Scientific Inquiry: From Metaphors to Abstraction

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In philosophy of science, abstraction tends to be subsumed under representation, often being described as the omission of a target's features when it is represented. This approach to abstraction sidesteps cognitive aspects of abstraction processes. However, cognitive aspects of abstraction are important in understanding the role of historically grounded epistemic criteria supporting modeling in science. Drawing on recent work on the relation between metaphor and abstraction, we introduce the concept of paths of abstraction, and use historical and contemporary examples to point to their role in guiding the development of relevance criteria which support modeling strategies in science.

1. Introduction

Metaphors are an important topic of discussion in many areas of philosophy and the social sciences. In all of these areas, it is widely recognized nowadays that metaphors are "necessary and not just nice," as the title of a 1975 article by Ortony puts it. In the philosophy of science, metaphors are often only recognized as relevant in the context of discovery,

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so they are seldom included as major players in discussions about the epistemic role of models, and more generally are not considered as playing a justificatory role in the kind of problems the philosophy of science is interested in. Mary B. Hesse and Richard Boyd famously talk about the role of metaphors in the construction of theories, but they do not claim an epistemic role for them (Hesse 1966; Boyd 1993). The more common approach towards metaphors and analogies in the philosophy of science consists in ignoring their role in matters epistemic and in particular in relation to their role in the evaluation of models. Things are changing, however. A recent volume dedicated to the topic of scientific imagination (Levy and Godfrey-Smith 2020) includes two articles on metaphors. In her contribution, Elizabeth Camp (2020) elaborates on a view of metaphors as playing a normative role not only in everyday cognition but also in scientific inquiry. Her idea is that metaphors are a special kind of what she calls "frames," and that these frames (which include other figures of speech and also some scientific models) generate abilities and cognitive structures that often play an epistemic role. Arnon Levy also recognizes in his contribution to the same volume (2020) that metaphors enhance our ability to think about specific targets of modeling.[1]

The importance of taking the cognitive dimension of scientific methodology into consideration for far-reaching problems in the philosophy of science has been overlooked (particularly in relation to questions about the epistemic role of modeling).[2] Abstraction is a major aspect of such cognitive dimension. The usual way of characterizing abstraction in the philosophy of science is as the omission of features of a part of the world in a representation of it (see section 2). It is assumed that the criteria leading to what may be omitted should be either black-boxed (as not of epistemic interest); or else that the norms leading scientists to decide what could be omitted can be identified and studied as part of the evaluation of theories and models, without the need for incorporating discussions about the historical or cognitive constraints playing a role in such evaluation.

The traditional way of understanding abstraction, then, suggests that the discussions in cognitive psychology and other areas of the cognitive sciences about what abstraction is are irrelevant for the kind of questions

1. It is not clear, however, whether Levy would go as far as Camp in claiming that such enhancing of the ability to think could have epistemic value.

2. There are, however, valuable contributions in this direction. For example, Nancy Nersessian (2002, 2008) has developed an approach to conceptual change and modeling that aims to consider historical and cognitive aspects in the development of scientific models that she refers to as the cognitive-historical methodology. She has underlined the role of metaphors in conceptual change, and in particular the relevance of what she calls "generic abstraction" in generating representations (see section 2).

addressed in the philosophy of science. Meanwhile, abstraction is a key topic of discussion in psychology. Lawrence Barsalou begins a well-known article on the topic as follows: "If a scientific construct's centrality reflects the variety of forms it takes, then abstraction is a central construct in cognitive science" (Barsalou 2005, p. 389). There is as yet no consensus on how to classify kinds of abstraction, and discussions are ongoing as to how abstraction and generalization are connected (Colunga and Smith 2003). This discussion involves the ways in which abstraction is embodied and/or situated.

Recently, there have been several lines of research in the cognitive sciences pointing to the significance of metaphors in guiding our construction of abstractions (Jamrozik et al. 2016; Gibbs 2013; Jensen and Greve 2019, and the special issue to which this latter article is the introduction). In this paper we argue for the philosophical significance of one kind of abstraction process guided by metaphors playing a constitutive role in the development of specific scientific practices. Our main claim is that such metaphorical abstractions[3] articulate criteria of relevance that play a justificatory role in modeling (and more generally in conceptual change). Moreover, we will show how metaphorical abstraction processes, what we call paths of abstraction, help to explain the epistemic role of cognitive-historical constraints in model-building. We do not claim that all abstractions are metaphorical abstractions. If one believes that all thinking is ultimately an elaboration of metaphors this will be the case, but our claim is much more modest. What we argue is that some metaphors play a useful role in model-building through their part in developing relevance criteria; and therefore, play a part in justifying the pursuit of a scientific agenda.

The reader might wonder whether we are not just confusing issues in the context of discovery, with issues belonging to the context of justification. But this is not the case. In the introduction to a collection of essays devoted to reopening the debate about the significance of context of discovery/context of justification distinction, Schikore and Steinle associate the marginalization of developments in the history and the philosophy of science (and in particular their implications for major open questions in the philosophy of science) to the way that this distinction is understood. As the editors put it, the problem is that the assessment of non-traditional efforts is "still governed by the very distinction that had seemingly faded away by the late 1980s" (Schickore and Steinle 2006, p. x). Several of the book's authors propose different ways of understanding the distinction and of questioning its exhaustivity. In his contribution, Thomas Nickles

3. When we refer to metaphorical abstractions, we do not mean abstractions used metaphorically, but rather, abstractions coming from metaphors.

proposes that instead of thinking in terms of a sharp separation between two contexts, we should realize that justificatory strategies in science could have different sources. Nickles distinguishes two components in the context of justification, what he calls epistemic appraisal (EA) and heuristic appraisal (HA). EA "attends to truth-conducive features of justification and decision-making, while HA attends to a variety of heuristic and pragmatic considerations relating to economy of research" (Nickles 2006, p. 159). We think Nickles is correct in pointing out the significance of recognizing different kinds of justificatory strategies. However, depending on what is considered a suitable account of scientific epistemology, what Nickles calls heuristic appraisal could count as a kind of epistemic appraisal. For instance, an understanding-promoting heuristic would be an epistemic heuristic in the context of an epistemology of understanding—the kind of epistemology that recognizes understanding as a main epistemic goal. Of course, there are discussions about how to characterize cognitive understanding, but if we are willing to accept that there are heuristics that promote understanding, and that cognitive understanding is a major epistemic goal that is not reducible to knowledge-why, then it makes sense to think of heuristic appraisal as an epistemic achievement. But the key point we are making in this paper is about the justificatory role of what we call metaphorical abstraction. Metaphorical abstraction plays its justificatory role through the development of what we refer to as paths of abstraction. We think there are good reasons to think such resource for justification plays an epistemic role (in model evaluation), but even if that is not conceded, the importance of what we call paths of abstraction in justifying modelling strategies remains.

