# The Limits of New Mechanism as a General Theory of Scientific Explanation

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"We should not allow it to be believed that all scientific progress can be reduced to mechanism." – Marie Sklodowska Curie[1]

## Introduction

In recent years, New Mechanism has become one of the most popular philosophical theories of scientific explanation. The theory of New Mechanistic Explanation (NME) argues that phenomena are explained in terms of mechanism, where a mechanism is understood to be a system[2] (or structure[3] or set[4]) of relevant component parts[5] or entities[6], which are real and ideally local[7,8], and which are organized in such a way that they casually interact[9] and perform various productive activities[10] which produce the phenomenon[11],

[1] Marie Skłodowska Curie is credited to have said at a congress in Madrid in 1933: "We should not allow it to be believed that all scientific progress can be reduced to mechanisms, machines, gearing, even though such machinery has its own beauty" (Curie, 1937).
[2] Glennan, 2002
[3] Bechtel and Abrahamsen, 2005
[4] Illari and Williamson, 2012; Illari & Williamson, 2011
[5] Glennan, 2002, 2018, etc
[6] Machamer, Craven, and Darden, 2000
[7] Illari and Williamson, 2011, 2012
[8] While Illari and Williamson (2011, 2012) argue that mechanisms are necessarily local, Bechtel and Richardson (2012) and Craver (2019) hold that mechanisms are "not necessarily localizable" as they may be widely distributed. However, Craver maintains that "levels of mechanisms are defined locally within a multilevel mechanism" (2019) and holds that mechanists prefer "local explanations" to "grand, overarching theories" (2019).
[9] Glennan (2002, 2018)
[10] Machamer, Craver & Darden, 2000; Craver, 2007; Illari & Williamson, 2012
[11] Craver, 2007, 2015; Illari & Williamson 2011, 2012

behavior[12], state of affairs, or event[13] or to be explained. Carl Craver has claimed that an account of some phenomena may be judged as explanatory based solely on whether that account describes a mechanism (2006, p. 367). Stuart Glennan similarly argues that "most or all" natural phenomena depend on mechanisms and that the construction of mechanist models is science's "chief business" (2017, p. 1).

In my dissertation, I propose to examine the limits of NME, while arguing against the claim that NME can provide a comprehensive account of scientific explanation. I will demonstrate that mechanistic models do not always explain, even when they provide a complete account of all mechanisms impacting on some system. I will argue that there is no convincing defense of the generalized form of NME, and will chart the limits of the applicability of NME as an illuminating theory of explanation.

The proposed dissertation will have the following structure: I will first review traditional theories of explanation in philosophy of science. This will include my attempt to outline the consensus position concerning requirements for a successful philosophical theory of explanation. I will present NME in the context of the history of competing philosophical theories of scientific explanation. I will then provide chapters explaining where NME cannot serve as a fully general theory of explanation in biology and physics, highlighting exemplary cases of valid, intellectually enlightening, and technologically useful scientific explanations in those fields which fail to be characterized in terms of NME. I will clarify why non-mechanistic explanations are legitimate scientific explanations which do what both scientists and philosophers expect explanations to do, and I will explain why NME is unhelpful in their cases. I will then explore the tension between NME and mathematical models, in particular dynamical models. I will highlight natural systems which operate via features describable only using math (e.g. fields, natural selection, waves, gravity, spacetime, and so on) are not amenable to NME, while presenting why mathematics is explanatory,

[12] Glennan (2002, 2018)
[13] Craver and Tabery (2019)

rather than merely descriptive or predictive in scientific contexts. I will show how NME fails to account for the utility of mathematics in scientific explanation, and then how any general theory of explanation in the philosophy of science must account for the necessity of recourse to mathematics in multiple fields of scientific inquiry. In my last chapter, I will characterize what types of systems NME does work for (e.g., explanation in engineering applications, interventions). I will conclude that NME does not provide a complete theory of scientific explanation, but rather of a limited selection of interventions.

