



# Scientific explanation as a guide to ground

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## Abstract

Ground is all the rage in contemporary metaphysics. But what is its nature? Some metaphysicians defend what we could call, following Skiles and Trogon (Philos Stud 178(12):4083–4098, 2021), the *inheritance view*: it is because constitutive forms of metaphysical explanation are such-and-such that we should believe that ground is so-and-so. However, many putative instances of inheritance are not primarily motivated by scientific considerations. This limitation is harmless if one thinks that ground and science are best kept apart. Contrary to this view, we believe that ground is a highly serviceable tool for investigating metaphysical areas of science. In this paper, we defend a naturalistic version of the inheritance view which takes constitutive scientific explanation as a better guide to ground. After illustrating the approach and its merits, we discuss some implications of the emerging scientific conception for the theory of ground at large.

**Keywords** Ground · Constitutive explanation · Metaphysical explanation · Non-causal explanation · Naturalistic metaphysics

## 1 Metaphysical explanation as a guide to ground

This paper defends the fruitfulness of ground in improving our understanding of certain aspects of current scientific theorizing.<sup>1</sup> In Western philosophy, the idea of ground in nature has ancient origins— though tracing its history is riddled with exegetical

<sup>1</sup> For seminal papers on ground, see Schaffer (2009), Rosen (2010), and Fine (2012). For a recent overview of the concept and its ramifications, see Raven (2020). For loci classici of grounding scepticism, see Wilson (2014, 2016) and Koslicki (2015). We shall return to some objections against ground in Sect. 4.

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complexities and interpretative controversies. For instance, someone could argue that the roots of this idea are already to be found in Aristotle's notion of 'natural priority' (Corkum, 2016, 2020; Peramatzis, 2011). Others might also point out that we witness the first rigorous development of this scientific conception in Bolzano's theory of grounding as a relation between the objective truths of (proper) science (Roski, 2017; Roski & Schnieder, 2022). Perhaps more importantly, the applicability of ground in scientific theorizing has been explored before, albeit locally (see Sect. 2). Thus, the originality of our work does not consist in *what* we claim, namely that ground has a place in science. Instead, its novelty lies in *how* we argue for it. We will revise a popular contemporary approach taking metaphysical explanation as a guide to ground to defend a general strategy that takes certain forms of scientific explanation as pointing to instances of ground in science. For want of space and the sake of focus, we will forgo further exploration of the historical connections to those precursors who, like us, find a place for ground in science.<sup>2</sup> However, as it will become clear in due course, our view is in the spirit of philosophers such as Aristotle and Bolzano. Like them, we think that ground plays a key role in our scientific understanding of the natural, not just metaphysical, structure of the world.

The conception of ground we target is both determinative and explanatory. It "concerns how some phenomena hold in virtue of others" (Raven, 2015, p. 326). Moreover, along with many others, we maintain that ground is intimately connected with both absolute and relative fundamentality. Like Audi, we think it is plausible that "if a fact has no ground, then it is fundamental in one perfectly good sense: there is no explanation of why it obtains" (2012, p. 710). Similarly, we agree with Rosen that "if [q] plays a role in making it the case that p, then [q] must be 'more fundamental' than [p]" (2010, p. 116).

According to Raven (2020, p. 1), ground underlies 'some of philosophy's biggest questions'. If so, the demand for an account of its exact nature is legitimate. One popular way to fulfil this task among groundhogs is to bring forth the alleged built-in link that ground has with a non-causal yet determinative form of explanation, which is often labelled as 'constitutive'. As we understand it, the underlying idea is that the obtaining of the grounds accounts for *what-makes-it-the-case-that* the grounded obtain. Fine depicts this connection in a famous passage:

[I]t is natural in such cases to say that the explanans or explanantia are *constitutive* of the explanandum, or that the explanandum's holding *consists in nothing more* than the obtaining of the explanans or explanantia. (2012, p. 39).

Not everyone agrees that grounded facts are ontologically lightweight (e.g., Audi, 2012; Fiddaman & Rodriguez-Pereyra, 2018). But for our goals, we can suspend judgment on this view. We focus on a conception of ground taking the obtaining of the grounded as consisting, in this determinative or constitutive sense, in the obtaining

<sup>2</sup> As we will explain in this section, our conception of ground is somewhat *thick*: it comes with a set of specifications concerning its character and connections to other notions. Corkum (2020) argues that the conceptions of ground one can find in ancient philosophy are thinner. Perhaps, some Aristotelian variety may be closer to the contemporary notion (see Corkum, 2016). For the purposes of our argument, we need not take a stance on the possible Aristotelian pedigree of our view. We leave these matters to the scholars of Aristotle.

of its grounds. Someone might complain that this characterization of constitutive explanation obscures rather than illuminates matters. One of the aims of this paper is to persuade the reader that a grounding interpretation not only sheds light on the nature of constitutive determination but also brings other substantial theoretical gains for the metaphysics of science.

The canonical view that ground is explanatory is supported by a popular strategy that takes metaphysical explanation as a guide to ground. Following Skiles and Trogdon (2021, p. 4804), we could call this the *inheritance view*. This approach consists of defending true and substantial instances of the following schema (which is straight-up modelled from the schemata discussed by Skiles and Trogdon):

#### *Inheritance*

*Metaphysical Explanation:* the link between thus-and-so facts about  $x$  and  $y$  is an instance of metaphysical explanation.

*Inference:* if this link is an instance of metaphysical explanation, then we have reason on this basis for thinking that it is an instance of ground.

Instances of this strategy can be found in Audi (2012), Dasgupta (2014), Fine (2012), Litland (2017), Raven (2015), Schaffer (2016a) and Trogdon (2018), among others. Here is an example employing one of the most popular alleged cases of grounding:

#### *D–D Inheritance*

*Metaphysical Explanation:* the link between thus-and-so facts about a thing's determinates and its determinables is an instance of metaphysical explanation.

*Inference:* if this link is an instance of metaphysical explanation, then we have reason on this basis for thinking that it is an instance of ground.

If the D–D inheritance is true and substantial, we should believe that the determinable-determinate relationship is ground.

We shall discuss the inheritance view. However, unlike Skiles and Trogdon (2021), we won't be exploring how this doctrine creates tension between the alleged objective character of ground and the hardly-deniable subjective character of explanation.<sup>3</sup> Nor are we interested in evaluating whether the reasons for taking ground as an explanatory relation are compelling in the first place. We grant that for the sake of the argument. Our main business is different. We endeavour to defend an alternative version of the inheritance view that escapes an unnoticed issue arising from the idea of taking metaphysical explanation as a guide to ground.

To illustrate this problem, we must pay heed to the fact that many putative instances of metaphysical explanation are not primarily motivated by scientific considerations. Think of D–D inheritance and other stock examples, which include non-causal explanatory relations between singleton sets and their members, parts and wholes, moral facts and their supervenience base, complex logical formulae and their atomic components, categorical and dispositional properties, what is true and what the world

<sup>3</sup> Skiles and Trogdon undo the tension by presenting the range of options available to the grounder and showing that none risks undermining the grounding-explanation link. Others have already discussed problems with the inheritance view; for example, see Kovacs (2017), Thompson (2016) and Maurin (2019).

is like. Alternatively, think of putative “everyday cases” of metaphysical explanation involving, just to name a few, faculty meetings and social practices or victory conditions in the game of chess (Dasgupta, 2017, p.75. See also Miller & Norton, 2022 for an exposition of ‘everyday’ metaphysical explanation).