This article proceeds as follows: In section 2, we discuss the predominant characterization of abstraction (as omission of features) in contemporary philosophy of science, and briefly review some alternative ways of characterizing it. We suggest that the notion of abstraction as omission is too narrow to account for the epistemic value of the diversity of practices that interest philosophers of science. Subsequently, in section 3, we introduce the concept of metaphorical abstraction. We then proceed to examine how metaphorical abstraction functions in the development of early models in neurophysiology. Section 4 juxtaposes Galvani's and Volta's distinct models of the frog's leg contracting, as a contrast between two different paths of abstraction guided by different metaphors. Section 5 presents thermodynamic and electrochemical approaches for modeling the nerve impulse. We focus on the impact of the repeated use of related metaphors in the configuration of two alternative paths of abstraction, embodied in different traditions of inquiry: the valuable (yet disregarded) work and legacy of Ichiji Tasaki; and another supporting Alan Hodgkin and Andrew Huxley's renowned work. In section 6, we address the issue of how to interpret the alternative models emerging from contrasting paths of abstraction. We argue that different paths of abstraction can lead to a worthwhile diversity of models—even though at some point these models may be interpreted as excluding alternatives, at a later time they can be appreciated as advancing our understanding. We conclude that the epistemic value of a scientific agenda supported by a robust path of abstraction(s) cannot be reduced to (or cashed in in terms of) factive knowledge.

2. The Orthodox Notion of Abstraction in Philosophy of Science

In recent decades, there has been an interest in philosophy of science to address the question of how modeling epistemically supports scientific practice. One common strategy for tackling this issue is to account for the epistemic role of models in terms of model-world relations. A model is seen as an adequate representation of a target if it correctly captures enough of its features to promote epistemic aims (explanation, prediction, etc.). This widespread approach to models inherits a disregard for psychological notions of abstraction from logical positivism, leading to what we call the "orthodox approach to abstraction" in philosophy of science. In the orthodox approach, the term abstraction refers to the "mere" omission of features in a representation of a target or subject matter of scientific interest (Levy 2018; Godfrey-Smith 2009; Jones 2005). Abstraction is distinguished from idealization, which refers to aspects of the model that make false assertions about the target. Thus, abstracting makes a model incomplete (in the sense that it lacks detail), but not distorted (Levy 2018, p. 4). The orthodox approach relies in two commitments: First, that the relevant notion of abstraction in philosophy of science is abstraction-as-omission; and second, that abstraction is a feature of representations.

The second commitment does not follow from the first because it is possible to consider abstraction as omitting other things besides detail in a representation.[4] It is the two commitments taken together that lead to the idea that abstraction can be cashed in, in terms of the level of detail of the representations scientists produce. This level of detail is assessed with respect to the target, subject matter or topic (Godfrey-Smith 2009; Jones 2005) or to another representation of the same representanda (Levy 2018).

4. As an example, consider Radder's conception of abstraction as "setting apart," which involves the separation of the product of a process, from the process by which the product was obtained. According to Radder, "both leaving out and setting apart should be taken into account in a philosophical analysis of the process of abstraction" (2006, p. 110).

Inasmuch as abstraction is a feature of representations, it can be analyzed via a study of the representations that scientists produce, without having to deal with the psychological features of the process leading to their construction. In this analysis, the generalization attributable to the representation is set aside as a separate issue from abstraction. Thus, the intimate (and difficult to analyze) relation between abstraction and generalization is sundered. On the other hand, an important question in the discussion in psychology is about how abstraction and generalization are connected (Colunga and Smith 2003).

In the contemporary literature in philosophy of science, one can find approaches to abstraction that go beyond orthodoxy. Andrea Loettgers and Tarja Knuuttila (forthcoming) criticize Aaron Levy's and William Bechtel's rendering of scientists' modeling of biological systems with network motifs in terms of abstraction as omission and propose instead a modal reading that emphasizes the template-like nature of the motifs. Their work suggests that although abstraction as omission of features in a representation is adequate to describe some scientific practices, it does not work for all of them.

There are also some philosophers who claim that other attributes of representations, in addition to omission of detail, should count as abstractions. Gallegos Ordorica (2016) suggests that aggregation is a type of abstraction different from the omission of features (see also Jones 2018). Aggregation condenses details that are relevant, as they are captured in a single concept. Both Sergio Gallegos Ordorica and Nicholaos Jones consider the concept of "center of mass" to be a paradigmatic example of this type of abstraction. These authors suggest broadening the concept of abstraction relevant for philosophy of science; however, they remain committed to the idea that abstraction can be cashed in in terms of (incompleteness of) representations (Gallegos Ordorica 2016, p. 162; Jones 2018, p. 956). Thus, they are only challenging the first commitment of the orthodox approach.

Other authors implicitly or explicitly challenge the assumption that abstraction in science can be fully analyzed in terms of the representations produced by scientists, presenting a more radical disagreement with orthodoxy. In the process, alternative approaches to abstraction have been developed. They all exploit modal features of abstraction-as-process and ground the generalizing capacities of abstractions in scientific practices (Cartwright 1989; Radder 1996, 2006; Nersessian 2002, 2008; Martínez and Huang 2011). Radder considers features of experimentation such as repeatability and triangulation as part of the abstraction process that allows experimenters to pass from the local, material realizations of experimental practices to non-local regularities. Nersessian (2002) introduces the concept of generic abstraction. This abstraction strategy plays a role in the development of mathematical equations modeling physical systems. She shows how

James Clerk Maxwell's model of the electromagnetic field resulted from integrating a number of physical analogies, allowing him to treat different dynamical patterns generically. She is very clear that in this case, abstraction is not a feature of representations but rather that the representations are the result of generic abstraction: "mathematical representation of relationships between current and magnetism is derived from a model that is a hybrid of machine mechanics and fluid dynamics" (2002, p. 141).

