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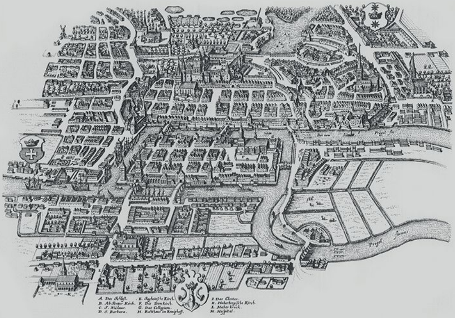

EXPLANATION BEYOND CAUSATION

PHILOSOPHICAL PERSPECTIVES ON NON-CAUSAL EXPLANATIONS

OXFORD

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Introduction

Scientific Explanations Beyond Causation

Alexander Reutlinger and Juha Saatsi

What is a scientific explanation? This has been a central question in philosophy of science at least since Hempel and Oppenheim's pivotal attempt at an answer in 1948 (also known as the covering-law model of explanation; Hempel 1965: chapter 10). It is no surprise that this question has retained its place at the heart of contemporary philosophy of science, given that it is one of the sciences' key aims to provide *explanations* of phenomena in the social and natural world around us. As philosophers of science, we naturally want to grasp and to explicate what exactly scientists are doing and aiming to achieve when they explain something.

In his classic *Four Decades of Scientific Explanation*, Salmon (1989) details the shift from Hempel and Oppenheim's "epoch-making" logical empiricist beginnings to a mixture of subsequent perspectives on scientific explanation involving ideas concerning causation, laws, theoretical unification, pragmatics, and statistics. Although Salmon believes that causal accounts of explanation (including his own version) are considerably successful, he ultimately advocated a pluralistic outlook. According to his pluralism, different approaches to explanation are worth pursuing and they should be understood as complementing one another rather than competing with each other. He articulates this pluralism, for instance, in his claim about the "peaceful coexistence" of causal and unificationist accounts.[1] According to Salmon, the four decades of intense philosophical activity on scientific explanation since 1948 did not result in anything like a consensus, and his prediction was that no broad consensus was likely to emerge after 1989, at least not in the short term.

However, Salmon's pluralist outlook and his portrayal of the history of the debate (articulated in his *Four Decades*) were largely lost in subsequent philosophical work. The two decades following the publication of Salmon's book in 1989 became the

[1] Salmon's well-known illustration of his pluralism is captured in the story of the friendly physicist (Salmon 1989: 183).

decades of causal accounts of explanation. As causal accounts came to dominate the philosophical scene, this tendency also resulted in establishing a research focus on causation itself, and since the late 1980s philosophers have made considerable progress in analysing various aspects of causation. For example, they have explicated different notions of causation, causal processes, causal mechanisms, and causal models, and they have achieved a better understanding of the connection between causes and different kinds of idealizations, of the link between causation and temporal order, and, indeed, of the kinds of explanations that causal information supports. According to causal accounts, the sciences explain by identifying the causes of the phenomenon to be explained—or, according to the mechanist version of causal accounts, by identifying the causal mechanisms for that phenomenon (for surveys see Andersen 2014; Woodward 2014).

Causal accounts have been considered to be attractive for several reasons. The focus on causal-mechanical aspects of explanation has undoubtedly been in many ways a good response to the shortcomings of the covering-law model (and of some alternative approaches to explanation). Moreover, the proponents of causal accounts have also taken a closer look at detailed case studies of real-life explanations in the sciences instead of merely analysing toy examples. The proponents of causal accounts have also advanced the field by taking seriously case studies from the life and social sciences, freeing the debate from a (formerly) widespread physics chauvinism. And, indeed, many paradigmatic explanations in the sciences rely on information about causes and mechanisms. Hence, philosophers focusing on causal explanation have achieved a great deal by studying this aspect of the explanatory practices of science. As a result, *today* hardly anyone denies the explanatory significance and epistemic value of causal-mechanistic information provided by the sciences.

