The Scope of New Mechanism

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Introduction

In recent years, New Mechanism has become one of the most popular and widely discussed philosophical accounts of scientific explanation. Some of its proponents see it as a successor to traditional deductive nomological and statistical approaches to the philosophy of explanation. Stuart Glennan argues that according to New Mechanistic Explanation (NME), "most or all" natural phenomena "depend on mechanisms", and that construction of mechanistic models is the "chief business" of science itself (Glennan, 2017, p. 1). Similarly, Carl Craver claims that models explain "when they describe mechanisms" and that "the distinction between explanatory and non-explanatory models seems to be that...(explanatory models) describe mechanisms", whereas non-explanatory mechanisms do not (2006, p. 367). New Mechanists thus argue for the generality of their approach as a model of scientific explanation.

As we shall see, the generality of NME as an account of scientific explanation is restricted. Most significantly, NME is widely recognized to have trouble in accounting for explanation in traditional physics. Yet, in the face of obstacles to NME in the physical sciences (Kuhlmann & Glennan, 2014; Felline, 2018), New Mechanists have yet to provide a convincing defense of the generality of their view. In this paper, I (1) summarize when and how NME works, (2) describe briefly what NME is not and can't be, (3) outline some areas of contemporary scientific explanation where New Mechanism misses the mark; and (4) demonstrate that New Mechanism does not constitute a general theory of scientific explanation but rather covers a restricted scope of explanations.

What is New Mechanistic Explanation (NME)?

New Mechanistic Explanation (NME) aims to explain scientific phenomena in terms of mechanism, where a mechanism 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). A “good” explanation of a behavior or phenomenon according to new mechanical philosophy is a description of a structure[1], system[2] or set of relevant[3], ideally “real and local” [4]component entities[5] or parts[6] organized in such a way that they interact[7] and perform various productive activities[8] which cause the phenomenon[9] or behavior[10] being explained. 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 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 (MDC) “Thinking about Mechanism” (2000) argued that philosophy of biology (and potentially science more generally) should be reorganized around new mechanistic explanation. This article soon became a standard reference for discussions of the NME perspective.

While some New Mechanists maintain that the common uniting thread between traditional early modern Laplacian mechanistic 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 his work routinely describes mechanisms using machine analogies such as “buttons and levers” (Craver,

[1] Bechtel and Abrahamsen, 2005
[2] Glennan, 2002
[3] Illari and Williamson, 2012; Illari & Williamson, 2011
[4] Illari and Williamson, 2011
[5] MDC, 2000
[6] Glennan, 2002, 2018, etc
[7] Glennan, 2002, 2018
[8] MDC, 2000; Craver, 2007; Illari & Williamson, 2012
[9] Craver, 2007, 2015; Illari & Williamson 2011, 2012
[10] Glennan, 2002, 2018

2020, p. 313) or comparison with Aristotle's "simple machines"(MDC, 2000, p. 15). Regardless of their relation to "machines" understood on the analogy with human artifacts, proponents of NME 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 in 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 relevant according to Craver because of their manipulability.

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; italics mine).

Craver relies closely on Woodward's manipulability account of causation (Craver 2007; Woodward, 1997, 2000, 2003), holding like Woodward 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). Craver goes on to specify that, in terms of constitutive relevance, a "component is relevant to the behavior of a mechanism as a whole" only "when one can wiggle the behavior of the whole by wiggling the behavior of the component and one can wiggle the behavior of the component by wiggling the behavior as a whole" (Craver, 2007, pp. 153-154). Given the centrality of manipulability, we may now understand MDC meant by stating that the "intelligibility" of a description arises from the "elucidative relation between the *explanans*...and the *explanandum*" (2000, p. 21). Whether something is truly explained in NME depends on whether in some ideal circumstance you could use your knowledge to manipulate it.