The different non-orthodox (cognitive) notions of abstraction that challenge both commitments of the orthodox approach should not be seen as excluding each other but as characterizing different abstraction strategies that are well suited for different purposes. Take for example the differences between Radder and Nersessian in their approaches to abstraction. Both authors relate abstraction to generalization. But whereas Radder (1996) emphasizes the role of experimental practices in providing the social structure of the knowledge-supporting generalization, Nersessian focuses on abstraction processes from the perspective of situated cognition. Both authors can be understood as describing ways in which abstraction leading to generalization takes place in the context of specific kinds of scientific practices. More generally, the skills and technology embodied in specific practices constitute resources for abstraction cum generalization. As Martínez and Huang (2011) put it: abstraction is embodied in different kinds of abstraction practices. We now proceed to clarify the relation between metaphor and abstraction before going into the case studies.

3. Metaphor and Abstraction

In this paper we will be interested in metaphor conceived as a cognitive tool that involves juxtaposing two domains. Within philosophy, a treatment of metaphor as not only a linguistic matter, rather part and parcel of human thinking, was proposed by Ivor Richards in 1936, and then further developed by Max Black in his "interaction theory of metaphor." In cognitive linguistics, metaphor as a linguistic expression is distinguished from conceptual metaphor, where the latter involves understanding one conceptual domain in terms of another conceptual domain. Such understanding is often spelled out in terms of a mapping, "in the sense that constituent conceptual elements of B correspond to constituent elements of A" (Kovecses 2010, p. 7).[5]

5. This is not to say that conceptual metaphor theory does not care for the justificatory role of metaphor. Lakoff and Johnson (1980) discuss how metaphor creates similarities in chapter 22.

Regardless of whether one refers to the exercise of juxtaposing domains in order to attain understanding in terms of metaphor or analogy[6] (we will use the term "metaphor"), there is a tendency to reconstruct such cognitive exercise in terms of comparison. Hesse for instance characterizes analogy in terms of similarity between two domains, say A and B. Formal analogy involves similarity between individuals of the domains, whereas material analogy involves similarity among the relations of individuals in domain A with relations of individuals in domain B (Hesse 1967). In the field of psychology, Gentner and others also developed an approach to metaphor as a kind of mapping (e.g., Gentner 1983). Note that without further discussion, claiming that metaphor is a kind of mapping leaves aside an important question—that of how the respects for similarity are established in the first place. There is no doubt that mapping and similarity are at play in metaphor. However, such similarity is always a similarity in some respects. Does metaphor also play a role in generating criteria of relevance that lead the agent to detect the relevant respects for a productive comparison?

In his interaction theory of metaphor, Black claims that metaphors do not simply call attention to likeness but have a role in the "creation of similarities." He compares the role metaphors play in thought to how slow-motion film brought about a new perspective for analyzing movement, previously unavailable without the cinematographic medium. Extrapolating this example, Black argues that similarly some metaphors are "cognitive instruments," that "enable us to see aspects of reality that the metaphor's production help to constitute" (Black 1977, p. 454).

In philosophy of science, the involvement of metaphor in the creation of similarities is related to the recent discussion in philosophy of science about the "framing" function of models and metaphors (Levy 2020; Camp 2020). For Camp, frames are representational vehicles that provide overarching principles or perspectives (2020, p. 319). This function of metaphors and models is to serve as organizing structures in the sense that they express principles for interpretation. This is not a question of representational content but rather a question of assigning prominence and centrality to some of its elements, as well as developing ways to conceive the purported prominent and central elements in relation to one another. This addresses the kind of cognitive work humans can achieve by way of juxtaposing two domains in a way that goes beyond the recognition of similarities into how criteria of relevance are established in the first place.

6. There is an overlap between cognitive metaphor and analogy if the latter is understood as a kind of reasoning prompted by the comparison of two subjects (e.g., Hesse's concept of formal analogy mentioned below). When the term "metaphor" is used to refer to a cognitive as opposed to linguistic phenomenon, it is possible to understand analogy as a special case of metaphor or as a development of metaphor (e.g., Lakoff and Johnson 1980), as we do in this article.

The contrast between approaches to metaphor (and analogy) as identifying similarities or as generating similarities appears also in psychology, where horizontal comparative views of analogy are opposed to vertical approaches, the latter claiming that analogy establishes respects in which similarities are significant in the first place (Morrison and Dietrich 1995; for a discussion on respects for similarity see also Medin et al. 1993; Glucksberg and Keysar 1990). Guerin, Ferreira, and Indurkha (2014) argue that rather than developing competing accounts, these two views should be understood as describing different processes involved in analogy (what we are calling metaphor): (i) "determining how best to represent or interpret two situations (often called source and target)," which may involve "imposing a representation that makes them similar"; and (ii) identifying similarities between two situations (2014, p. 16). Describing metaphorical reasoning in terms of identification of similarities means assuming that the respects for comparison are already in place (see Guerin et al. 2014, p. 16).

Even if one is willing to accept that metaphor establishes criteria of relevance, a question remains as to how such abstraction processes are grounded. The conceptual metaphor theory by Lakoff and Johnson (1980) promoted the idea that all concepts have an embodied origin, and more generally, that conceptual domains are understood in terms of other conceptual domains via metaphor. This has generated a very productive area of research that has advanced our understanding of the role of metaphors in human thinking. Nonetheless, their approach has clear limitations in accounting for the kind of abstraction processes that play a role in science, and in particular those involved in the production of what are often called "scientific representations." For Lakoff and Johnson, abstract concepts have to be understood as the result of our knowledge of concrete concepts (i.e., concepts with sensorimotor content). But, as pointed out by many authors, this is hard to sustain (cf. Jensen and Greve 2019). There are two related reasons why this approach fails to account for scientific concepts (and representations). On the one hand, conceptual metaphor theory conceives of cognition as taking place in the head, as processes that are ultimately reduced to mental gymnastics (Chemero 2009, p. 18). Yet on the other hand, and this has been the main difficulty with this approach to metaphoricity, we have the problem of how to account for abstract concepts. This is a well-known difficulty of earlier theories of embodied cognition.

Nowadays, several different lines of research in the cognitive sciences aim to overcome this difficulty by showing how metaphorical abstraction can explain abstract concepts. Jamrozik et al. (2016) for instance, suggest that abstract knowledge about a target is obtained when it is metaphorically appraised in terms of different bases. Repeated metaphor use drawing particular concrete experiences from different bases ends up constructing an abstract concept, which omits at least some of the original concrete features, but retains abstract shared features of the bases. The abstracted concept can then be applied in order to understand new situations.