The lack of engagement with science is anything but surprising if one believes that ground’s sovereignty is confined within the province of speculative metaphysics. We challenge this view. In what follows, we argue that ground is a fruitful tool to investigate and systematize metaphysical areas of science. This makes naturalistic metaphysicians our primary target audience. We will expand on this type of thinker later. For now, we can say that naturalists of this stripe believe that the legitimacy of a metaphysical notion in our theory hangs on whether it would improve our understanding of scientific theories, and whether it is primarily motivated by reasoning that draws from science and its practice. We wish to stress, however, that the discussion will be of independent interest from the reader’s naturalistic tendencies, if any. If considerations arising from science turn out to support the posit of ground, any grounding theorists will be in a stronger place. The case against this notion will become more difficult to lead. We shall say more about this in the last section.

Here is our case problem: if ground is mostly supported by *metaphysical* rather than *scientific* practice, its acceptance remains unwarranted for those who endorse a broadly naturalistic attitude toward metaphysics.

There are two reasons for improving the standard inheritance strategy. First, purely metaphysical approaches to inheritance fail to accommodate the fact that unravelling the structure of reality is an enterprise that both science and metaphysics share. Second, ground is a powerful tool for investigating metaphysical areas of science.<sup>4</sup> To accomplish this ameliorative goal, we aim to identify true and substantial instances of *scientific inheritance*:

#### *Scientific inheritance*

*Constitutive Explanation*: the link between thus-and-so facts about  $x$  and  $y$  is an instance of scientific constitutive explanation.

*Inference*: if this link is an instance of scientific constitutive explanation, then we have on this basis reasons to think it is an instance of ground.

Someone might complain that *Scientific Inheritance* subsumes under *Inheritance*. Namely, one could argue that scientific constitutive explanation falls within the category of metaphysical explanation. We prefer to regard them as distinct manifestations of the more general phenomenon of ‘in-virtue-of’ explanation (cf. Fine, 2012). But even if the subsumption claim were true, it would not follow that any instance of ground or metaphysical explanation is scientifically acceptable. The problem for the naturalistic metaphysician would remain: if they want ground, the support ought to come from scientific reasoning. The need for an improved version of *inheritance* would stay.

<sup>4</sup> Note that we are not claiming that non-inheritance approaches to ground are implausible by default. Our focus on the inheritance strategy is due to two reasons: first, it is a popular strategy in metaphysics. Second, for reasons that will emerge in due course, this strategy can be nicely implemented into moderate forms of naturalistic metaphysics of the kind we have in mind.

We proceed as follows. In Sect. 2, we introduce our conception of naturalized metaphysics and explain why naturalistic metaphysicians would benefit from including ground in their ideology. In Sect. 3, we articulate and defend the scientific inheritance strategy. We do so by discussing cases of constitutive explanation in topology, quantum physics, and economics. In Sect. 4, we defend our proposal from two objections against the serviceability of ground in science. We call these the ‘amorphousness objection’ and the ‘empirical acceptability objection’. After resisting both, in Sect. 5, we indicate some implications of our project for the theory of ground at large.<sup>5</sup>

## 2 Ground for naturalistic metaphysicians

Let us repeat our worry. Even if there were true instances of metaphysical explanation, the *Inference* step would be false on a reasonably ecumenical construal of naturalistic metaphysics. One possible reaction is shoulder shrugging. However, we believe that this attitude is mistaken. In this section, we defend five benefits that ground brings to naturalistic metaphysics. But before doing so, we outline the sort of naturalist metaphysician we have in mind.

Our favourite view is that naturalistic metaphysics is a stance to metaphysical theorizing. It embodies the principle that metaphysicians *ought to be*, as Amanda Bryant puts it, ‘scientifically responsible’ (2018, p. 2; see Bryant *ibid.* for other considerations in favour of naturalizing ground). The inputs of science, such as the available empirical data or well-supported models, should be privileged in the evaluation and assessment of metaphysical theories, hypotheses, and posits. Accordingly, the products of metaphysics gain credibility and value relative to the way they improve our understanding of scientific theories. When it comes to ground, this sort of naturalism implies that considerations from scientific practice should play a key role in justifying its acceptance. This approach is both *minimal* and *moderate*. It is minimal because it leaves open how a complete account of naturalistic metaphysics should look like. And it is moderate because it does not bestow upon science unrestricted legislative power to adjudicate whether to accept, reject or amend our metaphysical concepts. A priori metaphysical considerations are not wholly disenfranchised and remain independently valuable. This view is akin to what Morganti and Tahko (2017) call *moderately naturalistic metaphysics*.

One might argue that this characterization is not sufficient to substantiate the import of metaphysical notions such as ground into science. The worry is that by leaving open the specifics one can hardly make any judgement on the scientific acceptability of the notion. It is worth flagging that the question of under which circumstances a metaphysical notion becomes naturalistically acceptable is complicated and underexplored (but see Emery, 2023 for a recent work filling the gap). We do not have a complete answer to such an ambitious query. We believe, however, that our proposal does not require us

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<sup>5</sup> We invite the reader to consider two remarks while evaluating our proposal. First, we will speak as if ground is a relationship among facts. We consider the latter to be worldly, having items such as individuals, properties, and relations among their constituents. However, the upcoming discussion can be adapted to other conceptions. Second, we will avoid unnecessary technicalities since our primary goal is to persuade the reader of the overall approach rather than to show off formal competence.

to adjudicate the specific details concerning the definition of naturalistic metaphysics. For the purpose of discussing the scientific inheritance strategy, it suffices to rely on current scientific practice and extrapolate relevant scientific explanations as inputs. By doing so, we ensure that our target explanations bear an initial degree of scientific respectability.

That said, we acknowledge that naturalistic metaphysicians are a diverse bunch and that naturalists of a more radical bent might not be on board with our proposal. We suspect, for example, that some “extremists” will argue against the commitment to any metaphysical notion except for ‘structure’ (cf. Ladyman et al., 2007). Even so, we believe that there are five ways ground can contribute to our understanding of metaphysical aspects of science. These merits should be of interest irrespective of one’s favourite shape of naturalism. Better: they make our proposal initially appealing to anyone who is interested in ground, whether they wear the naturalist badge or not. Three of these merits concern the built-in determinative character of ground. The other two regard how ground can shed light on the structure of scientific theorizing.

## 2.1 Capturing determination

Ground is better suited for capturing the determinative character of some dependency relations of scientific interest. For example, McKenzie (2020) argues that a metaphysical interpretation of the dependency between symmetry groups and kinds of fundamental fields is not adequately understood as mere ontological dependence. The latter can obtain among relata that display no determination. To use McKenzie’s example, the singlet state relation that two electrons can entertain is plausibly regarded as being ontologically dependent on them. Yet, it seems incorrect to say that the electrons determine the obtaining of the relationship since the same properties are possessed by particles in a distinct triplet state (McKenzie, 2020, pp. 505–506). Reflections from quantum field theory and symmetry-based considerations (which we do not reconstruct for space reasons; but see (McKenzie, 2020) for the relevant physical details) support the view that facts about the features of the relevant symmetry groups determine (and in some cases entail) facts about the features of the associated kinds of fermionic and bosonic fields. McKenzie argues that a better candidate for capturing this determinative character is ground. Our proposal expands on McKenzie’s claim: ground is preferable to ontological dependence not just for making sense of the relationship between symmetry groups and kinds of quantum fields but also in other cases— some of which we illustrate in the next section.