NME has its Roots in Biotechnology and Bioengineering

It is helpful to briefly introduce some historical and sociological context in order to why NME takes the approach to scientific explanation it does. NME developed during the biotechnology boom of the late 1980s to mid 2010s, an era during which biology displaced physics as the headline-grabbing and most highly-funded science. Whereas physics increasingly focused on mathematically abstract speculative "strings" modeled at the empirically inaccessible Planck length, biotech developments focused on practical intervention-centric solutions to medical, genetic and agricultural problems. In the 1990s, gene cut and splice techniques brought advanced gene therapies which by 2012 were streamlined with the invention of "table-top" CRISPR splice kits; advances in cell nuclear transfer (SCNT) technique enabled the birth of "Dolly the Sheep" in 1996 as the first successful clone of an adult mammal; the demonstration of embryonic stem cell pluripotency in 1993 and programmed pluripotency of adult stem cells in 2006 spurred ongoing stem cell therapy research efforts; "real-time" brain monitoring enabled by the invention of fMRI in 1990 entered contemporary neuroscience; finally, biochemical interventions such as enzyme blocker-based cholesterol lowering "statin" drugs (c. 1987) and serotonin-absorption blocking SSRI prescription antidepressants such as Prozac (c. 1988), Paxil (c. 1993) and Zoloft (c. 1993) proved highly profitable. All of these emerging biotechnologies were understood to exploit manipulable features of causal mechanistic chains in order to intervene upon target systems. Statins could be modeled as a mechanistic intervention with which to drop cholesterol and improve heart health; SSRIs could be modeled as an intervention in the mechanism which stabilized serotonin and thus reduced the symptoms related to depression and anxiety. Many other examples of specific biotechnological or pharmaceutical interventions that were discovered during the 90s and 2000s could be mentioned here. Proponents of NME highlighted examples from cellular and subcellular neuroscience especially in this context.

Manipulability theories of causation (Menzies & Price, 1993); Woodward (2003)) and causal-mechanical theories of explanation (e.g., Salmon, 1984, 1989) became increasingly popular during this era, and New Mechanism emerged in this milieu as a popular philosophical account of explanation in the biological sciences and it assumed its position as a contender for a broader model of scientific explanation to replace more physics-centered deductive nomological and statistical approaches to explanation.

New Mechanistic Explanation (NME) Applied to Physical Situations

New Mechanist Explanation (NME) is unabashedly pragmatist in spirit—if a system may be changed via manipulation of parts which impact the system, the system will exemplify some of the main commitments of NME. Specifically, an ideal physical situation for applying NME is one involving a system of entities identifiable as component parts in order that we may index and track their activity along causal chains of interactions in order that we may intervene upon and manipulate them in order to affect the *explanandum*. If "a mechanism is represented schematically by A→ B → C, then the continuity lies in the arrows and their explication is in terms of the activities that the arrows represent" (MDC, 2000, p. 3).

But does this model generalize? Clearly, not all physical situations will satisfy these requirements, nor will all scientific claims that were traditionally understood to constitute explanations. Consider, for example, the kinds of dynamical and field theoretic explanations we find in physics. How we are to reconcile mechanism as a general approach to scientific explanation with the ubiquitous role of field theory in physics? On a first analysis, prospects look bleak for NME. What would a mechanistic or mechanical explanation of an electron cloud or a black hole look like, and perhaps more importantly, what could such an NME explanation tell us? How could a mechanistic explanation capture all the relevant explanatory content that is provided by field theory in quantum mechanics and general relativity? For the remainder of this paper I will reflect on cases like these in order to understand where mechanistic styles of explanation are properly applied and where they fail.

While proponents of NME recognize limits of NME, they tend to maintain that phenomena that fall outside the scope of NME are not relevant to explanation. For example, New Mechanists maintain that population dynamics and mathematical models are only outside of NME because such models are not scientifically explanatory or only related to temporal organization of mechanisms (Kaplan and Bechtel, 2011; Craver and Kaplan, 2011). Craver and Kaplan maintain that there is no “philosophically tenable sense” in which dynamical “models explain”—instead they are at “best…descriptive tools” (2011, p. 602). For reasons I will discuss below, this is an unpersuasive strategy for Craver given the apparent explanatory power of dynamical mathematical models in science. This power will be apparent once we examine the kinds of explanations we find in modern physics.

As is well known, deductive nomological and statistical approaches to explanation were largely inspired by examples from physics. These approaches suffer from well-known defects which I will not discuss in this paper (See Psillos 2014). New Mechanists frequently distinguish their approach by maintaining that “mechanistic explanation offers a welcome alternative to traditional laws-based explanation” (Illari & Williamson, 2011, etc). They have “distanced themselves...from the austere metaphysical world picture in which all real change involves only...a limited set of fundamental…forces” (Craver & Tabery, 2019 [2015]). They “want to provide a fruitful philosophy for the special sciences that diverges from (and) oppose(s)…the physics-centricity of traditional philosophy of science” (Krickel, 2018, p. 4). While physics is often seen as an old-fashioned source of error in the philosophy of explanation, advocates of NME cannot avoid recourse to physical terminology altogether. Even when the focus is on the so-called special sciences, proponents make appeal to notions that have their original home in physics.

