture at their own preferred account of scientific representation, the inferential-expressivist account (Khalifa et al. 2022).

Emily Sullivan's exchange with Michael Tamir and Elay Shech concerns the role of representation, understanding, and values in the context of machine learning (ML) models. In Chapter 24, Sullivan identifies three stages at which non-epistemic values determine the extent to which ML and deep learning models have an opacity problem. Specifically, she looks at ML model acceptance and establishing the link between the model and phenomenon, explanation with ML models, and attributions of understanding due to ML models. In all such contexts, Sullivan identifies how "questions of ML opacity, explanation, and understanding are entangled with non-epistemic values." Part of her argument is based on a claim argued for in Sullivan (2022) to the effect that the extent to which model opacity and complexity is a hindrance to understanding and explanation depends on how much "link uncertainty" the model has. Link uncertainty concerns the lack of empirical support linking a model to a target. In their contribution in Chapter 25, Tamir and Shech contrast how the term "model" in ML contrasts with traditional usage of scientific models for understanding and thus suggest the "Target of Machine Learning (TML) Hypothesis," namely, that the target phenomenon of understanding with ML models is the relationship(s) of features represented by the data. They then identify three modes of understanding given the said target, and disambiguate what they describe as the difference between implementation irrelevance and functionally approximate irrelevance in order to explore how this distinction impacts potential understanding with ML models. In so doing, Tamir and Shech address what they claim is an ambiguity in Sullivan's concept of link uncertainty, arguing that distinguishing empirical link failures from representational ones clarifies the role played by scientific background knowledge in enabling understanding with ML.

In her response in Chapter 26, Sullivan identifies various points of disagreement with Tamir and Shech, including issues having to do with the limits of implementation irrelevance, empirical versus representational link uncertainty, and the ostensible target of understanding with ML models. For instance, she notes that the TML hypothesis is modelcentric and thus overlooks important ways in which ML may provide understanding of the aspects of the world, for example, by inducing explanations of phenomena. In contrast, Shech and Tamir maintain in

Chapter 27 that we ought to moderate our expectations of the role that ML models play. For instance, they distinguish between the epistemic risk associated with making inferences based on an ML model that may turn out to be false and the practical risk associated with taking (or withholding) actions based on the inferences made using these models. They then argue that the notion of epistemic risk is not exclusively or especially problematic for ML models.

4. Understanding and Scientific Progress

Finally, issues of scientific understanding and representation figure prominently in philosophical discussions of scientific progress. A venerable view holds that science progresses as it achieves greater verisimilitude (Niiniluoto 2014, Popper 1972), which is clearly a kind of representational success. More pragmatically inclined philosophers characterize scientific progress in terms of its problem-solving capacity (Kuhn 1970, Laudan 1977). More recently, philosophers have proposed increased knowledge (Bird 2007) and increased understanding (Dellsén 2016) as alternative criteria of scientific progress. Finnur Dellsén and Casey McCoy explore the interrelations between several of these views in Part IV, titled "Understanding and Scientific Progress." In Chapter 28, McCoy argues that understanding is the principal epistemic or cognitive aim of science. He develops an understanding-based account of scientific progress with an eye on problem-solving practices in science. Scientists progress when they improve their theoretical understanding of the phenomena of interest. McCoy takes problem-solving abilities to be a measure of the understanding achieved or the potential understanding that could be obtained with a new scientific paradigm. In Chapter 29, Dellsén argues that scientific achievements (such as theories) need not be epistemically justified to be progressive (contra Bird's (2007) epistemic account of progress). Otherwise, scientific progress would be rarely achieved when scientists acknowledge that most previous theories about the phenomenon in question turn out to be false, when theories merely subsume or strengthen previous theories, or when scientific peers disagree on the correct theory for a given phenomenon. In all these cases, our scientific achievements are not justified, although they can be progressive, such as groundbreaking new work.

In his commentary in Chapter 30, McCoy submits that none of these cases need to be problematic when we analyze the progress made as occurring precisely at the point when we are adequately justified. He maintains that determining the beginning of a progressive period is subject to intuition—especially in Dellsén's cases. McCoy also points out that regardless of whether justification is necessary for progress, it plays such an integral part in the genesis of progress that it needs to be reflected in an adequate account of progress. In his commentary in Chapter 31, Dellsén argues that problem-solving does not constitute scientific progress. Following Laudan (1977), what a problem is and how it can be solved is determined based on the research tradition in question. Solutions to problems need not be (approximately) true. Dellsén suggests that this fails to make sense of the possibility of misunderstanding a phenomenon or misunderstanding when an achievement is progressive. If the role of problem-solving is merely to promote progress, it does not seem to be integral to scientific progress. On the one hand, problem-solving does not always promote progress, since solutions to problems might distract researchers or lead them astray in some cases. On the other hand, scientific achievements other than problem-solving, such as collecting new data, may also promote progress.

As we believe this introduction already suggests, scientific understanding, scientific representation, and their points of intersection stand as a touchstone for several related themes, including knowledge, explanation, scientific realism, reasoning, and scientific progress. As such, we hope that the chapters provide fresh insights on these perennial issues in the philosophy of science.

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