## 2.2 Illuminating an intriguing variety of non-causal explanation

*Non-causal* explanations conspicuously appear in science (for an overview with case studies and detailed references, we recommend Reutlinger & Saatsi, 2018). To give an incomplete list of examples, think of explanations involving geometry (such as explanations of the motions of particles in terms of the curvature of space; Woodward, 2018), symmetries (e.g., explanations involving global kinematic constraints such as the Pauli Exclusion Principle on the possible states of a quantum system with

more than one particle; French & Saatsi, 2018), and structural explanations (such as renormalization group explanations of why microscopically different systems exhibit universality in their macro-behaviour in phase-transitions; Morrison, 2018). These explanations do not involve the specification of underlying causal mechanisms. Some work by describing, to use metaphysical jargon (cf. Thompson, 2018, pp. 104–108), *what-makes-it-the-case-that* the target phenomenon obtains. Ground is said to illuminate this type of explanation in metaphysics. Our claim is that it does the same for various constitutive non-causal explanations in science.

### 2.3 Systematizing fundamentality and priority

Ground is an excellent tool to capture and illuminate priority and fundamentality in metaphysical contexts. It allows us to analyze priority in terms of the grounds as being more fundamental than the grounded (Schaffer, 2009, p. 373; Rosen, 2010, p. 112; Audi, 2012, p. 710; Raven, 2017, p. 613). It also gives us a natural view of the absolutely fundamental facts as those that are wholly ungrounded.<sup>6</sup> We claim that ground can perform the same beneficial service for scientific views. For example, Bianchi and Giannotti (2021) contend that a ground-theoretic interpretation gives us an insightful understanding of priority claims at play in ontic structural realism, a theory motivated mainly by contemporary physics. And A. Wilson (2022) has argued that ground can help us make sense of distinctions of fundamentality and emergence under decoherence-based approaches to Everettian Quantum Mechanics.

### 2.4 Ground unificationism

Explanatory unification is a *prima facie* desirable theoretical virtue. Grouping together different explanations as instances of the same explanatory connection allows us to systematize their shared nature in an informatively valuable way. Ground permits naturalistic metaphysicians to do that with constitutive types of scientific explanation, thereby yielding a unified framework. Superficially distinct non-causal explanations could be viewed as instances of the same explanatory connection. Our approach promotes the view that different scientific non-causal explanations are plausibly interpreted as species of the common genus of grounding explanation (cf. Schaffer, 2020). Someone can dispute whether this grouping is beneficial (e.g., Koslicki, 2015; Wilson, 2014, 2016). Since we shall return to this topic in the last section, let us postpone our response to this objection there.

### 2.5 Structural realism about grounding

Lastly, our approach paves the way to an intriguing form of *ontic structural realism* about non-causal determinative dependencies in science (for an overview of ontic

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<sup>6</sup> Either principle can be subjected to criticism (Wilson 2014, pp. 558–566). However, both can be further sharpened (e.g., Bennett, 2017, ch. 5; Correia, 2021).

structuralism, see Bokulich & Bokulich, 2011). The business of producing and improving scientific theories is unfinished. Thus, we may be wrong about the specific ‘small-d’ determinative connections that allegedly obtain in target cases of explanation. Future (or better) theories can supplant them with different small-d relations. However, as per the structuralist account of the history of science, these new theories might preserve some relational aspects of the phenomena under study. The ontic structuralist claims that we should be realists about the structure that is preserved across theory change. An analogous argument can be made for accepting the conclusion that some invariant grounding structure will be preserved across theory change. If we were to embrace a structuralist principle of ontological commitment, we would have to favour the reality of this less specific (or more coarse-grained) grounding structure over that of more specific small-d relations.

### 3 Scientific constitutive explanation

We sketched five benefits that ground brings to the table. These merits are *prima facie* compelling, and this is a reason for exploring a strategy that vindicates ground as a legitimate concept of naturalistic metaphysics. This section aims to do just that. In what follows, we illustrate three examples of non-causal scientific explanations that fit nicely with the template of scientific inheritance. Each case deserves a paper-length treatment, which here we cannot afford. Furthermore, each of them comes with extensive and often fascinating literature concerning the relevant minutiae, which we cannot do justice to. However, we hope to say just enough to persuade the reader of two things. First, these are true and substantial cases of scientific inheritance. Second, even if *these* cases were to fail, the scientific inheritance strategy would remain a fruitful approach worthy of investigation. But before continuing some necessary clarifications are in place.

To start, we refrain from offering necessary and sufficient conditions for individuating either constitutive links or grounding connections. The scientific inheritance strategy, as we see it, is not a matter of ticking boxes. Instead, it is best to proceed with a case-by-case analysis. Consistently with the methodology of naturalistic metaphysics, we start by looking at scientific practice and identifying possible candidates for scientific constitutive explanations.<sup>7</sup> Whether the candidates pass the *Constitutive Explanation* step is an a posteriori affair. Perhaps, it is practically helpful to begin the search for candidate explanations by looking at those that have a non-causal and determinative feel. Likewise, it might be insightful to revisit non-causal explanations that fail to be accounted for by purely modal notions. However, these features do not over direct our search for prospect constitutive explanations.

Similar considerations apply to the *Inference* step. As the discussion of the cases will reveal, the reasons supporting a grounding interpretation of the constitutive links are primarily related to its theoretical fruitfulness. Again, the procedure is case-by-case. Generalizing, we defend the proposal that for every instance of scientific constitutive

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<sup>7</sup> In addition to the cases we discuss, there are other examples one might attempt to fit into the template. We invite the reader to check the volume edited by Reutlinger and Saatsi (2018) for more examples.



explanation, we proceed by assessing the benefits that a grounding interpretation would bring to the naturalistic metaphysician. If they outweigh the costs of accepting a piece of primitive ideology, we have a reason for believing that the connection is an instance of ground.

Five more specific considerations are needed to avoid possible confusion. First, we do not wish to imply that every instance of non-causal explanation in science is an instance of constitutive explanation. This should go without saying. But it is better to be explicit.

Second, we do not claim (nor does our argument imply) that the presence of a constitutive explanation is incompatible with other forms of explanation. For instance, the link between thus-and-so facts about  $x$  and  $y$  might be properly understood in both constitutive and causal terms. Plausibly, what guides the choice of one form of explanation over another is related to the inquirer's goals. The latter is a heavily context-dependent affair.

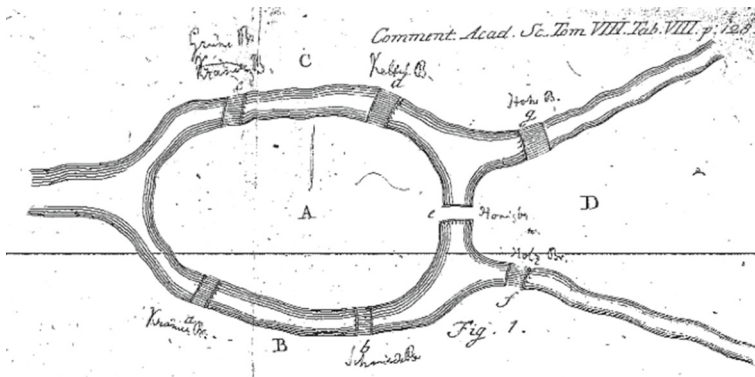
Third, we acknowledge a terminological difference. In the philosophy of science literature, the term 'constitutive explanation' appears to be primarily used to denote explanations of "what composes the phenomenon [under study] and how that composition makes the phenomenon obtain" (Pincock, 2018, p. 41). For instance, Craver calls constitutive explanation an explanation of a phenomenon by the organization of component entities and activities (2007, p. 9) or an explanation of the behaviour of the whole in terms of the activities of their parts (2007, p. 59). We agree with Craver that the metaphysicians' use of the label is not meant to be restricted to part-whole or mereological explanations (cf. Craver, 2007, fn. 9). As such, we make it clear that our use of the term 'constitutive explanation' is not meant to refer to an explanatory relationship between parts of a complex system and the totality of the system itself. As the examples below will illustrate, there are cases of non-causal explanation where a mereological account of the explanandum is unavailable or otherwise unsatisfactory. Instead, it is preferable to regard the explanandum as constituted by the explanans in the Finean metaphysical sense.