As we shall see, physics poses a challenge for NME since mechanists cannot provide explanations that are more fundamental than those given by field theorists. As I will show in more detail below, field theoretic explanation can be used to explain mechanistic phenomena but mechanisms cannot explain fields (conceded by Glennan, 1996). Similarly, while energy and forces may be mentioned as parts of mechanistic explanation, mechanisms do not easily explain energy and forces.

Bechtel and Bollhagen (2021) recently noticed that NME bottoms out in discussions of “constraints and energetics”. They call for NME to expand by integrating mechanistic explanations with these concepts. Bechtel claims to “reconceptualize mechanisms as imposing constraints on flows of free energy” (2018, p. 1), but this is less a “reconceptualization” of mechanism than a return to conceptualization of mechanism in terms of constrained energy flow, a.k.a. thermodynamics and energy conservation of the kind we find in standard physics. Bechtel and Bollhagen posit, “Unless one embraces activities as foundational, understanding activities in mechanisms requires an account of the means by which entities in…mechanisms engage in their activities" (2021, forthcoming). Yet, if mechanisms and activities must be explained using some deeper science, then mechanism is obviously not a fundamental. If mechanism is not model of scientific explanation that speaks to ontologically or explanatorily fundamental features of scientific explanation, we might wonder what special virtue it can claim as a theory of explanation.

Usually, proponents of NME allude to scientific practice, alluding to the styles of scientific explanations that they notice in favored regions of biology. The argument goes something like the following: While NME might not capture epistemically or ontologically fundamental aspects of the explanation, it captures the way that explanations are given in scientific practice. Unfortunately for NME, reference to observed practices and pragmatic payoff are not sufficient for them to make their argument. In fact, if it were the case that in practice we relied solely on mechanisms for explanatory power we would suffer a significant loss of both scientific content *and* pragmatic utility. Appeals to practice by NME are selective at best.

How is pragmatic utility lost? Very simply for example, it may be possible to utilize knowledge of gravitational fields in order for a spacecraft to evade a pass beyond the event horizon of a black hole and thus avoid the unsanitary sounding fate of "spaghettification". Scientists use gravity assistance technology to slingshot space craft into deep space, but the mechanism of craft acceleration would remain unexplained – and unusable – without an understanding of fields. Everything from the electricity in our homes, to the study of the dynamics of pandemics relies on explanatory strategies that invoke non-mechanistic features. Clearly we would not want to abandon the pragmatic advantages of non-mechanistic explanations. Nor pace Craver would we want to say that the kinds of field theoretic accounts of rocket slingshots are merely descriptive given that they support counterfactual judgments about where our rocket might end up, given alternative parameters. In this case, a field theoretic account clearly supports explanations of the rocket's motion and has an obvious pragmatic payoff.

Another supposed virtue of NME is avoidance of "external forces" – the active entities are "not passive…(their) behavior is not due to forces external to the behaving entity" (Krickel, 2018, p. 74). Yet in various physical scenarios such the gravitational slingshot, the causal activity relationships between various entities in mechanisms are only instantiated via contributing forces. Perhaps it is troubling that no metaphysical alternative to forces nor any "reductive analysis" of causation is offered by NME. As Bechtel and Bollhagen (2021, forthcoming) put it, "The standard account of mechanistic explanation explains activities in terms of activities and does not offer an explanation other than to appeal to other activities." While we may discuss causation in terms of manipulability and intervention, "intervention is an ineliminably causal concept" introducing circularity (Craver, 2007, p. 94), as are "productive activities", which are simultaneously performed/caused by entities and also in and of themselves fundamental units of cause.[11] To some extent, proponents of NME have appreciated this problem with their view.

As others have noted, truly escaping a force picture is difficult for NME. According to Bailer-Jones (2009), mechanisms as described by New Mechanists are simply "abstractions of the notion of motion of a body as affected by force (p. 37), an idea which is bolstered by Craver's description of "causal powers" as "understood as forces that push and pull, attract and repel, bond and break bonds, restore equilibrium, and so on" (2007, p. 211). NME's pragmatism therefore fails to offer a fully developed alternative to law-based explanation, and thus we find that NME does not truly escape the physical force worldview it seeks to distance itself from. Instead, critics might suspect that the general strategy of the proponents of NME is simply to change the subject. While mechanisms are distinguished from contributing causal powers in that the mechanisms "require the organization of components in cooperative and inhibitory interactions that allow mechanisms to do things that the parts themselves cannot do" (2007, p. 216), they do not escape reliance on such causal powers or "laws" in order to operate. Thus the physics force picture of science has not been evaded within NME but rather the role of force seems simply to be ignored.

