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Explanations of and in Worlds

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Abstract: Our scientific explanations should have a character which matches their subject-matter: if a fact is not apt for causal explanation, we should not try to explain it causally. In this chapter, I first review some cases where causal explanation has been extended beyond its proper limits, identifying a pattern of error which I call the *problem of causal overreach*. I then relate these considerations to the debate over causal locality in Everettian (many-worlds) quantum theory (EQM), in the context of three metaphysical distinctions which are central to recent discussions of locality: event causation vs. worldshaping causation, local branching vs. global branching, and overlapping worlds vs. diverging worlds. I argue that worlds in EQM are not properly regarded as themselves subject to causal explanation: Everettians should instead regard causation as a wholly in-world matter. This approach avoids any non-local causal explanation; quantum entanglement instead supports a new category of non-causal worldshaping explanations. I conclude by considering the implications of worldbound causation for principles of causal inference, in particular for the Causal Markov condition; I recommend the use of quantum causal models as a foundation for in-world causal inference.

1. Introduction

Not every element of reality is apt for causal explanation. Our explanations of the world should have a character which matches their subject-matter: if a fact is not apt for causal explanation, we should not try to explain it causally. Perhaps we should try to explain such facts in some other way – metaphysically or mathematically, for instance – or perhaps we should regard them as not being proper subjects for any kind of explanation at all. Either way, pressing the demand for causal explanations in these cases seems at best fruitless. But causal explanation is extremely natural, and the habit of causal reasoning is hard to shake, so the demand frequently resurfaces. This generates what I will be calling the *problem of causal over-reach*, in which causal explanations are attributed in cases where the underlying structure of reality supports only non-causal explanations.

In the foundations of quantum theory, the locality – or non-locality – of causal explanations is the focus of a long-standing debate. Only part of what is at stake in interpretive discussions is *what explains what*; a further part of what is at stake is *which of these explanations are causal.* There is an extensive literature on whether quantum mechanics (QM) – either generically, or in specific formulations such as Everettian Quantum Mechanics (EQM), requires us to recognise causal explanations in which the cause and the effect are located at spacelike separation – that is, at spacetime locations which lie outside each other's light-cones. While the broad idea of causal locality and the various technical notions of factorizability, parameter independence, and outcome independence which are associated with it are not generally seen as essential to an adequate interpretation of QM, they are generally seen as a significant desideratum. An interpretative picture which retains causal locality is regarded as, ceteris paribus, more plausible than one which does not. In this connection, the claim that EQM can secure causal locality has been the basis of various arguments in support of EQM (see e.g. Vaidman 1998, Brown & Timpson 2002) – as well as of various arguments in support of retrocausal approaches to QM (see e.g. Price and Wharton 2021).

My main aim in this paper is to argue that EQM indeed does not require any non-local causal explanation. However, my route to that conclusion differs from that of most other proponents of EQM, in the previous literature and in this volume. Bacciagaluppi (this volume), Blackshaw et al. (this volume) and Timpson & Wallace (this volume) regard branching as a local phenomenon, taking place at the edge of expanding light-cones of determinacy. I defend instead a view of branching as global, constituted by *divergence* of parallel worlds, and show how this picture sharply limits the scope of causal explanation. I argue that Everettians should regard causation as an intraworld rather than interworld phenomenon: branching is not itself a causal process, and all causal relations live inside individual Everett worlds. This wholly-in-world causality respects relativistic constraints.

Restricting causal relations to apply in-world only is a heterodox approach in the broader context of EQM. Historically, defenders of EQM have generally been ready to grant causal status to explanations which have what I will describe below as a *worldshaping* character. Worldshaping explanations include explanations in which features of some Everett world(s) at a later time are explained in terms of features of some Everett world(s) at an earlier time, as well as explanations in which the universal quantum state at a later time is explained in terms of that state at some earlier time. They also include more controversial cases in which events in one world may explain events in another (cf. Deutsch 1997). It has in fact frequently been seen as an innovative feature of EQM that it can give straightforward-seeming causal explanations of these kinds.

As we shall see in section 3, there is no consensus about the nature of worldshaping causation amongst proponents of EQM. What might appear to be small differences amongst the different ontological pictures for EQM lead to very different conclusions concerning the bounds of causal explanation. Sebens and Carroll (2018) and Wallace (2012) apparently come to opposite conclusions concerning worldshaping explanation, despite agreeing on much else. Those who use decoherence to solve the preferred basis problem tend to adopt a local view of branching (e.g. Wallace, Timpson) while those who see no key role for decoherence tend to adopt a global view (Deutsch, Vaidman).