Fourth, we anticipate potential disagreement with our selection of cases of constitutive explanation or some of their details. However, the success of our strategy does not hang on these particular cases. We offer them to give an idea of the pervasiveness of constitutive explanation in science. The scientific inheritance strategy is meant to be general. Insofar as there are constitutive explanations in science, it is possible to run our argument.

Lastly, in discussing the *Inference* step for our case studies, we aim to defend the claim that the grounding connection is *at least* partial. This is the minimum requirement for the scientific inheritance strategy. As is standard, we take that a fact is a partial ground of another iff the former fully grounds, on its own or with other facts, the latter (e.g., Fine, 2012, p. 50). Perhaps not all partial grounds are completable (Leuenberger, 2020). Even so, we believe that the notion of partial ground is intuitively graspable.<sup>8</sup>

With these remarks in place, we move on to the discussion of three plausible cases of scientific constitutive explanation. One is from topology, the other is from quantum physics, and the further other is from economics.

<sup>8</sup> If not we suggest adopting a different definition; see Trogon and Witmer (2021).



**Fig. 1** from “Solutio problematis ad geometriam situs pertinentis”, Eneström 53 [source: MAA Euler Archive]

### 3.1 Topological explanation

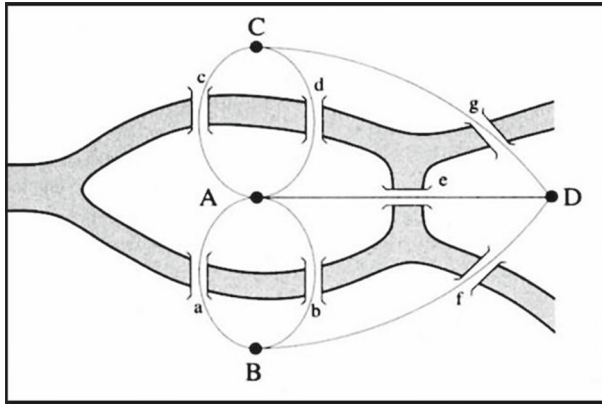
Topological explanations work by citing relevant facts about specific topological properties of a system under study. The latter capture certain formal, mathematical, or otherwise structural features that are non-causal and independent from the microphysical details concerning their realization. Following Huneman (2018), we take it that there are various ways of explicating the idea of topological properties. In one sense, the system under study is associated with a topological space, and the topological properties of the system are features encoded by such a space, which is typically more abstract than the actual system (such as a phase space or a graph). In another sense, the topological properties of systems are those specifying their invariance regarding a class of continuous transformations. Like Huneman we think that graph-theoretical properties of topological spaces fall within the class of topological properties.

We contend that *at least some* topological explanations of concrete systems, such as systems of bridges or ecological systems, qualify as constitutive.<sup>9</sup> As a paradigmatic case, we propose a famous case from the literature on non-causal explanation: that of the seven bridges of Königsberg.<sup>10</sup>

The Königsberg bridge system displayed a peculiar layout, as shown in Fig. 1: there used to be seven bridges connecting two central islands with the surrounding land masses.

<sup>9</sup> We acknowledge that the distinction between causal and topological explanation is not always as clear-cut as the literature suggests. For more on this topic, see Ross (2021).

<sup>10</sup> Lange (2015, 2018) discusses the Königsberg case as a paradigmatic case of explanation by constraint. This is a distinctively mathematical explanation that works “by describing how the explanandum arises from certain facts (‘constraints’) possessing some variety of necessity stronger than ordinary laws of nature possess” (Lange, 2015, p. 10). We are inclined to think that grounding explanations are not explanations by constraint. Unlike constraints, the grounds need not be modally stronger than what is grounded. However, we do not wish to rule out the identification of these types of explanation by fiat. As in the coexistence of causal and non-causal explanations of the same phenomenon, we are happy to accept the coexistence of constitutive explanations and explanations by constraint. A discussion of the precise relationship between ground and explanation by constraints is a topic for a different paper.



**Fig. 2** From “Problem Solving Across the Disciplines” by R. R. Kadesch, Prentice Hall, 1997

The system had a peculiar feature: it could not be traversed by a path that crossed each bridge exactly and only once. It lacked the property of *being traversable*. Why did the Königsberg bridge system lack this property? Euler offered a topological explanation. The associated graph representing the system has specific topological features that account for its lack of traversability. If we graph-theoretically represent the bridges as edges and the landmasses as nodes, the system looks like this (see Fig. 2).

Euler proved that a graph is traversable just in case it satisfies two conditions: (1) all nodes are connected to each other, and (2) there are either zero or two nodes of odd degree (the degree of a node  $v$  is the number of edges that touches  $v$ ). All the nodes in the graph of the Königsberg system had an odd degree. Accordingly, a very plausible explanation of the non-traversability of the system is the fact that it failed to meet condition (2).

Let us pause for a moment to address some worries concerning the delicate relationship between grounding and mathematics. It might be suggested that the Königsberg topological explanation (and analogous ones by extension) is purely mathematical (i.e., it concerns only facts about mathematics) or logical (i.e., the system fails to be traversable because the conjunction of facts corresponding to the conditions fails to obtain). A potential objection, then, is that the link between grounding and mathematics is already well-established and has respectable historical advocates, such as Aristotle and Bolzano (Roski, 2017; Roski & Schnieder, 2022).<sup>11</sup> Similarly, one might think that it is already widely accepted that conceptual and logical explanations are grounding explanations (Correia, 2014, 2015; Fine, 2012; Poggiolesi, 2016, 2018). Thus we would be guilty of triviality masqueraded as originality. To this concern, we offer two responses.

<sup>11</sup> Bolzano develops his conception of grounding in connection with the idea of (objective) proof which is in turn inspired by Aristotle’s demonstrations (Malink, 2022; Rusnock, 2022). For more references including a discussion of some historical antecedents about the link between grounding and mathematics, see *inter alia* Detlefsen (1988), Harari (2008), Betti (2010), and Roski (2018). For a general overview, see Mancosu et al. (2023).

First, as we explain in a moment, what matters for applying the scientific inheritance strategy to the topological case is that this is an important form of constitutive scientific explanation. We need not deny that topological explanations are mathematical in character. However, unlike *purely* mathematical explanations, the mathematical properties of the Königsberg topological space represent or correspond to a concrete system. We are not focusing on the explanatory goings-on involved in answering the more abstract question of why *any* graph having such-and-such properties is not traversable. Instead, we focus on cases where facts about concrete systems are explained by facts about the associated topological space they instantiate. Yet, the type of purely mathematical topological explanations and the type of explanations we focus on are not in competition. The former are explanations at a higher level of abstraction. We are happy to give a similar rejoinder for logical explanations. Our target kind of topological explanations does not work by focusing primarily on the mathematical or logical structure of the explanans and explanandum. But we need not spurn the idea that topological explanations can be abstracted from the details of the concrete case and turned into mathematical or logical explanations.