## Chapter 1: Models of Explanation in Science and NME as a Model of Explanation

Philosophers of science have sought a general theory of scientific explanation. In this chapter, I will examine competing theories of scientific explanation, review NME's position amidst these theories, and propose criteria for judging when something counts as a satisfactory theory of scientific explanation.

### *Does Science Explain?*

First, we might ask, does science explain? A contemporary scientist might claim that the task of science is to explain phenomena, or even all phenomena (e.g., Stephen Hawking, 1988) in nature. According to Wesley Salmon (1998), "Virtually all philosophers of science…agree that science can teach us, not only *that,* but also *why"* (p. 181). Hempel and Oppenheim (1948) further claim that "scientific research….strives to go beyond mere description of its subject matter by providing an explanation of the phenomena it investigates" (Hempel and Oppenheim, 1948, p. 8). In 1954, Erwin Schrodinger claimed that science is in the business of providing comprehensibility, arguing that a fundamental tenet of science is that "the display of nature can be understood" (p. 90) and arguing against the receding "solipsist" view that physical science cannot explain.[14]

[14] Schrodinger denounces the view that science cannot give explanations, which he describes as "impossible to refute, like solipsism" and maintains that science makes nature comprehensible, then attempts to answer the question: "what does comprehensibility mean….and in what sense…does science give explanations?" He says the most extreme positivist such as

*What is a Scientific Explanation?*

How we begin to theorize concerning the nature of scientific explanation depends to some extent on what we would regard as an intuitively acceptable explanation. Recently, Wesley Salmon (1998) has characterized the contemporary view that most if not all scientific explanations are "answers to the question 'why'?" and maintains that "in attempting to explain an event" we "are trying to assemble a total set of relevant conditions" for the occurrence of that event (p. 74). Salmon further claims that "a satisfactory scientific explanation depends on certain contingent facts about the universe" (1989, p. 181). I will review Salmon's characterization of three views of explanation in science, (1) the ontic view, (2) the epistemic view, and (3) the modal view (1984).[15] I will briefly survey a number of theorists of scientific explanation (e.g, Aristotle, Newton [1713], Leibniz, Du Chatelet, Laplace [1812], Duhem, Pearson [1892] and Mach, Hempel and Oppenheim [1948], Bronoswki [1951], Schrodinger [1954], etc).

I will then present my criteria for a successful theory of scientific explanation. Briefly, I maintain that a good theory of scientific explanation must shed light on why some statements and theories count as scientific explanations while others do not (demarcation), while also providing a way to understand how some statements and theories are systematically connected to our capacity to understand and intervene in phenomena unders scientific consideration (intellectual and pragmatic virtues of explanations).

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Mach and Pearson should recognize that even if scientists are only "observ[ing] and register[ing] facts and put[ting] them into…convenient…arrangement, there are factual relations between our findings in the various, widely distant domains of knowledge, and again between them and the most fundamental general notions…so striking and interesting, that for our eventual grasping and registering them the term 'understanding' seems…appropriate" (1954).

[15] In brief, Salmon characterizes (1) the ontic view as the perspective that explanation is "to exhibit [the event] as occupying its (nomologically necessary) place in the discernable patterns of the world" (1984 p. 18). He characterizes (2) the epistemic conceptualization of explanation as "an argument to the effect that the event-to-be-explained was to be expected by virtue of the explanatory facts" (1984 p. 16). Finally, he characterizes the modal view of explanation as taking the following form: "given the explanatory facts, [the event] had to occur" (p. 17).

We are entitled to expect  that a scientific explanation will help us achieve a number of other important goals; scientific explanations can help us to identify the phenomenon's origin, the constituting factors which contribute (often causally) to the phenomenon, and the spatial and/or temporal or causal organization of those factors which lead to the phenomena. My view is that a scientific explanation ought to illuminate those key factors which characterize the phenomenon. Thus, the ways that  a scientific explanation is supposed to do this may be addressed by a theory of scientific explanation. In the next sections, I will discuss the attempts to characterize and model explanation in the 20$^{th}$ century, and then attempt to develop a model for what a model of explanation should give us.