The orthodox approach to abstraction assumes that scientists rely on criteria as to what can be omitted, however the origin and development of such criteria are not seen as linked to the abstraction process. In contrast to the notion of abstraction-as-omission, metaphorical abstraction involves not only omitting or setting apart, but also the construction of relevance criteria. One way this kind of abstraction has been addressed in the psychological literature is by claiming that such metaphors are not comparisons, but class-inclusion assertions.[7] Metaphorical abstraction in such cases invites a systematic identification of similarities, in accordance with a set of abstract relations that are common to the base and target as members of the class (Glucksberg and Keysar 1990). Metaphorical abstraction has important implications for the role of abstraction in science (and its relation to modeling). At the very least, it suggests ways in which metaphors can play a role in the generation of relevance criteria (via the creative role of metaphors), which then play a role in the development and assessment of representations. Of course, this means that at least some kinds of abstraction epistemically precede representation. This is not entirely compatible with the orthodox account of abstraction as a feature of representations, since it subsumes abstraction to representation and instead, we are observing that metaphorical abstractions enable meaningful representation in the first place. Next, we turn to a line of enquiry in the cognitive sciences which supports this idea, namely that whatever representations are, they should be understood as products of abstraction processes.

In the following sections, we proceed to examine the way that metaphors promote abstraction in science. We will observe how repeated metaphorical abstractions that draw from different bases trace paths of abstraction. The identification of such paths will help to explain the justificatory role of cognitive-historical constraints in model building. The resulting criteria do not sit well within the traditional discovery/justification divide since they are normative and yet one cannot fully understand them with independence of the contexts in which they emerge, because of the way their justificatory character is associated to the situated nature of the abstraction paths that generated them. Our main thesis in this paper is that metaphors (incorporated in paths of abstraction) play an active role in articulating criteria of relevance in scientific modeling. These metaphorical abstractions then play a role in the development and evaluation of scientific

7. We do not intend to suggest that all metaphors that lead to criteria of relevance do so by way of class-inclusion assertions. We just mention this as one way in which such function of metaphors is being discussed.

representations and explanations. Since many of these criteria are not explicit but part of the situated nature of the abstraction processes involved, the context in which they emerge is essential to pick out some of the (implicit) commitments that result from the abstraction path. We begin illustrating these ideas in the scientific context by discussing the dispute between Galvani and Volta in the late eighteenth century.

4. The Animal Leyden Jar

At the end of the eighteenth century, Luigi Galvani discovered that a dissected frog leg contracts when the nerve and muscle are touched simultaneously with a metal arc. He conjectured that the contraction was produced because the animal tissue contained electricity. We know from unpublished memoirs that in order to explain this "animal electricity," Galvani resorted to modeling the frog muscle-nerve complex on a Leyden jar, a device that was known to have the capacity to store charge.[8] This "Leyden jar model," as Piccolino and Bresadola (2013) refer to it, was a crucial step in the development of Galvani's explanation for the contraction of the frog's leg.

Galvani had accumulated experience with the Leyden jar throughout his professional career. His familiarity with the apparatus was not, however, invested in increasing his understanding of animal electricity; it was simply one of the resources used in the laboratories of the day. Thus, in developing the Leyden jar model Galvani was not constructing some object (a representation) that is playing the role of a surrogate for the muscle-nerve complex. Instead, Galvani exploited his familiarity with the Leyden jar to suggest what about the frog's leg could be relevant to understand its electrical capacities. His newly-minted metaphor (model) led him to think that the frog's leg could be working as a capacitor if, between the muscle and nerve, a separation of positive and negative charge was taking place (known at the time as a "separation of positive and negative electricities," [Piccolino and Bresadola 2013, p. 316]; see figure 1 below).

The Leyden jar metaphor allowed Galvani to identify a generic causal mechanism that could explain animal electricity. However, the initial idea that there is a separation of charge between muscle and nerve in the frog leg was unsatisfactory, since electrical disequilibrium was thought to be impossible within the organism. While addressing this issue, Galvani became interested in tourmaline. This mineral becomes electrically charged when heated; and physicists had recognized that this entailed

8. Leyden jars, a precursor of modern capacitors, consist of a glass jar that insulates the charge accumulated in the internal armature (a metal foil coating the inside of the jar) from the external armature. They become charged when electricity is conducted to the internal armature, which then attracts an opposite charge externally.

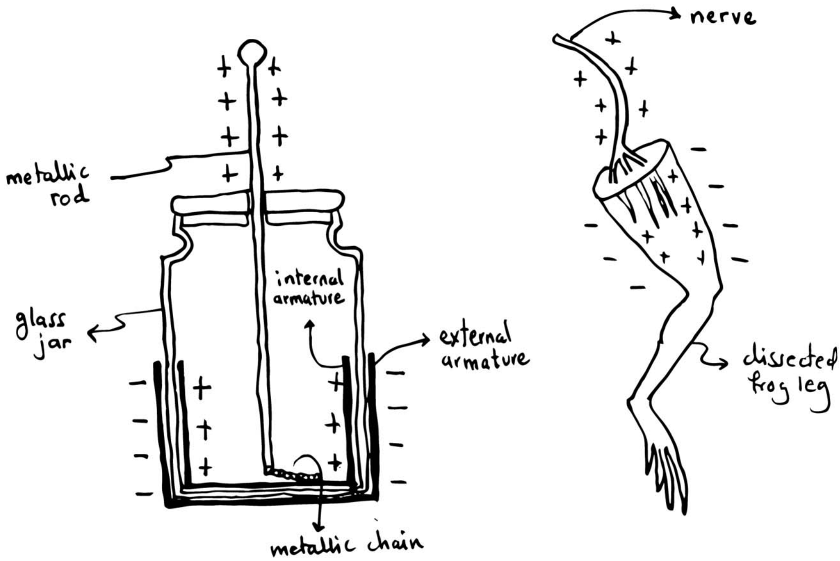

Figure 1. *Left*: The distribution of electricity in a charged Leyden Jar. *Right*: Galvani's first model of the muscle-nerve complex of the frog leg as an "animal Leyden jar."

an electrical disequilibrium in the same conductor. In tourmaline, separation of electricities takes place on a different scale, leading Galvani to a critical insight: "The double electricity of tourmaline is not just situated in the entire stone, it is in every fragment. Similarly, in muscles, the admitted double electricity does not belong only to the entire muscle body, but to every part of it" (Galvani 1787; as cited in Piccolino and Bresadola 2013, p. 134). Via the tourmaline metaphor, the issue of scale became salient. Galvani elaborated on his first model and proposed a causal (insulating) role for fatty parts of muscle, which visually resembled the tiny lines in tourmaline that Galvani believed operated as insulators. The evolution of the modeling process towards this explanation involved the merging of two metaphors that provide a composite grounding for generalization: the muscle-nerve complex separates electricities like a Leyden jar, but the insulation operates on a microscale, as it does in tourmaline. Piccolino and Bresadola refer to this as Galvani's "minute Leyden jar model," emphasizing the combination of the two insights from the Leyden jar and tourmaline metaphors (Piccolino and Bresadola 2013, sec 5.3).