In recent work Bechtel and Bollhagen (2021) have acknowledged some of these issues. They encourage new mechanists to "explain" constraints and energetics ("Activities are not primitive posits. They can be explained"), claiming that "one can plausibly infer that these activities result from the constrained flow of free energy through the mechanism and so organize the account of

[11] He mentions that causal powers are often treated as a necessary "addition...to entities" in order to allow for objects to impact on and be impacted by the world and thus enable change ((2007), p. 211), but he crucially imparts such powers to activities, stating that activities "have precipitating conditions or enabling properties...and effects" (2007, p. 95); activities themselves are "kinds of causings" (Craver & Tabery, 2019 [2015]).

the mechanism around that flow" (2021). But one does not need to infer anything: classical physics already provides such an explanation. Thus both the "autonomy" of explanation in the biological sciences suggested by NME (Krickel, 2018, p. 4) and NME's status as a model of sufficient and autonomous scientific explanation is challenged. But perhaps this was not the goal of NME in the first place. For the remainder of the paper I will attempt to unpack some of these observations about the status of NME in more detail.

What NME Is Not

In this section, I examine some of the things which NME is not. In the subsections that follow, I examine mechanism's distinctness from (1) mathematical dynamic and phenomenal models, (2) probabilistic models, and (3) top-down and acausal (ie, nontraditionally cause related) models**.**

NME vs "Phenomenal", Mathematical, and Dynamical Models

I argued briefly for the explanatory role of dynamical physical models such as those we find in gravitational physics. I made the point that these models are genuinely explanatory since they illuminate counterfactuals and they are pragmatically fruitful. Of course there are also other epistemic benefits, such as unification, simplification, generality, etc. Strikingly, proponents of NME are quite dismissive of large parts of physics for reasons we will explain here.

Examples from physics such as Snell's law (a law stating that the ratio of the sines of the angles of incidence and refraction of a wave are constant when it passes between two given media) describing are described as "phenomenal" or phenomenally descriptive by Craver and Kaplan, who say that such models "do not explain" (2020). Craver and Kaplan maintain "One can know perfectly well how to apply Snell's law to predict how a beam of light will bend when it passes through a piece of glass without understanding anything about why light bends when it passes from one medium to the next" (2020).[12] So, they hold that Snell's law does not explain, despite the fact that Snell's law is relevant for manipulating the path of light beams. Yet it is equally possible to level the same objection to mechanisms. Mechanisms are often pragmatically

[12] Nevertheless, Craver does not attempt a mechanistic explanation for light bending. I suspect the dual wave-particle nature of light may have raised some difficulties. On the subject of light bending under gravity, the great Isaac Newton famously said: *"Non fingo hypothesis"* (1713).

useful without being explanatorily illuminating. Yet Snell's law is integrated within a broader physical account of electromagnetism that opens up the possibility of further explanation and understanding in addition to its merely pragmatically useful applications.

Crucially, NME cannot be used to explain whatever usefulness a dynamic model might have. Dynamic modelling explanations (DME) are described as merely "descriptive" by Craver and Kaplan (2011) and as incompatible with the NME picture (Isaad & Malaterre, 2015). While Kaplan and Craver imply DME becomes useful only when mapping to descriptions of spaciotemporal relations in mechanisms (2011), and Bechtel and Abrahamsen (2010) have optimistically implied that it would be possible to integrate DME as a necessary extension of NME, Isaad and Malaterre (2015) are skeptical, maintaining that DME and NME are fundamentally incompatible, as the "ME gains explanatory force by rehearsing a causal story" but "the DME gains explanatory force by providing and solving a mathematical modelling condition" (Issad & Malaterre, 2015). Brigandt (2015) and others have claimed that mathematical models are (at least sometimes) explanatory in and of themselves, apart from NME.

Probabilistic Explanations

Probabilistic phenomena exist in tension with NME. In some cases, truly random systems may straightforwardly resist MDC's requirement that "mechanisms...are productive of *regular* changes" (2000, p.3). In the context of biology, this becomes relevant in the study of evolution. Levy questions whether the "regularity that mechanists recognize" is "apiece with the probabilistic character of selection" (2013, p. 15). While stochastic and chaotic dynamics may ultimately reduce to deterministic reactions to small differences in initial conditions, this does not suggest that population dynamics are not better explained probabilistically (Levy, 2013) or that they are not best explained via "appeal to less than strict regularities" (Levy, 2013, p. 16). Here, we can make a case that understanding the statistical mechanics of gas molecules is more practical for predicting and influencing the behavior of molecules than is some mechanical explanation which cannot predict the large-scale behavior or allow us to manipulate it. Without accounting for stochastic behavior, mating patterns of animals become difficult to model (Levy, 2013) and Walmart would have issues predicting shopping cart traffic at check-out. A mechanistic explanation of how humans shuffle through the checkout is not helpful for Walmart;

The Walmart management wants an explanation of how to practically manage stochastic traffic flow. NME fails to provide such models.