Second, we wish to report disagreement concerning the question of whether mathematical explanations are grounding explanations. Against the charge of triviality, we believe it is not obvious that all mathematical explanations are grounding explanations (e.g., Lange, 2019). Moreover, even if we were to accept that some mathematical explanations are grounding explanations, we think that the kind of grounding at work in the mathematical case is *conceptual* or *representational* rather than *worldly*. Namely, it deals with connections of semantic priority between *propositions* or *truths* due to the (mathematical) concepts involved in them (Poggiolesi & Genco, 2023; Smithson, 2020), rather than facts having individuals, properties, and relations as constituents. For example, a historically significant case of grounding in mathematics is Bolzano's theory. However, Bolzano's conception of grounding is explicitly representational in that it relates true propositions understood as abstract objects (Roski & Schnieder, 2022). One might feel a natural tendency towards the idea that the representational and the worldly conceptions of ground must be connected. However, to the best of our knowledge, the gap between the two remains unbridged (see Correia, 2020 for a more technical discussion of these two conceptions). We therefore prefer stressing two points. One is that we are operating under a worldly rather than representational conception of ground. And the second is that we wish to profess agnosticism on whether mathematical explanations are grounding explanations. Our argument does not require us to choose sides.<sup>12</sup>

Now let us return to the Königsberg case. To apply the scientific inheritance strategy, we first need to establish the *Constitutive Explanation* step. In this case, the purported link is between the fact that the graph associated with the Königsberg system does not have either zero or two nodes of odd degrees and the fact that the system is not traversable. It *just* seems to us that this case is a limpid illustration of a constitutive connection. What it is to account for the non-traversability's holding 'consists in

<sup>12</sup> Note, however, that it is perfectly compatible with our strategy to accept that purely mathematical explanations are underpinned by a different kind of ground. One could even envisage a view on which more than one type of scientific explanation is supported by a plurality of different grounding connections.

nothing more than' (Fine, 2012, p. 39) the obtaining of the fact that the system fails to have either zero or two nodes of odd degree.<sup>13</sup>

The next step is the *Inference*. We need to defend the claim that the connection between the fact that the Königsberg system was not traversable and the fact that its graph failed to have either zero or two nodes of odd degrees is a grounding link.

We offer two main reasons. First, a grounding interpretation captures the determinative character of the dependency displayed by design. The non-traversability of the system not only supervenes on (or merely ontologically depends upon), but is also determined by, its topological properties. By contrast, a purely modal reconstruction of the link in terms of the supervenience (or other forms of non-determinative dependency) of the traversability upon the topological features fails to capture the manifest determinative character involved.

Second, the proposed grounding interpretation fixes an ontological scaffolding for capturing relevant asymmetric counterfactual dependencies. The explanation of the non-traversability of the bridges in terms of their topological properties implies the acceptance of specific asymmetric counterfactual dependencies of the form 'had the topological features of the bridges been different, the system would have been traversable'. Such an asymmetry should be reflected in the semantics of the relevant counterfactuals such as:

- (a) Had some changes modified the topological features of the Königsberg bridge system, the system would have been traversable.
- (b) Had some changes modified the non-traversability of the Königsberg bridge system, its topological features would have been different.

Accepting Euler's explanation, we should judge (a) as true and (b) as false.<sup>14</sup> (b) gets the explanation the other way around since it implies that the non-traversability of the system explains the topological features of the graph. What guarantees the correct explanatory directionality? Ground offers an answer.

On the grounding approach, (a) comes out as true because a change in the grounds, namely the topological properties of the system, amounts to a change in what is grounded, namely the non-traversability of the system. By contrast, the truth of (b) requires an inversion of the grounding relationship between the topological features and the non-traversability of the system. Such an inversion demands a violation of the grounding structure taken to obtain in this case.<sup>15</sup>

If you agree with us, we have reasons to countenance a grounding connection between the fact that the system of the Königsberg bridges is not traversable and the fact that its associated graph does not have zero or two nodes of odd degree.

<sup>13</sup> As Fine clarifies, it is not implied that the explanandum *just is* the explanans or that it is unreal in some sense. Instead, what is implied is that there can be no stricter account of that in virtue of which the explanandum holds (Fine, 2012, p. 39).

<sup>14</sup> Different explanations might result in different truth-value judgments. Counterfactual intuitions will diverge. Our goal is to offer a way to recover the relevant asymmetry, not to establish the correct semantics.

<sup>15</sup> The idea that grounding can secure patterns of directed counterfactual dependencies is explored by grounding interventionists. For an extensive discussion of the approach, see Schaffer (2016a) and Wilson (2018a).

Consistently with our case-by-case analysis, we do not claim that *every* topological explanation reveals grounding connections. But we think that sufficiently similar topological explanations are amenable to analogous reasoning.

### 3.2 Quantum entanglement and non-separability

Next, we consider the explanation of the non-separability of particles in entangled states. Arguably, entanglement is the distinctive feature of quantum theory. If ground underlies a non-causal explanation of this phenomenon, the case for a naturalistic approach to it is strengthened. Below, we argue that the non-separability of entangled components is plausibly grounded in facts about the composite quantum system. A textbook outline of quantum entanglement is, therefore, in place.

Standard quantum mechanics assigns formal representations in the form of wave functions in mathematical Hilbert spaces to physical systems. The vectors associated with the elements of the system provide probability functions based on possible measurement outcomes. A particle's wave function specifies how likely it is for that particle to behave in a certain way provided some experimental setting. An entangled state occurs when the wave function of a complex system of particles is not the result of the product of the wave functions associated with each individual particle that makes up the system. The entangled components are such that their behaviour is individually unpredictable, but it is jointly constrained in a way that allows us to predict the behaviour of one of the components based on information about the other.

To illustrate, we can think of the famous EPR setup. It is possible to send particles through a rotatable magnet deflecting them such that when they hit a detector screen we can measure the spin state of the particles along the magnet's axis of orientation. Consider now Romeo and Juliet, two x-spin  $\frac{1}{2}$  particles that are prepared in the singlet state Romeo + Juliet such that the total x-spin of the compound system is 0. Formally, the singlet state is expressed as follows:

$$\text{Singlet} : |\psi\rangle_{\text{Romeo, Juliet}} = 1/\sqrt{2}[(|\uparrow\rangle_{\text{Romeo}} \otimes |\downarrow\rangle_{\text{Juliet}}) - (|\downarrow\rangle_{\text{Romeo}} \otimes |\uparrow\rangle_{\text{Juliet}})]$$

The singlet state formalism predicts modally strong and systematic anti-correlation between the particles. If Romeo measures x-spin down, the formalism predicts that Juliet measures x-spin up. And if Romeo measures x-spin up, the formalism predicts that Juliet measures x-spin down. Surprisingly, these anticorrelations hold even when the particles are fired at arbitrary distances.

On a plausible interpretation of their modal connectedness (e.g., Ismael & Schaffer, 2020), the entangled components are *non-separable*: the intrinsic state of each individual component fails to describe the intrinsic state of the composite system (namely, the entangled system as a whole).<sup>16</sup>

<sup>16</sup> Non-separability is not the only game in town. For example, there are hidden variables approaches that account for non-separability in terms of instantaneous causation at distance (cf. Bell, 1964). Since our focus is on non-causal scientific explanations, we shall not discuss this view. We register, however, that accepting spooky instantaneous causation at distance is a price too high even for quantum mechanics.

An explanatory challenge arises: In virtue of what are Romeo and Juliet, the entangled components, non-separable? On a plausible approach, the answer involves the fact that the wave function of the Romeo + Juliet system encodes all the relevant information about the (pre-measurement) x-spins of Romeo and Juliet. In a sense, the entangled state as a whole ‘hosts further information’, specifying everything there is to say about Romeo and Juliet (pre-measurement), which is not captured by the wave functions of the individual entangled components (Ismael & Schaffer, 2020, p. 4145). One could argue that this talk of information expresses an epistemic view about what we can know from the quantum formalism. This interpretation remains available. But it is not ours. We understand the idea in ontic terms: the formalism of the entangled composite (*Singlet*) portrays, we think, how reality is.