Although initially infatuated with Galvani's work, Alessandro Volta soon challenged Galvani's views and instead came up with a different framework for generalization. Volta proposed that the muscle-nerve complex is not a Leyden jar of sorts, but an electroscope—it responds to electricity but does not store it. This turned out to be a productive metaphor (i.e., a metaphor leading to generalizations with explanatory value) as well. He experimented with combinations of metals and even used the muscle-nerve complex as a device to detect electricity: the electroscopes of the time were not sensitive enough to detect the electricity generated by the metals Volta investigated, yet the muscle-nerve complex seemed to respond to it. Based on these interactions, he developed a theoretical approach to explain the frog leg's contraction, whereby the electricity is rather in the metallic arc with which the frog leg was being stimulated. Volta eventually convinced the scientific community of the existence of such "metallic electricity," by inventing a device capable of multiplying metallic electricity to the point of generating a spark: the pile.

Probably because animal and metallic electricity were presented in the context of seeking to explain the contraction of the frog leg, they were believed to be incompatible representations. Incompatible representations are different representations of a thing or process that cannot be seen as aggregative descriptions—they cannot be interpreted as representations of *parts* that can be added to a *complete* representation. Judging the two different representations as incompatible led to their perception as competitors for truth. Then, the confirmation of metallic electricity was taken as a rejection of the hypothesis of animal electricity. This interpretation became widespread, despite the fact that Galvani had developed experiments in which he observed muscular contractions without the presence of metals (Piccolino 1998).

Although we now consider Galvani as a pioneer of electrophysiology, in the years following his controversy with Volta, the animal electricity hypothesis was so discredited that posterior experiments measuring currents in animal tissue were wrongly interpreted as thermoelectric effects. There were no substantial achievements in animal electricity research for the next three decades, until those experiments were adequately interpreted by Carlo Matteucci, who was able to observe that the intensity of measured current depended on the number of thighs piled up, reproducing the principle of Volta's pile (Piccolino 1998, p. 390). Paradoxically, the concept of the battery thus played a role in successfully recuperating the research into animal electricity, and the battery—the device itself—later became instrumental in examining the electrical capacities of animal tissue. We can say in retrospect that both of these abstraction processes, and the representations they produced, were integral in the development of our current understanding of electricity and nerve excitability.

Underlying the disagreement between Galvani and Volta, are two contrasting abstraction paths. Abstraction paths are the path-dependent trajectories of situated abstractions (processes of abstraction), that arise from exploiting productive generalizations grounded in particular sets of cognitive tools (skills, metaphorical abstractions, etc.), articulated in scientific practices. Representations are (often) the result of such situated abstractions. Below we examine another case of contrasting paths of abstraction, and we discuss an alternative to conceiving the resulting representations as competitors for truth.

5. Abstraction Paths in Nerve Impulse Research

The generally accepted theory nowadays for the generation and propagation of nerve impulses[9] explains nerve excitability in terms of ionic currents across the bilipid membrane of nerve cells. The main idea is that protein "pumps" continually exchange sodium from inside the neuron for potassium outside, creating an imbalance in the concentrations of these ions. Protein "channels" bridge the inside and outside of the cell, with a gating mechanism that opens when the nerve cell is stimulated. Once these channels open, the electrically charged ions cross the membrane, changing the electrical field around it. This variation in voltage is understood to be the signal that travels along the axon.

For this explanation, we are indebted to the work of Hodgkin and Huxley, who, in the 1950s, presented a set of equations that reproduced the ionic currents recorded experimentally in squid axons. Research into the mechanism of nervous transmission had already advanced significantly by the point in which Hodgkin and Huxley began their research. In the beginning of the nineteenth century, scientists proposed that the nerve membrane is a "galvanic cell"—a metaphor which still appears in textbooks to this day (Purves et al. 2018, p. 40). Galvanic cells were developed in physical chemistry in the late nineteenth century and consist of two compartments separated by a semipermeable membrane—a boundary that allows some ionic species to cross, but not others. These artifacts became crucial for neurophysiologists at the turn of the century, because of their potential to answer a question that had lingered since Galvani's day: namely, how could organic tissue possibly store electric energy?

It was Ostwald, in 1890, who was the first to propose that the electric potentials in nerves could be explained if nerve excitability was interpreted in terms of the electrochemical behavior of galvanic cells. Julius Bernstein successfully exploited this idea in his famous "membrane theory" (Bernstein 1902). He proposed that there is a differential concentration

9. The "nerve impulse" (also referred to as "nervous transmission" or "action potential") is the transmission of a signal along a single neuron. This should be distinguished from synapses, which are signals between neurons.

of certain ions between the inside and the outside of the membrane. When the membrane is excited, it "collapses" and the ions move freely towards their electrochemical equilibrium, changing the electrical field in the vicinity of the membrane. Cole and Baker (1941) and Hodgkin and Huxley (1952b) later interpreted the transport of charge accompanying the diffusion of ions across a semipermeable membrane, in terms of the electrical current in a Resistor-Capacitor circuit. The RC circuit metaphor laid the groundwork for the development of Hodgkin and Huxley's (1952b) famous equations, obtained by calculating the currents in the equivalent circuit.