The domination of the causal accounts has shaped the subsequent debate on scientific explanation in several respects: in how arguments have been perceived and evaluated; what the criteria for an adequate account of scientific explanation have been taken to be (for instance, everybody had to talk about flagpoles, for better or worse), and so on. This spirit of a 'causal hegemony' can easily be detected in extant survey papers (such as Woodward 2014; Craver and Tabery 2017),[2] also in influential works advocating a causal approach to scientific explanation (for instance, Woodward 2003; Craver 2007; Strevens 2008), and last but certainly not least in the tacit presumptions and 'common knowledge' one encounters at various conferences and workshops.

The state of the field after six long decades suggests that something close to a consensus was reached: scientific explanation is a matter of providing suitable information about causes of the explanandum phenomenon. However, over the past decade or so this consensus has come under increasing scrutiny and suspicion as philosophers have more widely begun to rethink the hegemony of causal-mechanist accounts.

[2] However, Woodward's entry in the *Stanford Encyclopedia of Philosophy* remains open-minded about the possibility of non-causal explanations (Woodward 2014: §7.1).

There are important precedents to this recent development. Indeed, although causal accounts did indeed dominate the philosophical scene in the 1990s and the 2000s, they were far from being the only game in town. From early on, a number of authors have drawn attention to non-causal ways of explaining, in particular in relation to unificationist accounts (Friedman 1974; Kitcher 1984, 1989; Bartelborth 1996), pragmatic accounts (van Fraassen 1980, 1989; Achinstein 1983), analyses of asymptotic explanations in physics (Batterman 2000, 2002), statistical and geometrical explanations (Lipton 1991/2004; Nerlich 1979), and other specific examples from various scientific disciplines (for instance, Forge 1980, 1985; Sober 1983; Ruben 1990/2012; Frisch 1998; Hüttemann 2004).

Over the past few years, this resistance to the causal hegemony has burgeoned quickly, and the present volume demonstrates this turning of the tide. Looking at the current literature, one particularly striking recent development is the increasing interest in the *limits* of causal accounts of explanation. The guiding idea is that although causation is certainly part of the truth about scientific explanation, it is unlikely to be the full story. Following this idea, philosophers have begun to explore the hypothesis that explanations in science sometimes go *beyond causation*. For instance, there seem to be genuinely non-causal explanations whose explanatory resources go 'beyond causation' as these explanations do not work by way of truthfully representing the causes of the phenomenon to be explained. Other scientific explanations go 'beyond causation' in the sense that their explanatory assumptions do not tell us anything about the causal mechanisms involved. In this spirit, a number of philosophers have argued that the repertoire of explanatory strategies in the sciences is considerably richer than causal accounts suggest. (See Reutlinger 2017 for a detailed survey of the present debate on non-causal explanations.)

The motivation for this shift of focus to explanations that go 'beyond causation' is easy to appreciate: there are plenty of compelling, real-life examples of *non-causal* explanations that causal accounts of explanation seemingly fail to capture. To be more precise, the new development in the philosophy of *scientific* explanation is the increasing recognition of interesting and varied examples of non-causal explanations of *empirical phenomena* to be found across the natural and social sciences.

Unsurprisingly, physics is a fertile ground for such examples, ranging from explanations involving symmetries and inter-theoretic relations, to theoretically more abstract explanations that rely on, for instance, renormalization group techniques. Moreover, in the more fundamental domains of physical theorizing, it seems relatively easy to find explanations that seem non-causal—in the first blush at least. Perhaps this does not come as a surprise to those sympathetic to increasingly popular scepticism about causation as a fundamental metaphysical category in physics (originating in the work of Ernst Mach and Bertrand Russell among others; see, for instance, Mach 1905; Russell 1912/13; Scheibe 2007: chapter 7). Such causal 'anti-foundationalism' is a contested topic in its own right, of course, but perhaps the difficulty of interpreting fundamental physics in plain causal terms already indicates that explanations in fundamental physics operate in terms that go beyond causation (Price 1996; Price and Corry 2007).