Top-Down and Acausal Scenarios

Felline (2021) mentions a “significant limit” for NME offered by systems which display top-down behaviors “independent of the...micro-dynamics of the systems displaying” them. She lists examples such as Archimedes principle, the conservation of energy, and matter behavior at “critical points” (2021, p. 4), holding that NME cannot easily be used to explain these phenomena. Yet these phenomena, as understood by physics, may be used for manipulating physical objects.

Kuhlmann and Glennan maintain that causality may be the most basic requirement of New Mechanism (Kuhlmann & Glennan, 2015). Glennan “discards” the “possibility that there is no causation at the fundamental level….because he thinks that higher-level causation should be grounded at the most fundamental level.” Felline (2016) argues that “no-causality-at-the-fundamental-level solution – has been unjustly dismissed as a viable option.” Scenarios in quantum mechanics furthermore suggest that no-causality-at-the-bottom may turn out to be the only acceptable option. We will return to this later.

What NME Does Not Explain

In this section, I present examples of physical situations in where NME does not work particularly well or even fails. I start with situations in (1) changing systems and systems of non-distinct and/or changing entities including biological entities, then move on to (2) situations in classical physics, (3) situations in relativity, (4) field-related situations, and (5) situations related to quantum mechanics and quantum field theory.

Changing Systems and Systems of Non-Distinct Entities

Levy (2016) suggests that NME must be expanded to accommodate for systems with parts that are not distinct entities, systems with non-fixed (malleable or changing) organization of parts, and systems with parts that change over time. According to Levy, traditional NME must grow to explain “not only [how] the parts undergo changes” but also the process of how “which

parts interact with which other parts changes as the mechanism functions" (p. 5). Along similar lines, Glennan (2017) suggests that the concept of "ephemeral mechanisms" evolving through time without fixed spatial-temporal arrangement should be introduced. Yet, it may be difficult to reconcile "ephemeral mechanisms" with the notion that mechanisms must consist of local and real, distinct interacting parts. If a mechanism's parts are only briefly present in the world in order to act upon a mechanism, are they a "real" component of that particular mechanism when they have ceased to partake in that mechanism? Is the mechanism defined moment to moment, or over some period of time? And how would a disappearing component "wiggle" the entire whole of the system (ala Craver, 2007) once it has disappeared from that mechanism?
I argue that such problems with ephemeral mechanisms simply have not been fully explored, by the proponents of NME.

Examples of systems with non-distinct entities might include stream/buoy systems wherein buoys knocked about by difficult to distinguish directional "currents" in a stream. Systems with non-fixed organization and/or parts that change over time might include growing biological embryos and cells which change their metabolic strategies in order to accommodate different energy sources. Lack of complete accommodation for these sorts of systems suggests that NME may require tweaking to explain complex biological structures or other adaptable structures.

Classical Mechanical Statics

We have seen above that the explained "phenomena" of mechanisms are almost always described as systems with moving, changing parts. While the common statics problem of engineering physics can be represented as a number of component parts (say, a pier and arch) which together keep some greater object (say, a flying buttress) stable and at rest, mechanical phenomena always seem to be described in active terms such as "activities" (MDC, 2000, p. 3), "changes" (MDC, 2000, p. 3) or "behaviors" (Glennan, 2002). Objects which work together to keep a form at rest are not producing "regular changes", or "changes" at all, let alone any obvious activities, except on levels not critical to the stasis of the object (such as light reflection, thermal activity and radiation, etc; see Glennan (2017, p. 21). We might ask, *reductio ad absurdum*: if science is the search for mechanisms (Glennan, 2018), and mechanisms are about "regular changes" (MDC, 2000), do static objects belong to the study of science at all?

According to Felline (2018), “There is general consensus that there is no (NME without change and production” (p. 2). By this standard, static objects are not mechanisms!

While we could attempt to treat the zero-sum force-vector statics of a buttress as an “absence of causation” producing motion and thus a “mechanism failure” (see Barros, 2013) or a mechanism of “causation by absence” (Mebius, 2014), characterizing the induced stability of a buttress in terms of “absence” or “failure” is descriptively inadequate for an object designed explicitly to stay still. No “compelling account of causation by omission and prevention” in mechanisms as suggested by Craver (2007, p. 225) has been developed. “Absence” and “omission” may not be the best or most explanatory terms for discussing causes of stability. In any event, including absence and omission would require a significant extension of the resources of NME.