The Hodgkin and Huxley model was widely recognized as a major breakthrough after its publication in 1952. Still, many questions remained unanswered. As Hodgkin himself pointed out, Abbott's measurements of temperature change during the action potential (Abbott et al. 1958) are difficult to explain from the electrical approach endorsed by the Hodgkin and Huxley model (Hodgkin 1964, p. 70). Also, although Hodgkin and Huxley had been able to empirically characterize the shape of the variation in voltage with intracellular recordings in squid giant axons, how the ions managed to cross the membrane was still a mystery. The research program continued in the quest for the voltage-sensitive mechanisms responsible for changing the ionic conductance of the membrane; and finally, 24 years later, evidence of protein ion channels in the membrane was found (Neher and Sakmann 1976). As the program continued to advance, these protein ion channels embedded in the membrane were eventually proposed as being responsible for the conductance changes. Thus, our current mainstream understanding of the nerve impulse is based on this rendering of excitable membranes stemming from the original galvanic cell and electric circuit metaphors. The importance of permeability changes is incorporated in the galvanic cell metaphor, and the details of currents across the membrane and voltage were stitched into the electric circuit metaphor—which also introduced the relevance of selective permeability mechanisms. These metaphors were integrated into what we continue to call the Hodgkin and Huxley model, but as we have seen, used in this broad sense, their model is actually a constellation of many different models, loosely woven into a paradigmatic account of the generation and propagation of nerve impulses.

A few contemporaries of Hodgkin and Huxley remained skeptical of the "electricity-centered" agenda (Drukarch et al. 2018) developed from the merging of the galvanic cell and electric circuit metaphors (Teorell 1962; Tasaki 1982; Lowenhaupt 1996). Ichiji Tasaki, a neurophysiologist famous for his work in saltatory conduction, thought that the discovery based on the squid giant axon led too quickly to entrenchment of a specific set of tools and skills transferred from electronic engineering to nerve impulse research. He laments that this meant sidestepping other tools that had been used at the beginning of the century to study nerve excitation. For instance, Nernst's equation (1889), which the Hodgkin and Huxley model exploits to calculate the electrochemical equilibrium of sodium and potassium ions, used calculations of thermodynamic potential (Gibbs free energy). However, the ability to perform those calculations was gradually replaced with abilities in electric engineering. According to Tasaki, the skills of the later generation of scientists who intervened in the squid axons explain in part the kinds of models they came up with:

> Most of the investigators in the field of biophysics are experts in electronic engineering. Laboratories engaged in research in this field are usually equipped with a variety of elaborate electronic devices which enable biophysicists to carry out delicate electrical measurements on biological material such as squid giant axons. Perhaps because of their intimacy with electronic equipment, electrophysiologists have a strong tendency to interpret the results of their measurements in terms of capacitors, resistors and rectifiers in the nerve membrane rather than on the basis of ion selectivities, mobilities and Gibbs free energy. It is entirely natural that the manner in which an investigator interprets some unknown phenomenon is strongly affected by his interest and his previous experience. This fact may account for the differences in the approaches used by different investigators for the study of nerve excitation. (Tasaki 1968, p. vi)

Tasaki is making room for his alternative account of nerve excitation by making two (implicit) claims. The first is that biophysicists use certain metaphors central to their training to guide their interpretations of results. The other is that the representations articulated in their models are grounded in abstractions emerging from the metaphors in question.

The electric circuit metaphor leads scientists to treat the material constitution of both membrane and circuit as irrelevant and focus principally on flow of charge. This abstraction enables certain kinds of representation since the electric circuit diagrams and equations then can be applied to analyze the ion flow across the membrane. The equivalent circuit representation is the product of the metaphorical abstraction and not the other way around, and the same can be said of the equations. In his work on nervous transmission, Tasaki defended the idea that other abstractions, stemming from a different set of skills and practices, can lead us to understand other features of nervous transmission that the electric engineering approach overlooks.

Tasaki oriented his work by two metaphors alien to the Hodgkin and Huxley model. One of the metaphors is based on the Oswald-Lillie iron wire model (Lillie 1936), and the other on Teorell's "hydraulic analogue" (1959). The hydraulic analogue is similar to the galvanic cells—it also has two compartments separated by a membrane, each filled with a solute. However, the membrane in this device is a "fixed charge system," meaning that the surface along the pores is electrically charged. Since these systems are subject to three forces (instead of two, in galvanic cells), the dynamics are more complex. If an electric field is applied across the membrane of the hydraulic analogue, the water level and concentration of certain ions in one of the compartments rise, as the level in the other compartment lowers. If the electrical field is maintained constant, though, the water and concentration levels eventually reverse, generating relaxation oscillations that neurophysiologists also observed in nerve cells. Throughout the oscillations in the hydraulic analogue, the movement of ions is accompanied by movement of water, resulting in changes in pressure and volume.

Looking at nerve excitation through the lens of the hydraulic analogue backed up Tasaki's challenge to the widespread idea that the relevant cell barrier can be abstractly conceived as a "wall," changing only its permeability. Instead, it was possible that the membrane could change shape during excitation. This is how Teorell formulated the idea:

> It is not likely that biological membranes are rigid; they may rather be distendable and elastic [...]. Different layers in the composite membrane may have varying charge densities and hydraulic permeability [...]. It might perhaps be possible that this (membrane) structure can be subject to swelling or shrinkage. (Teorell 1962, p. 306).

This new view of the membrane opened up an avenue of experimentation for the few scientists interested in challenging the status quo. In the eighties, Tasaki and Iwasa examined mechanical properties of nerve cell axons and found that they shrink, swell and undergo density changes when excited (Tasaki and Iwasa 1980, 1982; Iwasa and Tasaki 1980). Such empirical results regarding the mechanical effects of nervous transmission are not easy to address from axon electrophysiology alone. Mechanical changes play no role in the electrical rendering of the Hodgkin and Huxley model—pressure, density and volume are not among its variables and parameters.

Whereas the hydraulic metaphor justified the investigation into mechanical effects associated with nervous transmission, the iron wire model brought thermodynamics back to the table. This model is comprised of an iron wire immersed in nitric acid. When the iron is scraped with a zinc rod, it becomes active and the activation (a bubbly reaction) travels along the wire. This behavior can be interpreted as a kind of excitability due to a change of state in the iron-acid interphase. This preparation drew Tasaki's attention to a potential relation between excitation and phase transitions. Previously, Tasaki had empirically identified that the macromolecular filamentous structure attached to the inside of the bilipid membrane is essential for excitable behavior in neurons (Tasaki 1982, pp. 161–2). He proposed a macromolecular model of nerve excitability, according to which, the filaments of macromolecules in the interior of the cell undergo phase transitions as part of the excitatory process. In Tasaki's model, the "barrier" of the nerve cell is the bilipid layer plus the interior macromolecular structure of the axon (Tasaki 1968, 1982).