One need not plunge the depths of fundamental physics to find compelling instances of non-causal explanations, however. Various philosophers have suggested that there are other kinds of non-causal explanations in the life and social sciences, such as mathematical, statistical, computational, network, optimality, and equilibrium explanations. Moreover, some of the most popular examples in the philosophical literature—the present volume included—involve rather simple empirical set-ups of strawberries and bridge-crossings. Philosophers' love of toy examples is due to the fact that simple though such examples are, they are sufficiently instructive to challenge the philosophy of explanation centred around causal accounts, giving rise to fruitful engagement between competing philosophical analyses. For instance, what explains the fact that 23 strawberries cannot be distributed equally among 3 philosophers (cf. Chapter 1)? Is this explanation non-causal? Is it non-causal because it is mathematical? Is it mathematical in some *distinct* kind of way (in which familiar mathema*tized*, and possibly causal, explanations in science are not)? As the essays in this volume demonstrate, thinking carefully about some exceedingly simple cases alongside real-life scientific explanations is not only fun, but philosophically profitable![3]

Let us pause for a second. Surely, one might think, the existence of non-causal explanations is old news. After all, the empirical sciences are not the only epistemic project striving for explanations. Proofs in logic and pure mathematics are at least sometimes taken to be explanatory—and if so, then proofs explain in a non-causal way (see, for instance, Mancosu 2015). In metaphysical debates, too, one finds a straightforward appeal to non-causal explanations: for instance, if some fact *A* grounds another fact *B*, then A is taken to be non-causally explanatory of B (see, for instance, Bliss and Trogdon 2016). However, the fact that mathematicians, logicians, and metaphysicians sometimes explain in non-causal terms is an interesting and related topic but it is not *the crucial motivation* for questioning the hegemony of causal-mechanist accounts of explanations in the natural and social sciences.[4] But even if non-causal explanations in logic, mathematics, and metaphysics do not motivate a challenge to causal hegemony in philosophy of science, it is certainly worth exploring the relationship between non-causal explanations in mathematics, logic, and metaphysics, on the one hand, and non-causal explanations in the natural and social sciences, on the other hand.

[3] Action or teleological explanations are also often treated as a particular kind of non-causal explanation, as, for instance, von Wright (1971, 1974) argues. However, the allegedly non-causal character of action explanations is (infamously) controversial and has led to an extensive debate (see Davidson 1980 for a defence of a causal account of action explanations). We will bracket the debate on action explanations in this volume.

[4] Although the existence of non-causal explanations internal to, for instance, pure mathematics and logic has long been recognized, detailed philosophical accounts of such explanations have been under-developed. The dominance of causal models of explanation in philosophy of science is partly to be blamed, since much of this work did not seem to be applicable or extendible to domains such as mathematics, where the notion of causation obviously does not apply.

Now, what would be an appropriate philosophical reaction to examples of non-causal explanations from the natural and social sciences? Let us canvass in the abstract three possible 'big picture' reactions:

1. causal reductionism,
2. explanatory pluralism, and
3. explanatory monism.

First, while some are happy to give up the hegemony of causal accounts of explanation and to welcome non-causal ways of explaining empirical phenomena, others feel less pressure to do so. Some philosophers—including some featured in this volume—take the *seeming* examples of non-causal explanations to rather point to the need for a more sophisticated account of causal explanation. If the seemingly non-causal explanations can ultimately be understood as causal explanations after all, perhaps non-causal explanations of empirical phenomena are indeed rare and exotic (if not wholly non-existent). The attraction of such *causal reductionism* about explanation, if indeed true, lies in the fundamental causal unity it finds underlying the prima facie disparate activity of scientific explanation. One and the same conceptual framework provides a pleasingly unified philosophical theory of explanation, if all explanations in science—including alleged examples of non-causal explanations—turn out to ultimately function by providing causal information. In other words, causal reductionists would like to maintain and to defend the hegemony of causal explanation (see, for instance, Lewis 1986; more recently Skow 2014, 2016).