Modern Physics

Fields

We now know that much of physics may be characterized (via quantum field theory) as the interaction of fields in spacetime, which is metrically described (according to general relativity) as a field, as well. Thus, physical situations at a basic level almost always involve interacting fields or, in approximation, “objects” under the influence of fields. This has repercussions for reducing scientific explanation (SE) to New Mechanistic Explanation (NME).

While 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 Illari’s “local” requirement). Fields themselves defy New Mechanistic Explanation; as Stuart Glennan puts it, if we “decompos(e)...the field into parts, the parts of the system are not real objects” (1996, p. 53). Glennan believes 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 mechanisms can only be explained via recourse to fields, and fields cannot be explained using mechanics, then such fields are a more primary explanatory component than mechanisms themselves. The incompatibility of fields with NME creates an incompatibility which permeates most of physics, from classical orbits to quantum field theory.

Relativistic Situations

Numerous relativistic situations fail to lend themselves to explanation via NME. For example, consider length contraction in Special Relativity (SR). According to Felline (2018), the usual explanation is not an ME, since the dynamical features of the object in question "are irrelevant and the relativistic effects are not understood as dynamically or causally produced". Instead the usual explanation "depends on the fundamental geometrical features of four dimensional objects in Minkowski space-time" (Felline, 2018).

In relativity, we are presented with gravitational field structures such as black holes (gravitational wells in space-time so powerful as to puncture the spacetime fabric and from which nothing, not even light can escape). It is difficult to imagine how black holes (let alone the gravitational wells caused by massive objects more generally) could have been discovered if mechanical features in science were the only concern and if mathematical features were considered only relevant when mapping onto mechanical situations. Without utilizing mathematical field models, it would be impossible to predict or explain the changing geometry at various levels of distance from a black hole, or to pinpoint one's distance from the point of no return, a ring around the black hole known as the event horizon.

Quantum Theory

A common refrain amongst physicists is that "quantum mechanics" is not really mechanics at all[13] or that "quantum mechanics" is a kind of oxymoron. Crucially, a "quantum mechanical" or quantum field theory account of nature does not assume local causal interaction, nor does it assume "real" objects (Emary, 2013) or objects with definite properties (Kuhlmann and Glennan, 2014). Quantum mechanics describes the physics of fundamental particles such as photons and electrons, which exist as physical wave-particle-field objects ("wavicles") whose behavior is

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[13] "The…term 'quantum mechanics' is very much a misnomer. It should, perhaps, be called 'quantum non-mechanics'" (Bohm, Quantum Theory, p. 167)).

described probabilistically by a mathematical construct called the “wave function”. (Larger objects like cats and buildings are thought to obey quantum rules, too, but typically so many wave functions of so many particles are involved in such macro objects that the stability or “coherence” of the wave functions interfere and cancel in a process called “decoherence”; if it were possible to keep the wave functions of larger objects in phase, these objects might exhibit quantum properties, too.) The Heisenberg Uncertainty principle suggests that quantum particles are not able to possess or exhibit “complimentary” properties, such as location and velocity, at the same time (see Brumfiel 2012), and thus quantum particles do not move in standard classical trajectories, but rather exist in a “cloud” or field of varying probability densities which are mapped by the wave function. The higher the probability density of some area of the cloud, the more likely the particle is of being located or pinned down there. Each time the particle is captured in a measurement, it has some chance of turning up anywhere in that cloud, even (as we shall examine more closely later) if there is some physical barrier in place that would trap a classical particle at some particular cloud point.

According to Meinard Kuhlmann and Stuart Glennan (2014), there are “at least 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”) (2014, 8).