This part of Tasaki's research has recently become significant, as contemporary neuroscientists theoretically reconsider recalcitrant experimental evidence for the Hodgkin and Huxley model (Abbott et al. 1958; Tasaki and Iwasa 1982). In this contemporary discussion, interest in experiments showing swelling of nerve fibers during nervous transmission has been rekindled (González-Pérez et al. 2016), and a number of alternatives to the Hodgkin and Huxley model have recently been proposed (Heimburg and Jackson 2005, 2006; Rvachev 2010; Shrivastava and Schneider 2014; El Hady and Machta 2015; Engelbrecht et al. 2016). Although the hypotheses that these new models propose do not coincide with Tasaki's macromolecular model, some of them can be said to explore related metaphors. In many of them, membrane density is an important variable, and phase transitions are also frequently considered to be explanatorily relevant. Many new research programs prioritize addressing the system from the perspective of thermodynamics and reintroduce analytical tools like calculations of Gibbs free energy to analyze nervous transmission.

The Heimburg-Jackson model is one of the most developed contemporary alternatives to the Hodgkin and Huxley model. Their model addresses the bilipid membrane as an elastic material sustaining signals formed by travelling mechanical (density) waves associated with phase transitions in the lipids. It also addresses the mechanical features of the nerve impulse, as well as other recalcitrant evidence that has no obvious place in mainstream electrophysiology: "If one assumes [...] that the nerve pulse is related to the propagation of an isentropic pulse, a temporal correlation between mechanical dislocations, forces, voltage, and heat release would not be surprising but rather an intrinsic property of the pulse" (Heimburg and Jackson 2005, p. 9794).

The Heimburg-Jackson model is empirically grounded in experiments showing that synthetic membranes (e.g., black lipid membranes, DPPC and DPPA membranes) and lung surfactant display the kinds of properties required for travelling phase transitions to behave as they describe. Moreover, Heimburg, Jackson and colleagues produced evidence showing permeability changes associated with phase transitions occurring in synthetic lipid membranes with *no* proteins (Laub et al. 2012). Like the galvanic cells and other systems that have served as bases for metaphorical abstractions, the synthetic membranes are part of the material culture of several scientific practices and have scientific importance in various fields (in particular in non-equilibrium thermodynamics). The extent to which a framework can be articulated in which these membranes can be seen as similar to the nerve cell membrane, dictates whether the study of these preparations can be extended to understanding nerve excitability. Likewise, to capitalize on our knowledge of synthetic membranes, scientists have to develop a rendering of the biomembranes where they can be studied by applying the formal templates used to study synthetic membranes. In this vein, in the Heimburg-Jackson model, the nerve impulse is represented by sound wave equations (as opposed to the electric current equations in the Hodgkin and Huxley model), and the membrane is conceived of as a compressible material undergoing phase transitions. The synthetic membranes are thus metaphors that enable abstraction, by entwining synthetic membranes and biomembranes into a story where phase transitions in both media form solitary pulses.

Important differences remain as to what is held to be explanatorily relevant in the Hodgkin and Huxley and Heimburg-Jackson models, leading to a number of tensions between them. Consider this statement, addressing the relevant features of the nerve cell to explain excitability:

> It is clear that the Hodgkin-Huxley model fails to explain a number of features of the propagating nerve pulse, including the reversible release and reabsorption of heat and the accompanying mechanical, fluorescence, and turbidity changes. (Heimburg and Jackson 2005, p. 9795)

In this passage, the scientists accuse the Hodgkin and Huxley model of failing to address what they consider to be explanatorily relevant features of nervous transmission. However, from the perspective of mainstream electrophysiology, the Heimburg-Jackson model fails to account for features of the nerve impulse considered to be "established" (e.g., the difference in the response times between sodium and potassium permeabilities, as characterized in Hodgkin and Huxley [1952a]). Moreover, whereas mainstream electrophysiology relies on protein ion channels to explain permeability changes, the Heimburg-Jackson model proposes that phase transitions could have the effect of opening lipid pores where ions can cross. In other words, proteins, which play a vital explanatory role in mainstream electrophysiology, may not be necessary to account for permeability changes, according to this alternative model. To sum up, these two scientific projects, engaged as they are with different paths of abstraction, operate according to different justified criteria of what counts as a good representation of the nerve impulse. These criteria then play a role in the assessment of scientific representations, and those models that do not address the features deemed relevant are taken to be inadequate. The justification of the criteria goes back to the metaphors that were exploited to propose the causal stories that provide explanations, in relation to the fruitfulness of the approach articulated by the path of abstraction that accumulates different criteria coming from different metaphors and other sources.

The Hodgkin and Huxley and Heimburg-Jackson models could easily be interpreted as competing for truth. But competition for truth assumes that the models can be compared as to how well they fare in representing the relevant features of the nerve impulse (Teller 2008). In the case of models supported by different abstraction paths, there may not be sufficient agreement in normative criteria for this perceived competition to take place. Our comprehension of the nature of abstraction and its relation to generalization, and thus to the articulation of relevance criteria, plays a role in how we frame the tensions between the different models. At the end of their philosophical appraisal of the contrast between the Hodgkin and Huxley model and its contemporary alternatives, Drukarch et al. suggest that "These models should [...] provide insight into this phenomenon by abstracting (i.e., leaving out irrelevant details with regard to the purpose of the model) from the complexity of it" (Drukarch et al. 2018, p. 183). We agree that the main contributions should be understood in terms of abstraction, and not in terms of the models as finished products. However, as we have shown, the issue is not one of mere omission of details, but of how the abstractions articulate criteria enabling representation.

6. Metaphorical Abstraction and the Epistemic Value of Diversity

The situated abstractions supporting the different case studies examined here often originate or express implicit commitments that can play an epistemic role. A contrast between models of the nerve impulse coming from different abstraction paths should take into account differences in what the modelers consider epistemically relevant, and in the tools they bring about to study the phenomenon. This does not imply, however, that any alternative set of criteria is robust enough to be taken into consideration. History matters.