I will argue that Everettians should abjure worldshaping causation. Regarding branching as a causal process misdescribes the character of the worldshaping processes in EQM, and encourages us to misattribute features of in-world causation to the inter-world setting where those features do not belong. In particular, world-level and universal-state-level explanatory connections do not stand in the appropriate connections to counterfactual conditionals, to objective probabilities, or to manipulability to qualify as causal. A diverging picture of EQM avoids any causal action at a distance by limiting causation to apply inside worlds only. In-world, the constitutive connections between causation and counterfactuals, probability, and manipulability can be sustained.

The plan is as follows. In section 2 I will identify a systematic pattern of metaphysical error which I call the *problem of causal over-reach*. Then in section 3, I will bring that problem to bear on the debate over locality in EQM, identifying three metaphysical distinctions: event causation vs. worldshaping causation, local branching vs global branching, and overlapping worlds vs. diverging worlds. I will argue in section 4 that in diverging EQM, causation is in-world and fully local, vindicating the argument from locality for EQM. However, a threat remains: the resulting causal explanations threaten to violate certain plausible principles of causal inference. In section 5 I discuss the options for restricting these principles and identify a class of non-local *common-ground* explanations in EQM over and above its local causal explanations. Section 6 is a conclusion.

2. The Problem of Causal Overreach

In this section, I review some cases where causal explanation has plausibly been extended beyond its proper limits. My starting point is the idea that our explanations of the world should have a character which matches their subject-matter: if a fact is not apt for causal explanation – if it is not the kind of fact which has a causal explanation – then we should not try to explain it causally. I understand this as an externalist norm: we may be unaware whether some fact is apt for causal explanation, hence unaware of whether we are violating the norm. My next claim is that this norm is regularly violated within philosophical theorising, generating a systematic pattern of error:

> **Problem of Causal Overreach**: The application of in-world causal-explanatory strategies which presuppose the existence of in-world physical structure to situations which lack that structure.

The problem of causal overreach arises when causal explanations are attributed in situations which have a structure that supports only non-causal explanations. Consider as initial examples causal explanations of mathematical truths – for example the idea that a divine designer might be causally responsible for arithmetical or geometrical facts – and causal explanations of cosmological initial conditions. Arithmetical truths, in particular, are widely regarded as not being the kind of thing which can be explained causally; but this has not stopped theorists from antiquity (e.g. Philo of Alexandria) through the modern period (e.g. Descartes) right up to the present day (e.g. Morris and Menzel 1986) from hypothesizing causes for them. I'll shortly discuss these and other candidate cases in a little more detail.

Why does the problem of causal overreach arise? A natural hypothesis is that our highly evolved (and highly effective) capacity for making judgments concerning causal explanation has a tendency to overextend itself. As embodied reasoners, we thrive on identifying the causal relationships afforded to us by our environment – and we don't always know when we ought to stop hypothesizing causes (or we can't help ourselves in doing so). Quite understandably, but sometimes erroneously, we humans see causation everywhere. I think a useful comparison is with the phenomenon of hypersensitive agency detection, as highlighted in a substantial body of work in cognitive psychology which is usually traced back to Heider and Simmel (1944). This literature documents a widespread and persistent tendency for people to falsely (or at least metaphorically) ascribe agency to objects (often in the context of describing animated scenes), despite knowing that those objects lack any genuine agency. I suggest that hypersensitive agency detection can be seen as an instance of an even broader tendency we have: to favour causal explanations of salient facts over non-causal forms of explanation, or over the hypothesis that there is no explanation.

Some of the examples I will discuss have a speculative metaphysical character. This presents no obstacle to the use I wish to make of them, which is to illustrate (by analogy) a mistake which I think is also made in serious philosophy of physics. Accordingly, for the sake of these examples we can set aside whether their framing hypotheses such as platonism and fundamental indeterminism are correct. The aim is to learn lessons relevant to actual physics.

My first example is the tendency to think causally within mathematics and logic. There is a long philosophical tradition of supposing that mathematical and logical truths are caused by an act of will of a divine designer. This creationist approach to mathematical truths is fairly clearly found in Descartes, for whom God's creative activity is contingent; Leibniz offers a more nuanced version of the strategy, according to which God's creative activity necessarily occurs as a result of God's own nature.

Setting aside the modal status of the relevant causal activity, these mathematical creationist views are rare today; Leftow (2012) for example prefers the idea that mathematical truths are ontologically dependent on God without being caused (contingently or noncontingently) by God. And the unpopularity of creationist views is understandable. It is hard to make sense of any kind of causal activity capable of creating logical or mathematical truths which is not itself bound by the logical/mathematical constraints that its supposed creations would impose.

My second example is the tendency to think that quantities not determined physically must instead be determined by some cosmic lottery. There are two prominent instances of this tendency in the metaphysics of physics – one concerns initial conditions for the universe, the other concerns outcomes of indeterministic processes.