*History of Philosophical Theories of Scientific Explanation*

In this section, I will expand upon the search for a theory of scientific explanation, which accelerated in the late 1940s when Hempel and Oppenheim formulated the Deductive-Nomological (DN) theory of scientific explanation, which was presented in a rigorously linguistic way in keeping with the trend of the times. In the DN model, an e*xplanans* (sentence of group of sentences describing the phenomena to be examined and explained) is explained by an *explanandum* (sentences "adduced to account for the phenomenon" (Hempel & Oppenheim 1948 [1965: 247]). The explanans is shown to be a logical consequence of the explanandum (Hempel 1948 [1965, p. 248]), which must be deduced via rational argumentation relying upon deterministic natural laws (i.e., nomological arguments). In my dissertation, I will examine reasons that the DN theory is now argued to be incomplete or to fail; for example, under DN, bizarrely, the length of a pendulum could be "explained" by the pendulum's period, or the height of a telephone pole might be "explained" by its shadow, since in either case, the second factor can be set up as an explanandum of the first explanans factor via recourse to some physical law. (For a more complete examination, see Jobe [1976].)

Hempel and Oppenheim's DN model was followed by the statistical relevance model of explanation, the unificationist model of explanation, and the causal-mechanical model which preceded NME. The description of each is beyond the scope of this prospectus, but in my dissertation I will briefly describe each of these models and examine their respective virtues and failings. I will then explore the rise of the New Mechanical philosophy ("New Mechanism") and examine its current position as a contender for a general model of explanation.

*New Mechanist Explanation (NME) Positioned as a Theory of Explanation*

In this section, I will present NME in the context of the search for a viable philosophical theory of explanation. In the 1990s, biology, bioengineering, and medical science began to surpass physics as recipients of scientific funding from governments (citation). This shift also affected the philosophy of science. Very roughly, while philosophical engagement with physics had emphasized theories and mathematics, philosophical engagement with biology emphasized models and practical interventions. This change was accompanied by interest in interventionist models of causation (i.e., the idea that X causes Y if a possible intervention on X changes Y, see Woodward [2003]) and causal-mechanical models of causation. In this context, the New Mechanical model of explanation (NME) arose, aiming to explain scientific phenomena in terms of mechanism, where a mechanism again is understood to be a system of causally interacting parts or entities organized in such a way that it produces the phenomenon under examination (see: Craver & Tabery, 2019 [2015]; Krickel, 2018; Glennan, 2002; Glennan, 2017; Glennan & Illari, 2018; Machamer, Craver, & Darden, 2000).

NME proper originated in 1993 with Becthtel and Richardson's *Discovering Complexity,* which framed the search for local mechanistic explanations as the central task of biological science (Krickel, 2018; Craver, 2015). Bechtel and Richardson were soon followed by Stuart Glennan, who argued (perhaps over-enthusiastically) that mechanisms constitute the "secret connexion" that Hume sought between cause and effect (1996). Soon after, Thagard's *How Scientists Explain Disease* (2000) framed medicine as a search for manipulable mechanisms to be exploited for medical intervention. Machamer, Darden & Craver's classic "Thinking about Mechanism" (2000) argued that philosophy of biology (and potentially science more generally) should be reorganized around New Mechanistic explanation.

While some New Mechanists maintain a uniting thread between the modern enlightenment  philosophy and New Mechanism today is the machine or mechanical device analogy (see Wright & Bechtel, 2007; Bechtel & Richardson, 2010), other New Mechanists (e.g. Craver, 2007) are ambivalent; Craver, for example, claims mechanisms do not have to be machines (Craver, 2007, p. 4; Craver & Tabery (2019 [2015]), yet routinely describes mechanisms using machine analogies such as "buttons and levers" (Craver, 2020, p. 313) or in comparison to Aristotle's "simple machines"(Machamer, Craven and Darden, 2000, p. 15). Proponents of NME tend to agree that phenomena are explained via active entities or components mechanistically contributing to some behavior.