However, Kuhlmann and Glennan retain hope that mechanical explanation of quantum systems could be preserved via (1) irrelevance of indeterminateness; (2) explanatory irrelevance of entanglement, or (3) a recourse to causality over location. In regards to (1), Kuhlmann and Glennan maintain, “While the quantum mechanical indeterminateness of properties (A) is a serious problem for fundamental ontology, it is usually not a concern for scientific explanations” (2014). This optimism is misplaced: Heisenberg’s principle of quantum uncertainty (the inability of a coherent quantum system to demonstrate location and velocity properties at the same time, or what Bohm called “principle of limited determinism in the structure of matter” (Bohm, 1951, p. 10), destroys the very notion of a trajectory in a pure quantum system, challenging our causal chain explanations of how a ball might get from point A to point B. In regards to (2), Kuhlmann and Glennan claim: “Even in those systems for which quantum entanglements are locally detectable and not irreversibly spread out into the environment by decoherence, mechanistic explanations (and mechanistic ontology) will still work so long as the specific entanglement correlations are irrelevant to the behavior of the system we want to explain" (2014). The issue here is that this kind of situation, on the quantum level of examination, occurs precisely never: what is done to one particle in a system immediately has repercussions on the states of any other particles in the entangled system. Lastly addressing (3), Kuhlmann and Glennan maintain hopefully that "The…fundamental mode of organization that matters in mechanisms is *causal dependence*, not spatial location… If it is indeed causal rather than spatiotemporal organization that matters for mechanisms, we should be able to offer a non-classical but mechanistic explanation of certain kinds of quantum phenomena" (Kuhlmann & Glennan, 2014). Yet as we might surmise from the problem of (1), mechanistic causality itself is called into question by the lack of location in quantum systems.

Behaviors of quantum systems are established as violating certain inequalities such as the Bell Inequalities and the Leggett Garg Inequalities. Yet, violation of the LG inequalities suggests that it may be impossible to explain certain quantum events as happening in a particular time ordering, as the violation may refute the assumption that "the outcome of a measurement on the system cannot be affected by what will or will not be measured on it later" (Emary, 2013). Bell inequality violation leads to the same kind of trouble; when reference frames are accounted for in Bell tests, physicists find that "not only are (quantum correlations between systems) independent of the distance, but it also seems impossible to cast them in any real time ordering…In this sense, quantum correlation is a basic (i.e. primary) concept, not a secondary concept reducible to that of causality between events: *Quantum correlations are directly caused by the quantum state in such a way that one event cannot be considered the 'cause' and the other the 'effect'".* (Stefanov, Gisin, Suarez, & Zbinden, 2002). While experiments rigorously testing quantum properties via inequalities did not manifest until the 1980s (e.g., the Aspect Experiment, 1982), the violation of causal assumptions by quantum systems has been well known since the 1920s. According to Werner Heisenberg, "the incorrectness of the law of causality is a definitively established consequence of quantum mechanics itself" (1972, p. 197). Niels Bohr (1928, qtd in Schilpp, 1949) argued that the quantum postulate entails "a renunciation as regards the causal space-time co-ordination of atomic processes."

So we see that (1) quantum in-determinancy is not irrelevant but of primary importance for explaining quantum systems, and likewise in (2) that quantum entanglement is of primary importance for such explanations, and (3) we find that causality cannot substitute for location in a New Mechanistic picture of quantum; just like our understanding of location, causality has to go.

Failing to account for quantum mechanics mechanistically, we may posit that quantum physics is just restricted the micro level, so maybe quantum physics isn't very useful towards understanding our world, anyway. Some critics suspect that quantum physics is just a mathematical theory and nothing more. This is not a strategy available for NME even if advocates sometimes say things along these lines. Failing to account for the accuracy and primacy of quantum physics leads to loss of practical knowledge of everyday events. The ubiquitous biological process of photosynthesis would be impossible without utilization of quantum effects (Romero, Augulis, Novoderezhkin, et al, 2014), suggesting that many biological mechanisms are underpinned by quantum processes. Without quantum effects, it is well understood that nuclear fusion in the sun and in contemporary nuclear reactors would not take place. Many of our everyday artifacts utilized today (such as the lasers used to read CDs) must take quantum principles into account in their design or the mechanical function of the device is lost. Quantum tunneling—a quantum particle's ability to propagate through a barrier, simply by chance, and arrive at the other side without actually travel through the barrier—makes transistor radios, solid state stereo systems, flash memory, MRI, and the scanning tunneling microscope possible.

One might ask, is it possible to describe quantum tunneling mechanistically? Quantum tunneling has no obvious mechanical cause—the energy it would take to traverse the barrier is higher than the particle's kinetic energy and thus traversing the barrier should be "impossible" for a classical machine to plow through. Instead, the particle simply has a certain probability of phasing through the barrier because some of the probabilities in its "probability wave" occupy the other side of the boundary. The wave function which determines the probability of passing across the boundary has no moving parts or physical location in space – it is simply a mathematical tool for predicting where the particle *might* by chance turn up at any particular point in time. While a higher barrier has a lower chance of being propagated through than a lower barrier, the particle has some small chance of propagating through *any* barrier placed. There is no easy way to describe this fundamentally random event as a "mechanism", particularly when no "real, local" objects are precipitating the behavior; whether or not the electron performs a "tunnel" event is merely a matter of chance.