Second, one way to deny such causal reductionism is to accept some kind of *explanatory pluralism*. Pluralists adopt, roughly put, the view that causal and non-causal explanations are different types of explanations that are covered by two (or more) distinct theories of explanation.[5] The core idea of a pluralist response to the existence of examples of causal and non-causal explanations is that causal accounts of explanations have to be supplemented with further accounts of non-causal explanations (a view Salmon was attracted to, as pointed out above, see Salmon 1989; more recently Lange 2016).

Third, an alternative to explanatory pluralism is *explanatory monism*: the view that there is one single philosophical account capable of capturing both causal and non-causal explanations by virtue of some 'common core' that they share. To take an analogy, consider the way in which some theories of explanation (such as Hempel's or Woodward's) account for both deterministic and probabilistic (causal) explanations. In an analogous way, a monist holds that one theory of explanation may account for both causal and non-causal explanation. Unlike the causal reductionist, the monist does not deny the existence of non-causal explanations. Rather, a monist holds that causal and non-causal

[5] This notion of explanatory pluralism has to be distinguished from another kind of pluralist (or relativist) attitude towards explanations, according to which one phenomenon has two (or more) explanations and these explanations are equally well suited for accounting for the phenomenon.

explanations share a feature that makes them explanatory (for a survey of different strategies to articulate monism, see Reutlinger 2017).

The 'big picture' issue emerging from these three reactions is whether causal reductionism, explanatory pluralism, or explanatory monism provides the best approach to thinking about the similarities and differences between various causal and (seemingly) non-causal explanations of empirical phenomena. However, this 'big picture' question is far from being the only one, and we predict that these debates are likely to continue in the foreseeable future due to a number of other outstanding questions such as the following ones:

- How can accounts of non-causal explanations overcome the problems troubling the covering-law model?
- What is the best way to distinguish between causal and non-causal explanations?
- Which different types of non-causal explanations can be found in the life and social sciences?
- Is it possible to extend accounts of non-causal explanation in the sciences to non-causal explanations in other 'extra-scientific' domains, such as metaphysics, pure mathematics, logic, and perhaps even to explanations in the moral domain?
- What should one make of the special connection that some non-causal explanations seem to bear to certain kinds of idealizations?
- What role does the pragmatics of explanation play in the non-causal case?
- What are the differences between non-causal and causal explanatory *reasoning*, from a psychological and epistemological perspective?
- What does scientific understanding amount to in the context of non-causal explanations?

Let us now turn to a preview of the volume, which divides into three parts.

Part I addresses issues regarding non-causal explanations from the perspective of *general philosophy of science*. By articulating suitable conceptual frameworks, and by drawing on examples from different scientific disciplines, the contributions to this part examine and discuss different notions of non-causal explanation and various philosophical accounts of explanation for capturing non-causal explanations.

Marc Lange presents a view that is part of a larger pluralist picture. For him, there is no general theory covering all non-causal explanations, let alone all causal and non-causal explanations taken together. But Lange argues that a broad class of non-causal explanations works by appealing to *constraints*, viz. modal facts involving a stronger degree of necessity than physical or causal laws. Lange offers an account of the order of explanatory priority in explanations by constraint, and uses it to distinguish different kinds of such explanations. He illustrates the account with paradigmatic examples drawn from the sciences.

Christopher Pincock probes different strategies for spelling out what pluralism—the view that, roughly put, explanations come in several distinct types—amounts to in relation to causal vs. non-causal explanations. He contrasts *ontic* vs. *epistemic* versions of pluralism, and he finds room within both versions to make sense of explanatory pluralism in relation to three types of explanations: causal, abstract, and constitutive types of explanation. Moreover, he also draws attention to several problems that explanatory pluralism raises requiring further consideration and, thereby, setting a research agenda for philosophers working in a pluralist spirit.