Take first cosmological initial conditions, and consider debates over their apparent fine-tuning (see e.g. Friederich 2021). Proponents of design arguments for theological conclusions are prone to comparing two hypotheses: the hypothesis that a divine designer set the values of the constants, and an alternative hypothesis that they took some alternative value 'by chance'. The immediate problem, of course, is that there is no known or even hypothesised chance process the operation of which led to the value of those initial conditions. There is therefore no chance-constrained way to put a measure of probability over the possible values according to the no-design hypothesis. To accept that the initial conditions came to be by chance is to play into the hands of the fine-tuning argument; opponents of design should not grant that assumption (cf. Colyvan et al. 2005).

I submit that the tendency to attribute initial conditions to chance is another instance of the problem of causal over-reach. To think that the initial conditions of the cosmos are a matter of chance is to think of them as caused by some chancy process. And this is a very natural-feeling assumption – if not as an effect of some chancy process, where could the initial values have come from? Nevertheless, it should be resisted – the salient hypothesis is that some values are *initial* conditions, and therefore there is ex hypothesi nothing from which they came. Since there is no cosmic lottery which settles the initial conditions, there is no physical structure out there to constrain rational credences concerning those initial conditions. This point makes compelling design arguments based on fine-tuning evidence much more difficult to construct.

A different instance of the tendency to try to causally explain the causally inexplicable concerns the outcomes of indeterministic processes. Sometimes deterministic underpinnings are offered for indeterministic processes, rendering their indeterminism only apparent. But in cases where we are dealing with a genuinely indeterministic process, there is nevertheless a persistent inclination to ask why the process eventuated in one outcome than another. Consider a radioactively-unstable isotope with a half-life of 87.7 years. A specific atom of the isotope is created, and decays after 45 years. Why did it decay then – not sooner and not later? It is part of the hypothesis of indeterminism that there is no answer to this question. But it is hard to rein in the feeling that there *must* be a causal explanation – and I suspect that over the course of the development of quantum theory, this thought has been a motivation for at least some defenders of hidden variable theories. To that extent, those theorists fall victim to the problem of causal overreach.

In this section so far I have surveyed some important broad types of cases of causal overreach. I now want to turn to one specific case of causal overreach, concerning a particular metaphysical theory: David Lewis's *modal realism* (Lewis 1986). Modal realism is a reductive theory of modality, which accounts for modality in terms of genuinely existing possible individuals – chief amongst them possible worlds. Worlds are understood by modal realists as networks of spatio-temporally-related individuals. These worlds are mereologically disjoint; their spacetimes are imagined to have a variety of different sizes and shapes, but they are all spatiotemporally isolated from one another.

In this setting of isolated possible worlds, Lewis looks to locate the phenomenon of causation. Per his doctrine of Humean Supervenience, he analyses causation in terms of counterfactuals, which in turn he analyses in terms of a notion of law of nature which sees laws as efficient summaries of matters of fact within a world. It follows immediately from this patchwork of analyses that causation is a wholly in-world matter. Laws summarise events within a given world; those laws give rise to counterfactual dependencies only between pairs of events which are wholly within the same possible world; only pairs of events related by suitable counterfactual dependencies are causally related. It would accordingly be a misinterpretation of Lewis to attribute to him any causal explanations of why the Lewisian plurality of worlds is as it is – indeed, it would be a misinterpretation to even take those questions seriously in the context of modal realism. Setting aside questions of Lewis interpretation, it would also be hopeless to try to object to modal realism itself on the ground that the ontology of worlds it requires lacks any causal explanation. It is part and parcel of the theory that its theoretical elements are not within the proper scope of causal-explanatory reasoning (Lewis 1986, p.78-80). To continue to push demands for causal explanation in the context of this theory would be an instance of problem of causal overreach.

This brings us at last to Everettian quantum mechanics. In this setting, it is not so clear that causal explanations of features of quantum worlds, or quantum multiverses, are unreasonable; we are dealing with physics rather than metaphysics, and – as we shall see – various elaborations of EQM are replete with causal language. Nevertheless, I will argue in the remainder of the paper that Everettians can and should take the same general approach as Lewisian modal realists to causal explanation: that is, they should restrict causation to apply in-world only. Attempts to give causal explanations of features of quantum worlds – in particular, to give a causal reading of a world-splitting process – may amount to further instances of causal over-reach.

3. Causal Explanation in Everettian Quantum Mechanics

In this section I will draw three metaphysical distinctions which I think help to articulate the range of possible positions concerning locality in EQM. Authors in this volume disagree on the status of branching within EQM (is branching a causal process?), on the topology of this branching (is it local or global?), and on its mereology (do we have overlapping worlds or parallel worlds?) Different combinations of stances with respect to these distinctions generate a varied menu of resultant views concerning causal locality in EQM.