Echoing Ismael and Schaffer (2020, pp. 4147–4148), we believe that the explanatory link between the fact that Romeo and Juliet are non-separable and the fact that the composite whole they form contains more information than the individual entangled components is a grounding connection. However, we must first offer reasons to believe that the explanatory link is constitutive.

The link between the fact that Romeo and Juliet are modally connected and the fact that they are part of an entangled system is not properly regarded as causal. Even granting that causation might relate facts, it seems wrong to claim that the fact that Romeo measures x-spin up is anti-correlated with Juliet’s measuring x-spin down is caused by the fact that Romeo and Juliet are entangled. One reason for thinking that causation is not a good interpretation is that the dependency between such facts is synchronic. Yet causation is typically diachronic: causes precede their effects.

Constitutive links, by contrast, need not follow any constraints of diachronicity (that is not to say that they cannot be diachronic, see Wilson, 2020 for examples). A constitutive understanding of the link between the non-separability of the particles and their entangled state is, therefore, a better starting point for its metaphysical interpretation.

There is another motivation for taking the explanatory link as constitutive. The fact that Romeo and Juliet are non-separable and the fact that the composite system Romeo + Juliet contains more information (encoded in the Singlet state) than Romeo and Juliet individually are supportive of the idea that the modal connectedness of these entangled components consists, at least partially, in the obtaining of specific facts about the entangled composite system Romeo + Juliet.

Now, we need to defend the *Inference* step. To this end, we offer three reasons. First, a grounding interpretation of the link between the fact that Romeo and Juliet are non-separable and the fact that Romeo + Juliet contain more information (specified by the Singlet state) than the individual components captures the determinative character of this dependency. Supervenience or mere ontological dependence fails to secure the idea that the non-separability of Romeo and Juliet originates or is produced by the entanglement relation. But a causal explanation, as mentioned above, is problematic for it violates the diachronicity of causation. Luckily, a grounding explanation is free from the constraints of diachronicity.

Second, like in the topological case, a grounding interpretation allows us to anchor in reality the directionality of counterfactual dependencies of interest concerning the

non-separability of Romeo and Juliet. Simplifying matters, if we explain the non-separability of Romeo and Juliet in terms of their composite state, we should expect to recover certain asymmetric counterfactual dependencies.<sup>17</sup> It should be retained the truth of:

- (iii) If Romeo and Juliet had not been entangled as specified by the Singlet state, then they would have been separable.

Complementarily, it should be recovered the falsity of:

- (d) If Romeo and Juliet had not been entangled as specified by the Singlet state, they would not have been separable.

And the falsity of:

- (e) If Romeo and Juliet had been separable, they would not have been entangled.

A grounding interpretation accounts for the asymmetry between (c) and (d) in reality. Taking the non-separability of Romeo and Juliet as being grounded, in the actual world, in facts about the entangled composite system fixes the asymmetric dependency of the grounded upon its grounds in such a way that a change in the former yields a change in the latter (but not the other way round), and any change in the grounded must be a result of a change in the grounds. In (c), this grounding connection is respected. Likewise, it is in (d). The counterfactual's falsity is retained because, accepting the aptness of the connection, in the nearest possible world where there is a change in Romeo + Juliet, we should expect a change in the separability of Romeo and Juliet. Instead, (e)'s falsity is preserved because it gets the grounding dependency between Romeo + Juliet's composite state and their individual non-separability the wrong way. This is not to say that we would violate a logical impossibility in claiming that (e) is true. Instead, the claim is that the grounding connection is supportive of a correct direction, so to speak, of the counterfactual dependency between the facts in question.

Lastly, a grounding interpretation reveals conceptually intriguing implications for the priority of the whole over the parts. In this case, we may wonder: which is more fundamental? (Facts about) the individual particles or (facts about) the entangled system as a whole? It is a popular view that the parts composing a whole are more fundamental than the whole itself. However, entanglement seems to challenge this received view, and the grounding interpretation supports the opposite view. This point has been explored in fair detail by Schaffer (2010) and, jointly, with Ismael & Schaffer, (2020). So, we shall be brief. If one believes that grounds are more fundamental than the grounded, then (generalizing the case of Romeo and Juliet) certain facts about the whole composite entangled states are more fundamental than some facts about the individual entangled components. Schaffer, individually and collaboratively, has even argued that under plausible interpretations of quantum mechanics, this grounding principle leads to the view that the whole cosmos is a vast entangled

<sup>17</sup> One faces delicate issues when it comes to specifying the semantics of grounding counterfactuals. Again, judgments will vary. Here we hope that some of the solutions offered by Schaffer and Wilson are easily transferable to our proposal. For recent work on counterfactuals in science focusing on non-causal explanation, see Reutlinger (2016, 2018), French and Saatsi (2018), Woodward (2018, 2022), and Hicks (2022).



whole which is more fundamental than its parts (for technical details, see Ismael & Schaffer, 2020, pp. 4150–4154). Our claim is not that Schaffer’s proposal is without bumps (for discussion, see Calosi, 2018). Instead, it is that a grounding interpretation not only allows us to settle questions of priority in the quantum case but also aids an underexplored view of what is fundamental.

In summary, we believe that the scientific inheritance strategy reveals a grounding connection between quantum non-separability and entangled states. Though we shall remain officially agnostic, we hope other constitutive physics explanations will follow suit.

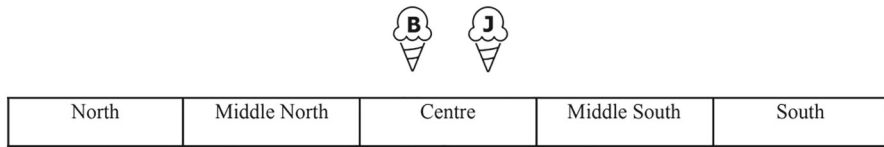
### 3.3 Equilibrium explanation

Our last case concerns equilibrium explanations. These are structural explanations that work by describing the global state of equilibrium of a system under study in order to explain its dynamics (i.e., how it behaves over time). Equilibrium explanations are common in game theory and economics. One illustrative example in non-cooperative games is explanations involving the fact that the system is in a state of *Nash equilibrium*. A strategy profile constitutes a Nash equilibrium if, given the strategies of the rest of the competitors, no player can modify their strategy without thereby generating a decrease in their own profit maximization. Equilibrium explanations can also be found in the social sciences, where the selection of optimal strategies in prisoner-type dilemmas is directly dependent on the actions of other players. Most notably perhaps, equilibrium explanations appear in behavioural ecology, where explanations of evolutionary stable strategies (ESS) are often deployed to account for the behaviour of populations whose individuals repeatedly engage in utility optimization strategies. Examples include species reproducing towards one-to-one sex ratios (Fisher, 1930; Hamilton, 1967), the study of intraspecies animal conflict (Maynard Smith & Price, 1973), and the case of long-term human-microbe associations (Suárez & Deulofeu, 2019). In short, the idea behind equilibrium explanations is that utility-maximizing strategies explain survival rates both in the evolutionary case, due to increased transmission of traits, and in the economic case, due to increased monetary profit. This, in turn, also explains why systems naturally tend to converge towards persistent states of equilibria.

As with topological explanations, our claim is that *at least some* equilibrium explanations (such as those involving Nash equilibria or ESS) are constitutive. To illustrate our case, we present a toy example from microeconomics: the ‘ice cream vendors’ problem.

Consider two ice cream vendors, Ben and Jerry, competing on a beach for an evenly distributed number of customers. Both offer the same flavours of ice cream, of which they have a constant supply at the same market price. Ben and Jerry only have five permissible locations where they can place their carts as per the illustration below (see Fig. 3).