Angela Potochnik argues that theories of explanation typically have a rather narrow focus on analysing explanatory dependence relations. However, Potochnik argues that there is no good reason for such a narrow focus, because there are many *other features* of explanatory practices that warrant philosophical attention, i.e., other features than the causal or non-causal nature of explanatory dependence relations. The purpose of Potochnik's contribution is mainly to convey to the reader that it is a serious mistake to ignore these 'other features'. She draws philosophical attention to features of explanations such as the connection between explanation and understanding, the psychology of explanation, the role of (levels of) representation for scientific explanation, and the connection between the aim of explanation and other aims of science. Her contribution is a plea for moving the debate beyond causal—and also beyond non-causal—dependence relations.

Alexander Reutlinger defends a monist approach to non-causal and causal explanations: the counterfactual theory of explanation. According to Reutlinger's counterfactual theory, both causal and non-causal explanations are explanatory by virtue of revealing counterfactual dependencies between the explanandum and the explanans (illustrated by five examples of non-causal scientific explanations). Moreover, he provides a 'Russellian' strategy for distinguishing between causal and non-causal explanations within the framework of the counterfactual theory of explanation. Reutlinger bases this distinction on 'Russellian' criteria that are often associated with causal relations (including causal asymmetry, time asymmetry, and distinctness).

Michael Strevens proposes to resist the popular view that some explanations are non-causal by virtue of being mathematical explanations. To support his objection, Strevens provides a discussion of various explanations that other philosophers regard as instances of non-causal *qua* being mathematical explanations (such as equilibrium explanations and statistical explanations). He argues that, at least in the context of these examples, the mathematical component of an explanation helps scientists to get a better understanding of (or a better grasp on) the relevant causal components cited in the explanation. Hence, Strevens's contribution could be read as defending a limited and careful version of causal reductionism. That is, at least with respect to the examples discussed, there is no reason to question the hegemony of causal accounts.

James Woodward's contribution displays monist tendencies, as he explores whether and to what extent his well-known version of the counterfactual theory of explanation can be extended from its original causal interpretation to certain cases of non-causal explanation. Woodward defends the claim that such an extension is possible in at least two cases: first, if the relevant explanatory counterfactuals do not have an interventionist interpretation, and, second, if the truth of the explanatory counterfactuals is supported by conceptual and mathematical facts. Finally, he discusses the role of information about irrelevant factors in (non-causal) scientific explanations.

Part II consists of contributions discussing detailed case studies of non-causal explanations from specific scientific disciplines. The case studies under discussion range from neuroscience over earth science to physics. The ambition of these chapters is to analyse in detail what makes a specific kind of explanation from one particular discipline non-causal.

Alisa Bokulich analyses a non-causal explanation from the earth sciences, more specifically from *aeolian geomorphology* (the study of landscapes that are shaped predominantly by the wind). Her case study consists in an explanation of regular patterns in the formation of sand ripples and dunes in deserts of different regions of earth and other planets. Bokulich uses this case study to argue for the "common core conception of non-causal explanation" in order to sharpen the concept of the non-causal character of an explanation. Moreover, she emphasizes that if one has a non-causal explanation for a phenomenon this does not exclude that there is also a causal explanation of the same explanandum.

Mazviita Chirimuuta focuses on a case study from neuroscience, *efficient coding explanation*. According to Chirimuuta, one ought to distinguish four types of explanations in neuroscience: (a) aetiological explanations, (b) mechanistic explanations, (c) non-causal mathematical explanations, and (d) efficient coding explanations. Chirimuuta argues that efficient coding explanations are distinct from the types (a)–(c) and are an often overlooked kind of explanation whose explanatory resources hinge on the implementation of an abstract coding scheme or algorithm. Chirimuuta explores ways in which efficient coding explanations go 'beyond causation' in that they differ from mechanistic and, more broadly, causal explanations. The global outlook of Chirimuuta's chapter is monist in its spirit, as she indicates that all four types of explanations—including efficient coding explanations—answer what-if-things-had-been-different questions which are at the heart of counterfactual theories.