New Mechanistic Explanations are explanatory in the sense that they reveal aspects of the world which can be manipulated. The activities contributing to an NME are productive in that they are not "mere correlations", but rather they are "most fundamentally…potentially... exploit(able) for the purposes of manipulation and control" (Craver, 2007, p. 6). Citing Woodward (2003), Craver argues that genuine "explanations afford the ability to say not merely how the system...behaves, but to say how it would behave under a variety of circumstances or interventions" (Craver, 2006, p. 358). NME is thus committed to the "instrumental value of explanatory knowledge" (Craver, 2020, p. 313) and the idea that a phenomenon is properly explained when under that explanation we are potentially able to manipulate and intervene upon the factors causing it (Craver, 2007, pp. 6, 63, 950; Craver, 2006, p.372). So mechanistic components are only relevant according to Craver because of their very manipulability.[16]

In my dissertation, I will expand upon Craver's reliance on Woodward's manipulability account of causation (Craver 2007; Woodward, 1997, 2000, 2003).[17] Whether something is truly explained in NME depends on whether in some ideal circumstance you could use your knowledge to manipulate it.

*What Makes a Good Theory of Explanation?*

Curiously, despite the plethora of models of scientific explanation proposed in the 20th century, there is ongoing disagreement in the literature on how best to rigorously define what we need from a *theory* of scientific explanation, and a dearth of exploration of what qualities we should seek out in such a theory. Surely the distinction of modes of scientific explanation deserves a rigorous treatment. In this section, I will highlight and discuss properties we want in a good theory of scientific explanation and elucidate why we might choose one theory of scientific explanation over another.

In this section, I will argue that a good theory of explanation should account for what goes into a valid scientific explanation, including how the explanation is arrived at, formulated, and used. I will argue that the theory should provide insight into why certain kinds of data, observations, and measurements are useful in formulation of a scientific explanation and others not. I argue that the theory should illustrate how scientists capture

[16]According to Craver, "A….scientist (who) knows more relevant details will know more of the buttons and levers in a system that might be used to make it work for us. In our view, this is why explanatory knowledge is important, why the mechanistic norms of explanation are justified, and why explanatory knowledge is rightly distinguished…" (Craver & Kaplan, 2020).

[17] Like Woodward, Craver holds that some component variable X is only "causally relevant" to some "variable Y in conditions W if some ideal intervention on X in conditions W changes the value of Y" (Craver, 2007, p. 94).

the relevant facts, properties and *relata* contributing to the phenomena, including any relevant causal connections and / or arrangements in time, space (or "elsewhere") involved in the production of the phenomena. Such a theory should furthermore illuminate why some explanations are valid or satisfactory, and why other explanations are invalid or unsatisfactory.

I will argue that a theory of explanation must be faithful to the actual practice of scientific inquiry. I argue that such a theory should reflect what scientists care about and should grant some insight into why a scientific explanation is considered intellectually satisfying. The content of the theory of explanation should provide insight into why explanation aids understanding (Psillos, 2014). A general theory of scientific explanation should apply to broad categories of scientific cases and apply widely across the sciences. If a theory of explanation applies only in one or a few areas of science, it fails as a general theory of scientific explanation.