Yet, as noted, quantum particles such as electrons may perform tunneling events as part of the makeup of a machine. For example, in quantum transistors such as tunnel field-effect transistors, a switch is activated by electrons which tunnel across a barrier. The switch could not be controlled, let alone invented, without understanding the electron's ability to tunnel. Analogously to Glennan's fields, such quantum systems can be *part* of a mechanism even though the *mechanism* does not explain the behavior of the electrons. While the barriers in the mechanism interact with the electrons, the barriers do not determine the makeup of the electron or explain its probabilistic behavior. Analogously to Glennan's coverage of fields, the quantum system can be a *part* of a mechanism, but the *mechanism* cannot explain the *quantum.* Here NME approaches a dead end: we must know about fields, or about quantum mechanics, to explain the *mechanism,* but the *mechanism* cannot be used to explain the components of the field or quantum object. Without knowledge of quantum properties, we cannot make many contemporary electronic devices work, since the mechanisms of those devices depend on quantum events which defy classical understanding of real objects following real trajectories through space.

Exclusive Reliance on Mechanism Leads to Lost Explanatory Power, Lost Scientific Content, and Lost Applications

We have now examined a number of situations in physics which are unexplainable without stepping outside of the NME picture of scientific explanation. This suggests that explanatory power and informative scientific content are lost when we choose to rely exclusively on NME. In the case of electromagnetic fields, we lose explanatory power if we rely on mechanism (a local object/part based concept) to explain fields (a non-localized, non-object/part like concept). We lose scientific content enabling prediction of physical behavior if we rely exclusively on mechanistic explanations—we cannot find the event horizon of a black hole or correctly predict behavior in a laser or transistor without taking into account the mathematical properties of fields or quantum effects. Finally, when we rely exclusively on mechanisms for our scientific explanations, we lose applicability in engineering situations such as quantum tunneling in transistors and the scanning tunneling microscope, quantum photonic effects in the laser, and gravitational field effects in aerospace technologies such as gravitational sling shots. Without information from mathematical models, engineering suffers and our understanding of the behavior of systems suffers.

New Mechanist claims equating either (a) mechanism with explanation or (b) science with a search for mechanisms must be incorrect. Various mechanist models actually rely on deeper explanatory powers such as field theories. We can help explain the mechanism of a refrigerator magnet utilizing magnetic fields, but we cannot reduce magnetic fields to mechanisms or explain magnetic fields as mechanisms. While Bechtel and Bollhagen (2021) are optimistic that it might be possible to expand NME to accommodate for mathematical models, this seems unnecessary and most likely (given the non mechanist, mathematical nature of "constraint" and "energetics") futile. Mechanism relies on physics, but physics at its field-theoretic foundations does not rely on mechanism. This limit on NME must be recognized in order for future work in modeling of scientific explanation to commence.

Furthermore, certain structural situations such as the statics example in classical mechanics as well as structures with changing parts, changing organizations of parts, or non-distinct parts violate the assumptions of NME.

Conclusion: The Scope of NME is Limited

In this paper, I have presented multiple areas of physical science that NME fails to explain. Rather than suggesting ala Bechtel and Bollhagen (2021), Levy (2016) or Kuhlmann and Glennan (2014) that NME must grow or change to accommodate these factors, it seems more practical to see these areas of failure as limits on NME itself. 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.

NME successfully describes many macro level situations open to human intervention and engineering, most specifically those involving distinguished indexed objects interacting at trackable locations in a specific local spatial reference frame, in order to complete a process of causal behaviors in time to produce a phenomenon, that most ideally could be intervened upon and manipulated by an engineer so as to change those behaviors and thus the resulting phenomenon. However, NME does not establish autonomy of biological sciences apart from physics as previously hoped, and NME does not successfully supersede physics as a source of explanation. In fact, many if not most NM explanations bottom out in physical "constraints and energetics" best explained to date by the physics predicting the behaviors of those structures.

In the future work, I will compare NME as applied to physics with other leading models of scientific explanation, such as the Deductive-Nomological (DN) model and Statistical Relevance (SR) model. With NME properly treated as a model for only a subset of scientific explanations, it remains to be explored (1) whether a general model of scientific explanation is possible or desirable; (2) what kind of theory of scientific explanation would best approach a general model compatible with both physics and biology; (3) if a general theory of scientific explanation is not possible, whether there is a method with which to decide what theory of explanation should be prioritized when in what situation of scientific inquiry; (4) whether multiple theories of explanation compete or are ultimately compatible or reconcilable, and (5) whether explanations in engineering applications situations and explanations in foundational scientific situations do or do not differ. In future work, I will address these questions in detail.

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