Steven French and **Juha Saatsi** investigate explanations from physics that turn on *symmetries*. They argue that a counterfactual-dependence account, in the spirit of Woodward, naturally accommodates various symmetry explanations, turning on either discrete symmetries (e.g., permutation invariance in quantum physics), or continuous symmetries (supporting the use of Noether's theorem). The modal terms in which French and Saatsi account for these symmetry explanations throw light on the debate regarding the explanatory status of the Pauli exclusion principle, for example, and opposes recent analyses of explanations involving Noether's theorem.

Margaret Morrison provides a rigorous analysis of the non-causal character of *renormalization group explanations* of universality in statistical mechanics. Morrison argues that these explanations exemplify *structural explanations*, involving a particular kind of transformation and the determination of 'fixed points' of these transformations. Moreover, Morrison discusses how renormalization group explanations exhibit important differences to other statistical explanations in the context of statistical mechanics that operate by "averaging over microphysical details". Although Morrison does not address the issue explicitly, it is clear that she rejects causal reductionism, and it is plausible to say that her non-causal characterization of renormalization group explanations is compatible with pluralism and monism.

Part III extends the analysis of non-causal explanations from the natural and social sciences to extra-scientific explanations. More precisely, the contributions in this part discuss explanatory proofs in pure mathematics and grounding explanations in metaphysics.

Mark Colyvan, John Cusbert, and Kelvin McQueen provide a theory of explanatory proofs in pure mathematics (aka intra-mathematical explanations). An explanatory proof does not merely show that a theorem is true but also why it is true. Colyvan, Cusbert, and McQueen pose the question whether explanatory proofs all share some common feature that renders them explanatory. According to their view, there is no single feature that makes proofs explanatory. Rather one finds at least two types of explanation at work in mathematics: constructive proofs (whose explanatory power hinges on dependence relations) and abstract proofs (whose explanatory character consists in their unifying power). Constructive and abstract proofs are two distinct 'flavours' of explanation in pure mathematics requiring different philosophical treatment. In other words, Colyvan, Cusbert, and McQueen make the case for explanatory pluralism in the domain of pure mathematics.

Lina Jansson analyses non-causal grounding explanations in metaphysics. In the flourishing literature on grounding, there is large agreement that grounding relations are explanatory and that they are explanatory in a non-causal way. But what makes grounding relations explanatory? According to some recent 'interventionist' approaches, the answer to this question should begin by assuming that grounding is a relation that is closely related to causation and, more precisely, that grounding explanations should be given an account in broadly interventionist terms (relying on structural equations and directed graphs functioning as representations of grounding relations). If these interventionist approaches were successful, they would provide a unified monist framework for ordinary causal and grounding explanations. However, Jansson argues that interventionist approaches to grounding explanations fail because causal explanations and grounding explanations differ with respect to the aptness of the causal models and grounding models underlying the explanations.

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PART I

General Approaches

1

Because Without Cause

Scientific Explanations by Constraint

Marc Lange

1. Introduction

Some scientific explanations are not causal explanations in that they do not work by describing contextually relevant features of the world's network of causal relations. Here is a very simple example (inspired by Braine 1972: 144):

Why does Mother fail every time she tries to distribute exactly 23 strawberries evenly among her 3 children without cutting any (strawberries—or children!)? Because 23 cannot be divided evenly into whole numbers by 3.