**Chapter 2: Limitations of New Mechanism in Biological Explanation**

In this chapter, I will examine the case that New Mechanism cannot cover all valid explanations in biology. I will plumb the implications of Bechtel and Bolhagen's (2021) claim that New Mechanism bottoms out in "constraints and energetics" and speculate about what a New Mechanistic philosophy would look like if it took constraints and energetics into account, arguing that such an NME would begin to resemble mathematical physics theories of energy transfer (i.e., thermodynamics, statistical mechanics and chaos, as described by Ilya Prigogine [1984] and others). I will explore Skipper and Millstein's contention that the paradigm of natural selection is not "adequately capture[d]" by New Mechanism as described by Machamer, Darden and Craver or Glennan. I will argue that Skipper and Millstein are correct in this claim, while contending (contrary to Skipper and Millstein) that the rubric of NME cannot cover natural selection and cannot be revised to cover it without completely changing the core commitments of NME. Next, I will briefly examine Lauren Ross's "pathways" and "cascades" (2021, 2022) as categories of explanation not covered by NME. I will finally examine cases in biology (e.g., sodium channels in neurons, photosynthesis, DNA mutation, enzymatic activity) that involve subprocesses describable only with recourse to thermodynamics and other mathematical physics and/or statistics. I will explain why NME is inadequate to capture some of the most relevant information contributing to such cases. I conclude Chapter Two by arguing that the fact that many biological phenomena are best understood using traditional physical and mathematical explanation indicates greater commonality between biological and physical explanation than is usually assumed in philosophical discussions of scientific explanation. At this point, my examination will lead into a discussion of NME's coverage of explanation in physics.

**Chapter 3. Limitations of New Mechanism in Explanation in Physics.**

In this chapter, I present cases of explanation in physics which are not amenable to explanation according to the tenets of NME. I will start with an example of a common question answered by physics: "Why does a ball move forward when I kick it?" The answer to this question, put simply, is that your foot passes on kinetic energy (and thus momentum) to the ball. But how does it do this? The electrons in the atoms of the surface of your feet and the electrons in the atoms of the surface of the ball come so close to one another that the fields of these electrons exert repulsion—the Coulomb force—on one another, which imparts kinetic energy to the ball. The Coulomb repulsive force arises via the Pauli exclusion principle, which is the principle that no two electrons with the same "spin" (a.k.a. the same magnetic moment, where a magnetic moment is the magnetic strength and orientation of an object which produces a magnetic field) may co-occupy an "orbital" (where an orbital is the shape of the probability map of the locations of electrons within the three-dimensional standing wave electron cloud). As soon as the clouds of two electrons with the same spin begin to overlap, a repulsive force arises between the clouds to keep the like-spin electrons out of the same orbital. (This is similar to what happens if you try to rub the north polls of two bar magnets together.) This repulsion of electrons causes your foot and the ball to repel one another, and since the ball is less massive than you are, it is unable to absorb all of the kinetic energy imparted by the repulsion, so it launches in the direction it is pushed. Thus, we see that the behavior of solid objects is reducible to—and explainable by--the electromagnetic behavior of non-solid field properties.

So now, for practical purposes, it seems we should try to better understand this concept of a "field". In physics, a field is a set of physical quantities represented by a scalar, vector or tensor in which a value is provided for each point in spacetime. While Carl Craver names "fields" among a list of entities (see 2007, p. 64) without further explanation, in practice it is very difficult to distinguish a field as a distinct entity, as it has no single location in space and extends to infinity unless redirected (thus violating lllari's concept of entities as "local" or Craver's concept of mechanisms as defined by "local levels" [2019]). Glennan furthermore notices that if we "decompos(e)...the field into parts, the parts of the system are not real objects" either (1996, p. 53). While a field may be produced by some activity (e.g., moving charges and currents) it is not an "activity" in and of itself but rather the product of that activity. If fields are not then entities or activities, fields seem to be a phenomenon, that should be described via mechanism if physics is mechanistically explainable.

Yet, a field itself is apparently not amenable to mechanical explanation, as admitted by Stuart Glennan, who says it is not "possible to give a mechanical explanation of the behavior of the electromagnetic field (as it is codified by Maxwell's equations)" (1996, p. 53). He holds that the field may be a component of a mechanism, but mechanistic components could not explain the field. Here we run into a problem of primacy. If some or all phenomena can only be explained via recourse to fields, and fields cannot be explained using mechanics, and if fields are not categorizable as “entities” or as “activities”, then such fields may be a more primary explanatory component than mechanisms themselves.