The classic textbook question asks readers to determine the optimal game strategy: where should the vendors position their cart to maximize their payoff?



**Fig. 3** Representation of the optimal positioning strategy in the ice cream vendor problem

According to game theory, the optimal location for both sellers is in the centre of the beach, next to each other. By opting for the ‘centre’ strategy, both players will attract all the customers located in the surrounding area as well as in the end, corresponding to each of the corners. More concretely, what explains that ‘centre’ is the optimal position for both Ben and Jerry is the fact that by positioning there, they generate a Nash equilibrium. This state of the system affects the players’ behaviour: neither Ben nor Jerry can modify their strategy without causing a decline in profit maximization.

We propose that such an explanation is constitutive. Then, we proceed to the *Inference* step, giving reasons to support a grounding interpretation of the link between the fact that ‘centre’ is the most optimal position for both Ben and Jerry and that Ben and Jerry generate a Nash equilibrium by being so placed.

Why do we think this explanation is constitutive? To start, it is non-causal. It is independent of any assumptions regarding the kind of entities and causal processes that are involved in the system. The causal goings-on leading Ben and Jerry to the decision to move their carts are irrelevant to the optimality of their positioning. What explains the latter is the fact that Ben’s and Jerry’s positioning gives rise to a state of Nash equilibrium. In other words, the fact that the system instantiates a state of Nash equilibrium is what-makes-it-the-case-that the strategy chosen by Ben and Jerry is optimal. In this sense, the optimality of the positions ‘consists of nothing more than’ the state of equilibrium that is instantiated by the system.

There is another source of interpretative pressure for a constitutive understanding of this explanation. The dependency between the Nash equilibrium generated by Ben and Jerry and their optimal positioning is diachronic. The obtaining of the former fact accounts for the obtaining of the latter, and these are co-temporally dependent. Insofar as the system is in equilibrium, ‘centre’ will remain the optimal economic position for both players.

Suppose one is persuaded that the explanatory link is constitutive. Now, we can move on to the *Inference* step. Namely, we can offer reasons for taking it as an instance of ground.

Like the above cases, a grounding interpretation captures the apparent determinative character of the relationship between the fact that the ‘centre’ positioning of Ben and Jerry is optimal and the fact that they generate a Nash equilibrium. The dependency is not merely modal. We leave something out in claiming that the optimal positioning supervenes on or merely ontologically depends upon the fact that Ben and Jerry generate a state of Nash equilibrium.

Next, we can invoke considerations from counterfactual asymmetries. If we accept the directional explanatoriness of the fact that the system is in equilibrium, we should guard an asymmetric counterfactual dependency of the optimality of the positioning

upon this fact. We should recover an asymmetry between the truth of (f) and the falsity of (g):

- (f) Had the system not been in a state of equilibrium, then the ‘centre’ position would not have been the most optimal strategy.
- (g) Had the ‘centre’ position not been the most optimal strategy, the system would not have been in a state of equilibrium.

A grounding interpretation anchors the directionality of the counterfactual dependency in the world, reflecting it in the semantics of (f). (Once more, counterfactual judgments may clash. Like in the previous cases, we are primarily focused on securing the asymmetry of relevant counterfactual dependencies.) We do not claim that (g) is implausible tout court. Instead, the claim is that the truth of (g) would demand an inversion of ground and grounded.

Lastly, a grounding interpretation adequately reflects the explanatory priority of the global state of equilibrium over the optimality of the individual players’ positioning. The grounding-fundamentality link yields a corresponding relative fundamentality relationship between the facts. The optimality of Ben and Jerry’s positioning is less fundamental than the fact that Ben and Jerry’s positioning generates a Nash equilibrium because it is grounded in the latter. The grounding interpretation reveals, similarly to the quantum entanglement case, conceptually interesting implications about priority. It opens the way to a priority view of the equilibrium of the global state of the system over the behaviour of its parts. If certain facts about the behaviour of a system are grounded in certain facts about its global state of equilibrium, we have reasons to think some facts about the entire system are more fundamental than some facts about its parts. We think clearing the path to this (to our knowledge) unexplored view is a sign of the fruitfulness of the applicability of ground to this case.

Notwithstanding our case-by-case approach, we suggest that analogous considerations can be offered to defend the scientific inheritance strategy in similar equilibria explanations in other domains.

## 4 Two objections alleviated

### 4.1 A brief recap

Thus far, we have argued that there are good reasons for believing in true and substantial instances of scientific inheritance. Defending the *Constitutive Explanation* step of the strategy for some candidate scientific facts about  $x$  and  $y$ , we defended that:

- It is eminently plausible to regard  $y$  as being constitutively explained in terms of  $x$ .
- The connection between  $y$  and  $x$  displays a *prima facie* manifest determinative character that is not suitably captured in terms of purely modal dependencies.

Then, we offered reasons supporting the *Inference* step. Generalizing, we argued that a grounding interpretation of the connection between  $x$  and  $y$  is fruitful in three manners:

- It straightforwardly secures that the link between  $x$  and  $y$  is determinative.

- It offers an ontological scaffolding for recovering the directionality of counterfactual dependencies of interest between  $x$  and  $y$ .
- It establishes and reveals interesting priority relationships between  $x$  and  $y$ , giving us further insights for investigating the layered structure of reality.

Controversy about the cases we discussed is to be expected. For example, someone could disagree on the explanatory direction of  $x$  and  $y$ . Others could quibble over the specific facts replacing  $x$  and  $y$ . However, such divergences should not cloud the general appeal of the proposed view.

Suppose one agrees with us concerning all the above. If so, naturalistic metaphysicians have a way to legitimize ground in their theorizing, which is not just consistent with their approach but is also motivated by it. Unsurprisingly, the scientific inheritance strategy is not immune to criticism. Two compelling objections allow us to sharpen our proposal. After that, we close by offering some thoughts connecting the scientific inheritance strategy with the theory of ground at large.

## 4.2 The amorphousness objection

We call the ‘amorphousness objection’ the first concern. Informally, it goes like this: ground is too amorphous or generic to yield any perspicuous categorization of heterogeneous and informationally useful scientific constitutive explanations. Worse, by lumping different scientific explanations under the umbrella of grounding, we miss out on valuable informational details. Here the charge is that we are bringing in dispensable metaphysical murkiness that does not serve any valuable explanatory purpose.

The objection resembles some sceptical arguments against the coarse-grainedness of ‘big-G’ ground as opposed to ‘small-g’ grounding relations (e.g. Koslicki, 2015; Wilson, 2014, 2016). However, these criticisms should not be conflated. Our opponent might concede the serviceability of ground in metaphysics and protest only its application to scientific cases. Thus, we reply in two ways.

First, we can avail of extant responses defending the usefulness of the coarse-grainedness of ground (e.g., Dasgupta, 2017; Kortabarria, 2023; Schaffer, 2016b). These replies support the shared idea that big-G ground and small-g grounding relations are not in competition. Instead, they serve different yet compatible theoretical purposes. Even if it does not offer answers to fine-grained questions, ground can still prove helpful in illuminating and shaping coarse-grained inquiries for which the specific small-g relations of determination are not apt.

Second, we can defuse the objection through an analogy with causation. Our strategy is to argue that both ground and causation are equally amorphous. However, since we tolerate causation in science, we should do the same for ground by parity of reasoning.