In a closely related non-causal explanation, the explanandum is simply Mother's failure *on a given occasion* to distribute her strawberries evenly among her children (without cutting any), and the explanans is that Mother has 3 children and 23 strawberries on that occasion and that 23 cannot be divided evenly by 3. Although Mother's having 3 children and 23 strawberries are causes of her failure on this occasion, this explanation does not acquire its explanatory power by virtue of specifying causes. Rather, Mother's strawberries were not distributed evenly among her children because (given the numbers of strawberries and children) they *cannot* be. The particular causal mechanism by which she tried to distribute the strawberries does not enter into it. Even a physically impossible causal mechanism (as long as it is mathematically possible) would have failed.[1]

Similar remarks apply to explaining why no one ever succeeded in untying a trefoil knot or in crossing all of the bridges of Königsberg exactly once (while remaining always on land and taking a continuous path)—with the bridges as they were in 1735, when Euler showed that such an arrangement of bridges (let's call it "arrangement K") *cannot* be crossed. These explanations explain why every attempt to perform a given

[1] Although the explanandum holds with mathematical necessity, this is a scientific explanation rather than an explanation in mathematics: the explanandum concerns a concrete, spatiotemporal system, not exclusively abstract mathematical objects or structures. Everything I say in this chapter should be understood as limited to scientific explanations. (I discuss explanations in mathematics in my 2014 and 2016.)

task failed. These explanations work not by describing the world's causal relations, but rather by revealing that the performance of the task (given certain features understood to be constitutive of that task) is *impossible*, so the explanandum is *necessary*—in particular, more necessary than ordinary causal laws are. The mathematical truths figuring in the above non-causal explanations possess a stronger variety of necessity ("mathematical necessity") than ordinary causal laws possess.[2]

Like mathematical truths, some laws of nature have generally been regarded as modally stronger than the force laws and other ordinary causal laws. For example, the Nobel laureate physicist Eugene Wigner (1972: 13) characterizes the conservation laws in classical physics as "transcending" the various particular kinds of forces there happen to be (e.g., electromagnetic, gravitational, etc.). In other words, energy, linear momentum, angular momentum, and so forth would still have been conserved even if there had been different forces instead of (or along with) the actual forces. It is not the case that momentum is conserved because electrical interactions conserve it, gravitational interactions conserve it, and so forth for each of the actual kinds of fundamental interactions. Rather, every actual kind of fundamental interaction conserves momentum for the same reason: that the law of momentum conservation requires it to do so. The conservation law limits the kinds of interactions there could have been, making a non-conservative interaction impossible. This species of impossibility is stronger than ordinary physical impossibility (though weaker than mathematical impossibility).

Accordingly, the conservation laws power non-causal explanations that are similar to the explanation of Mother's failure to distribute her strawberries evenly among her children. Here is an example from the cosmologist Hermann Bondi (1970: 266; 1980: 11–14). Consider a baby carriage with the baby strapped inside so that the baby cannot separate much from the carriage. Suppose that the carriage and baby are initially at rest, the ground fairly smooth and level, and the carriage's brakes disengaged so that there is negligible friction between the ground and the wheels. (The baby's mass is considerably less than the carriage's.) Now suppose that the baby tosses and turns, shaking the carriage in many different directions. Why, despite the baby's pushing back and forth on the carriage for some time, is the carriage very nearly where it began? Bondi gives an explanation that, he says (let's suppose correctly), transcends the details of the various particular forces exerted by the baby on the carriage. Since there are negligible horizontal external forces on the carriage-baby system, the system's horizontal momentum is conserved; it was initially zero, so it must remain zero. Therefore, whatever may occur within the system, its center of mass cannot begin to move horizontally. The only way for the carriage to move, while keeping the system's center of mass stationary, is for the baby to move in the opposite direction. But since the baby is strapped into the carriage, the baby cannot move far without the carriage moving in about the same way. So the carriage cannot move much.

[2] The literature on distinctively mathematical explanations in science includes Baker (2009); Lange (2013); Mancosu (2008); and Pincock (2007).