I will examine problems with various scientific explanations which are non-mechanical, including flying buttresses and other static systems indescribable via activity (see Nielsen, 2021, citing and confronting Mebius, 2014), the probabilistic laws of statistical mechanics, optical laws such as Snell’s law (Craver and Kaplan, 2020), the laws of special and general relativity (Felline 2018, 2021), and quantum problems such as tunneling in circuits (Nielsen, 2021). We will examine Glennan and Kuhlmann’s “three non-classical features in quantum mechanics that seem to clash with the ontological commitments of the New Mechanists: (A) Indeterminacy of properties, (B) Non-localizability of quantum objects, (C) Non-separability of quantum states due to entanglement (“quantum holism”) (Kuhlmann and Glennan, 2014, 8) and using the Heisenberg Uncertainty Principle (1927), Bell’s inequalities (1987), and other core principles of quantum mechanics (Bohr, 1928, Stefanov et al, 2002, Emary et al, 2013, etc.), strike down their three attempts to preserve mechanism in quantum systems (i.e., [1] the supposed irrelevance of indeterminateness, [2] the supposed explanatory irrelevance of entanglement, and [3] the supposed relevance of causality over locality). I will argue further that, given mechanism is unable to account for quantum systems, it subsequently fails to satisfactorily explain many practical everyday processes and objects relying on quantum phenomena to exist, such as photosynthesis (Romero, Augulis, Novoderezhkin, et al, 2014), transistor radios, solid state stereo systems, flash memory, MRI, and the scanning tunneling microscope.

## Chapter 4: About The Inevitable Recourse to Mathematics

We have found that many of the systems that NME most struggles to explain are systems in science explained via mathematical relationships and dynamic models. In this chapter, I will argue that inclusion of mathematical explanation and admission of its relevance is necessary in a general theory of scientific explanation. Certain facts of reality are obviously and trivially mathematical: if a mother rabbit has five berries, there is no way for her to evenly divide those whole berries amongst her four baby bunnies; this fact does not require explanation beyond the definition of odd and even numbers. I will examine cases like this which are only amenable to mathematical explanation. I will furthermore argue that certain types of scientific situations are best explained via dynamic modeling (citing Brigandt, 2015) or statistical explanation (Levy, 2013) while noting the incompatibility of such DME with NME (citing Issad & Malaterre, 2015). I will furthermore examine geometric properties of objects and their influence upon the world as it actually is.

To the aim of arguing for understanding of science via geometry, I will examine the plenitude of possible structures and the impossibility of a regular seven-sided polyhedra despite the possibility of six and eight sided regular polyhedra (Bricker & Almog, 1991). I will explore how the number *pi* contributes to our understanding of circles, recognizing that *pi* allows us to explain how to find the perimeter of some real physical object shaped like a circle and why one can only approximately "square" that circle, and yet pi is a purely mathematical conceptualization.

To counter the notion that these geometric explanations exist merely in the abstract, I will present a consideration of Pincock's (2007) example of the bridges of Konigsberg. I will examine why a person in the real world can't cross all of the bridges of Konigsberg exactly once (while remaining always on land or bridge and while crossing any bridge completely once having begun to cross it). (The answer [see Lang, 2017] is that the network of the bridges is arranged such that every vertex—or every vertex but two—is touched by an even number of edges, and a crosser of the bridges would have to enter a given vertex as many times as they leave it unless the vertex is the start or end of the trip, and thus among the vertices, either none or two could touch an odd number of edges).

I will also examine situations in nature such as the helical structure of DNA and its limitations; if we want to know why DNA cannot maintain in the form of a triple helix, we must consider the DNA's helical geometry and structure: the third strand would have to be made up of an unpaired strand of RNA, thus breaking the structure. To explain the irrationality of the triple helix proposition, one must only rely on the nature of odd numbers and the geometry of the helix. There are numerous such examples to be explored in the dissertation.

Nevertheless, it has been argued that some of these aforementioned mathematical laws could be restated without recourse to number (e.g., calculus as deduced by the infinitesimal rather than via the reals). For example, Field (1980) has argued that explanation in science is possible without recourse to mathematics (see *Science without Numbers*). In contrast, I will argue, in agreement with Leng (2010), that Field's program fails to subsume mathematics, as it requires a "powerful logical apparatus" which is "at root mathematical" or which at least forces us "to accept the existence of mathematical objects" (p PAGE).