Like ground, causation has a corresponding category of explanation, which, aside from being allegedly underwritten by the same relation, comprises very different phenomena that are only coarse-grainedly unified. Think of the explanatory causal interactions between two physical particles, the causal happenings that supposedly explain the value collapse in cryptocurrencies, and the causal chain of events that

explain the firing of a neuron.<sup>18</sup> Even without the relevant details, it should be evident that the causal mechanisms involved in these explanations are distinct. One should be forgiven for believing that different small-c causal relations are involved in these examples. Yet those who accept causation in the first place will tend to believe these cases involve the same relation. We are optimistic that the believers in causation would find grouping the above cases under the same category of explanation unproblematic. Analogous judgements, we think, should be upheld for the grounding case.

Why maintain that both causation and grounding are analogously amorphous? They are both generic and coarse-grained relations. They are, at least on the orthodox view, both productive or generative relations, they both relate facts or events, they both are directional or have, by design, a priority direction (i.e., causes are prior to effects, and grounds are prior to the grounded), they both have a temporal character (i.e., causation is typically diachronic, and grounding is typically synchronic), they both are supportive of counterfactual dependencies, and many believe that both are mediated by lawlike connections or principles.<sup>19</sup> Moreover, both grounding and causation are the target of analogous sceptical objections and have contested structural or logical features—think, for instance, about discussions surrounding their transitivity (e.g., McDonnell, 2018; Paul, 2000 for the causal case; see Schaffer, 2012 and Makin, 2019 for the grounding case).

If one countenances the amorphousness of causation in science, the same ought to be for a relationship that is equally amorphous, namely ground. The amorphousness objection can be therefore resisted.

### 4.3 The empirical acceptability objection

An initially more promising complaint is that ground and causation differ in empirical acceptability: causation, but not ground is empirically acceptable. This objection, if sound, would undermine our appeal to a naturalized theory of ground. Fortunately, we believe that this concern can be successfully mitigated.

Presumably, there are various ways to cash out the idea of empirical acceptability. Here we think that our opponent believes that causation is empirically acceptable in the sense of being epistemically privileged in a way that ground is not. This inequality is allegedly reflected in the corresponding explanations. Causation, the proponent of the objection would claim, has robust scientific evidence. An expression of the tangibility of causation is perhaps best captured by interventionist theories (e.g., Halpern, 2016; Woodward, 2003). Roughly, these views take causation to be essentially connected to manipulability. The business of inferring causal relationships in the world is done by making things happen in appropriate structural equation models. The latter heavily

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<sup>18</sup> The particle example is supposed to be merely illustrative. We leave open the possibility that there is no causation in fundamental physics. The reader is encouraged to think of other examples from non-fundamental physics.

<sup>19</sup> For more on the analogy between grounding and causation, see Schaffer (2016a) and Wilson (2018b). For discussion on how to demarcate between them or where the analogy breaks down, see Schaffer (2020) and Wilson (2020). We are of the inclination that ground and causation are irreducibly distinct members of the same family of determination. But someone who fancies our proposal need not buy this view.

rely on statistical approaches to causal modelling. In a very clear sense, the resulting conception of causation is measurable.

One initially intriguing response is to defend an interventionist approach to ground (e.g., Schaffer, 2016a; Wilson, 2018a).<sup>20</sup> However, the interventionist view faces important challenges making this a suboptimal strategy. For example, Koslicki (2016) and Jansson (2018) have argued that the applicability of structural equations to grounding faces severe limitations. And Bryant (2022) has objected that the epistemic credentials of grounding interventionism are lower than those of its causal counterpart.

Our strategy is different. We believe that the scientific inheritance strategy renders ground empirically acceptable *by courtesy*. Advantageously, we can skirt the contentious claim that we have the same scientific evidence for both grounding and causation.

Recall that we defend the legitimacy of ground within the toolkit of naturalistic metaphysics by taking the *Constitutive Explanation* step as our starting point. This procedure *begins* with the identification of candidate instances of constitutive connections among non-causal scientific explanations in science. It should be uncontroversial to claim that the candidate explanations are empirically acceptable by the standard of current scientific practice. If the *Inference* step of the strategy is true of the target constitutive scientific explanation, the empirical acceptability of the constitutive link transmits to the resulting grounding connection.

Why believe in such a principle of transmission? One plausible answer is that if one begins from an empirically acceptable connection, its empirical acceptability is not revoked by there being a posteriori reasons to think it is a grounding connection. Again, an analogy with causation is illuminating. If we have a posteriori reasons to believe that an empirically acceptable link between events is causal, the connection does not lose its scientific status. Of course, we may be wrong in taking the connection as empirically acceptable in the first place. However, our response concerns relationships *already* deemed empirically acceptable in light of relevant scientific evidence and practice.

Someone could reject the principle of transmission. This denial amounts to the claim that there is something special about grounding, which makes it empirically unacceptable. But this move shifts the argumentative burden on the shoulders of the objector. It is up to them to explain what features of grounding thwart the empirical acceptability of constitutive links. Once a list of criteria is submitted, we should argue that each item is unsuitable—excuse the predictable pun—to ground the exceptionality of ground. However, we shall not attempt to identify and evaluate these candidate features that the objector might invoke. Instead, we conclude by offering some remarks on the scope of this work.

## 5 Conclusions

Our proposal makes naturalistic metaphysicians the primary and immediate beneficiaries. We gave them a strategy to justify the acceptance of ground among their

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<sup>20</sup> There are other responses that we cannot explore for reasons of space. For example, one could design some counter-responses to the effect that causation is *not* empirically acceptable.

theoretical tools. Not only we defended that there are true and substantial instances of scientific inheritance (Sect. 3), but we also argued that ground is apt for investigating metaphysical areas of scientific theorizing (Sect. 2). However, the emerging conception has a wider reach. Our argument reinforces the idea that constitutive explanation and ground are not exclusive to metaphysics, they can be found in science too. Thus, our view supports the idea that ground is more pervasive outside the philosophy room than one might initially suppose (cf. Dasgupta, 2017, pp. 75–76; de Rosset, 2023, Sect. 1.1). Three implications of this view are worth stressing.

First, scientific cases of ground make life harder, philosophically speaking, for those who object against the notion. This outcome should be well-received by enthusiasts of ground, irrespective of whether they are naturalistically inclined. If we are right, protesters must not only challenge the purely metaphysical variety of ground, but also resist the scientific considerations supporting a constitutive understanding of the relevant case.

Second, our proposal affects the philosophy of scientific explanation. Despite the growing literature on non-causal explanation, *causal imperialism*—the view that all scientific explanations are causal—remains the default position (see Bokulich 2018 for more on this view). However, the success of the scientific inheritance strategy incentivizes the anti-imperialist movement. Ground is definitionally non-causal. If there are scientific grounding explanations, it becomes harder for imperialists to defend their positions.

Lastly, the approach we defend paves the way toward a scientific conception of grounding, which full potential is yet to be tested. Recall Kit Fine’s opening lines (2012, p. 37; emphasis added):

A number of philosophers have recently become receptive to the idea that, *in addition to scientific or causal explanation, there may be a distinctive kind of metaphysical explanation*, in which explanans and explanandum are connected, not through some sort of causal mechanism, but through some constitutive form of determination.

The moral of this paper is partially but not fully Finean. We vindicated the existence of a constitutive form of explanation. Nevertheless, echoing the spirit of Aristotle and Bolzano, we argued that some grounding explanations are not distinctively metaphysical in the sense of being wholly prized apart from scientific explanation. Perhaps, this kind of grounding explanation is what Kit Fine had in mind when speaking of a sibylline ‘natural in-virtue-of’ relation that ‘will be of special interest of science’ (Fine, 2012 p. 39). This points to a much larger and interesting research project on the relationship between scientific and metaphysical ground, which we shall put on hold for now.

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## Declarations

**Conflict of interest** We have no conflict of interest to declare.

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