The problem of interpreting incompatible models in terms of competition for truth has been very clearly stated by Teller: "any intelligible notion of 'closeness to the truth' must be, at best, relative to characteristics of interest or importance. And it is doubtful that some preferred system of characteristics could be justified" (2008, p. 256). Van Fraassen famously argues for the importance of developing a perspectival view of scientific models (in 2008, for example). Even if the models are not true, they contribute to scientific understanding. Starting with Giere (2006), views of perspectival scientific knowledge and perspectival truth that go beyond the kind of (what we can call) theoretical perspectivism proposed by Teller and Van Fraassen have been developed. Giere claims that not only measurement results but also the representation of phenomena is perspectival. This idea of perspectival science has been developed more recently by several authors (Rueger 2005; Massimi 2018). Perspectivism provides an alternative to seeing models as competing for truth to the extent that this position defends the epistemic value of model diversity. We are proposing a related but different kind of epistemic perspectivism.

Giere's perspectivism extends the perspectival metaphor of color vision to the whole of science. Our perspectivism extends the metaphor of path dependence from the social sciences to the structure of scientific inquiry. Paul David, a well-known historian of economy has extensively argued for the importance of the concept of path dependence which according to him provides precise definitions of what is meant by describing a dynamical process as being historical (David 2007, pp. 91–114). The concept of path dependency is of course initially a metaphor that has turn into the established concept of path dependence. David claims that this concept encourages and enables the analytical historian and the economist alike to entertain the possibility that, instead of a unique-equilibrium-seeking dynamic, one should envisage a process that is seeking an evolving and historically contingent equilibrium (David 2007). In other words, David is saying that the concept of path dependence promotes a healthy pluralism. We extend this idea metaphorically to the cognitive processes we call metaphorical abstraction.

As we have seen in the case of Galvani and Volta, the path from metaphor to model is closely related to the way in which a metaphor can guide the development of concepts through a process of interpretation of theories and (experimental) practices, within the context of a research program. This guidance, in turn, is closely related to the way the cultivated metaphor is able to help us organize different experiences as part of a credible narrative. The metaphor of the animal Leyden jar we discussed in section 4 is a good example of how the affordances of an artifact such as the Leyden jar become embodied in a metaphor promoting abstractions. Galvani did not reason inductively to arrive at his claim about the electrical capacities of the frog leg. Seeing the frog's leg as a capacitor was afforded by Galvani's experience with Leyden jar-type artifacts, and a long series of experiments that prepared the context in which the frog's leg could be interpreted as a capacitor. Generalization was grounded in a metaphor, but the metaphor in question is not just a figure of language, it is a skillful experience, developed through years of practice with the kinds of artifacts exemplified by the "Leyden jar." In this sense, the metaphor is a material metaphor, one developed through a series of (mainly laboratory) practices cultivated by Galvani. Such metaphors (and concepts) are historically situated, and as we have seen in section 4, they change as the practices grounding the metaphor change.

The metaphors that end up being incorporated into the scientific practice can be appreciated in retrospect as having epistemic value. Prospectively, however, such value is not always easy to identify. At least part of the significance of Galvani's metaphor was only appreciated decades later. The same seems to have happened with Tasaki's thermodynamic metaphors: they have gained attention only now that other ways of developing thermodynamic models are being explored.

Norton Wise (2021) provides a good example of how two different abstraction paths – which from a factive perspective could be considered as leading to representations that exclude one another—contribute to scientific understanding. One of these is Faraday's lines of force. Wise tells the story of how Maxwell gradually made Faraday's concepts of lines of force and electro-tonic state credible, through a series of papers written over twenty years. The second concept was Wilhelm Weber's theory of action at a distance between particles. Both sets of concepts were "highly successful at drawing together disparate elements, even if fictional" (Wise 2021, p. 41). Such fictions are abstractions grounded in different metaphors (distinctive of their different approaches).

Maxwell and Weber devoted decades to promoting the importance of the metaphors they proposed. Maxwell dedicated many papers to supporting the concept of the electro-tonic state, even though he recognized its fictive character—and even recognized that Weber had already given a widely accepted and well-known account of time-dependent forces acting at a distance. Similarly, Weber devoted many years to backing up the importance of a time-dependent force.

For both scientists, the robustness of these abstractions justified investigating their scope. Maxwell did not think that one should look at both accounts as competing for the truth. He believed, "it is a good thing to have two ways of looking at a subject, and to admit that there are two ways of looking at it" (as cited in Wise 2021, p. 60). The subsequent history of physics makes it clear that Maxwell was right, in that both lines of research were worth developing. Both models ended up contributing to our understanding of electromagnetism, even though they would not be part of what is nowadays considered factive knowledge. The point of this story for us is that recognizing each individual project's worth involves the recognition that scientific knowledge cannot be reduced to a set of equations, axioms, or isolated models corresponding to, or describing, what is indeed the case. Models contribute to epistemic understanding as parts of lineages of models-cum-practices and traditions of inquiry. Such lineages are (often, at least) the result of cultivating metaphors, which become explicit in the sort of narratives that historians of science reconstruct.

7. Conclusion

In the philosophy of science, and particularly in discussions about the role of abstraction in modeling, the cognitive dimension of abstraction is sidestepped. We have defended that a broader framework for thinking about abstraction in science has applications for open questions in the philosophy of science. In particular, abstraction in science is important to understand how material culture (technology and the associated practices and skills) constrains and enables conceptual innovation. We have shown how metaphors often turn into scientifically important abstractions as they become integrated into what we call abstraction paths. As the contrast between the Hodgkin and Huxley model with Tasaki's macromolecular model and Heimburg-Jackson's model shows, the criteria of relevance resulting from the abstractions play a role in assessment of whether a model is adequate or inadequate. Models that do not address the features that the paths of abstraction delineate as relevant will be deemed unsatisfactory.

Criteria of relevance become more sophisticated in the historical development of a metaphor (or the merging of a set of metaphors) through scientific practices cultivating specific skills and know-how. Which metaphors end up contributing to the development of such abstraction paths is not an arbitrary matter—the criteria of relevance suggested by the metaphor are tested with regard to their potential to advance understanding. Whether a metaphor will be productive is, however, difficult to know in advance, and in most cases a posterior assessment in terms of the reach of the approach articulated by the path of abstraction is required. Path-dependent (metaphorical) abstraction should be understood as a cognitive situated phenomenon, in the sense that the skillful engagements constitutive of a scientific practice ground the (path of) abstraction and support its epistemic value. As we have seen, in cases like those reviewed here, relevance criteria guiding model construction and appraisal are backed by paths of abstraction that have shown their epistemic value in the past. The situated character of such abstractions means that different traditions of inquiry can develop different modeling strategies, based on different criteria which should not be seen as competing for truth, but as contributing to understanding, and fostering future lines of inquiry.

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