I will furthermore examine acausal scientific explanations as enabled by mathematics, demonstrating that certain problems in quantum physics as noted by Kuhlmann and Glennan become less paradoxical if features of mathematical and structural explanation are upheld over and above explanation via "cause". While Kuhlmann and Glennan maintain that causality may be the most basic requirement of New Mechanism (Kuhlmann & Glennan, 2015) and "discard" the "possibility that there is no causation at the fundamental level….because [of a belief that] higher-level causation should be grounded at the most fundamental level", Felline has argued that "no-causality-at-the-fundamental-level solution – has been unjustly dismissed as a viable option" (2016). I will argue that mathematical, non-causal foundations of explanation are the only viable option, explaining that even the notions of time and space themselves rely on concepts of spatiotemporal structural ordering that reduce to concepts of order in mathematics.

I will thus argue that mathematics is indispensable to most if not all kinds of scientific explanations. Whenever we enumerate, measure, and examine patterns of relationships in ther world, we are exploiting mathematical processes of thinking. It is the business of science to reveal patterns and relationships in the natural world, patterns and relationships that can only be explored, revealed, and explained with recourse to mathematics. Without knowledge of the mathematical ratio of the perimeter to the radius of the circle ("*pi")*, for example, no physical calculation utilizing those vectors which explain the dynamic properties of objects would be possible. Scientific experimental confirmation furthermore relies upon scientific measurements which are inherently mathematical, and thus there is no way to explain the data sufficiently without recourse to mathematical reasoning. The scientific study of patterns and relationships and sets of properties in nature inherently reveals itself in ways explainable only with recourse to mathematical knowledge. To eliminate mathematics from scientific explanation is to castrate it and is to eliminate those processes which make science the most explanatory.

We can say with confidence that most if not all scientific theories rely inherently upon mathematical details which cannot be explored with purely causal mechanistic thinking. Mathematics is not mechanics. If even some scientific explanation requires math as a fundamental component of its intelligibility, then mechanism is no longer the fundamental unit of scientific explanation that NME claims it to be. Any working general theory of scientific explanation should work to accommodate all kinds of explanations, especially those most important and fundamental. NME does not work as a general theory.

## Chapter 5. Where NME Works (And Why It's Not General)

In this chapter, I will examine where NME works and explain why it works in those areas. I will conclude that NME functions well as a model of engineering sciences and in sciences where interventions are of principal concern. I will argue that NME successfully describes many macro level situations open to human intervention and engineering, most specifically those involving distinct objects interacting at trackable locations in specific local levels to complete causal processes which produce phenomena, and which most ideally could be intervened upon and manipulated by an engineer so as to change those behaviors and thus the resulting phenomenon. We can recognize the virtues of NME in these domains without accepting the idea that NME establishes the autonomy of biological sciences apart from physics. Similarly, there is no reason to believe that because of its success in engineering and intervention centric contexts NME supersedes traditional physical explanation as a source of explanation.

By this point in my dissertation I will have presented multiple areas of physical science that NME fails to explain. Rather than suggesting ala Bechtel and Bollhagen (2021) or Kuhlmann and Glennan (2014) that NME must grow or change to accommodate these factors, it seems more practical to acknowledge these areas of failure as limits on NME itself. In my concluding sections I will examine NME in light of my criteria for a general explanation of science, and will determine that by many of my criteria, NME comes up lacking. Particularly, as certain aspects of science are not explainable by NME, and as NME fails to explain certain features of science, therefore NME is not a general model of scientific explanation.

## Conclusion

The constructive contribution of my dissertation will involve providing a set of criteria for what counts as a successful general theory of scientific explanation in philosophy of science. Our examination of cases in physics, biology, and mathematics shows that NME certainly does not qualify. Part of my remaining work involves being as clear as possible in defending the mathematical component of scientific explanations.

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