3.1 Event Causation and Worldshaping Causation

We can begin by distinguishing locality of event causation from locality of worldshaping causation. While to my knowledge this distinction has not been explicitly drawn elsewhere, I think it helps to articulate a number of recent debates concerning local causality in EQM.

The distinction between event causation and worldshaping causation is primarily a matter of the nature of the causal relata. In event causation, a localized event explains another localized event – with the problematic cases being those which hold between events at spacelike separation. In worldshaping causation, by contrast, a localized event explains a global change.

A canonical example of event causation would be injecting a silver atom into a Stern-Gerlach device causing the atom to be deflected either up or down. Here we have an experimental intervention – the cause – and a clear, measurable, effect – the deflection. There are of course more controversial and more complex candidate examples, including those particularly at issue in the debate over locality in EQM, e.g. the prospect that an observer Alice making a measurement might explain another observer Bob getting some outcome at spacelike separation. But the basic structure of event causation is no different in quantum physics from in classical physics.

In worldshaping causation, a relatively ordinary and unassuming event, such as Alice measuring the spin of a particle, leads to an extraordinary change: a collapse of the wavefunction, a change to the global Bohmian guidance field, or – most saliently for present purposes – a splitting of the universe into multiple branches. This kind of change is, on the face of it, of a very different kind from anything described by classical physics. It is frequently the source of intuitive resistance when students encounter EQM for the first time – how could something as innocent, as commonplace, as a spin measurement possibly split the entire universe? Sophisticated Everettians are typically unmoved by the intuitive weirdness of worldshaping causation. But it has been a distinctive source of disquiet in the context of the debate over locality. In particular, it has been objected that EQM is causally non-local in the worldshaping sense (McQueen & Waegell, this volume).

Worldshaping causation takes different forms in different versions of EQM, as we shall see below. But the basic problem is simple: *branching splits the whole universe, so actions which trigger branching have non-local effects on the universe.* This line of thought leads Sebens and Carroll (2018) to reject the claim that EQM is causally local. To illustrate the problem, take an EPR-style case where observers measure entangled particles at spacelike separation. A straightforward Everettian reading of this case from has it that when one observer measures their particle, they split the entire universe – including the other observer. When Alice makes a measurement, she splits into two Alices. But it is very natural to think that there are exactly as many Alices as Bobs. So, when Alice makes a measurement, Bob splits into two Bobs. And since the entangled particles, as is familiar from decades of discussion of non-locality, may be at spacelike separation, the worldshaping causation which ensues from a measurement appears to be nonlocal. Indeed, in causing a global change, it appears to be as nonlocal as it could possibly be.

Straightforward though Sebens and Carroll's argument is, it puts pressure on the widespread presumption that EQM is causally local. Strategies in response have differed. Some Everettians reject global branching, as we shall see in the next subsection. But other Everettians accept global branching and argue that worldshaping causation in EQM is in fact causally local even in the context of global branching (McQueen & Vaidman 2019, Ney forthcoming, Ney this volume).

McQueen and Vaidman accept the premise of global branching. But they deny that global branching caused by Alice leads to intrinsic change in Bob. How is this combination of views coherent? The esoteric metaphysical idea of multilocation comes to the rescue. According to the McQueen/Vaidman proposal, when Alice makes a measurement, she splits into two Alices (seeing distinct measurement outcomes – Alice_{up} and $\text{Alice}_{\text{down}}$. Bob is not intrinsically affected: there remains one Bob. But Bob is extrinsically affected: he is now multilocated. Bob is in branch W_{up} with Alice_{up} *and* in branch W_{down} with $\text{Alice}_{\text{down}}$. If causal locality means that intrinsic change is never caused at spacelike separation, then locality is preserved by the McQueen/Vaidman proposal. But *is* that all that causal locality means, once the possibility of multilocation enters the frame?

Alyssa Ney (forthcoming) considers a natural objection to the McQueen/Vaidman solution: becoming multilocated is still a physically real change for Bob. I tend to agree with this objection, even though Ney rejects it. There is a real physical difference for Bob between being monolocated in a single world vs. being bilocated in two worlds, just as there would be a real physical difference for Bob between being monolocated vs. bilocated within a single world. (Consider: you suddenly acquiring a second location within the actual world would be a startling and surprising physical change which would be of significance to you, even if it is not an intrinsic change.) If that is right, McQueen and Vaidman do not avoid the most relevant kind of non-local worldshaping after all.

Much more could be said here. But I want to set this particular dispute aside and focus on an alternative response to the threat from non-local worldshaping causation. Carroll & Sebens' objection and McQueen and Vaidman's response both presuppose a *global* conception of Everettian branching as opposed to a *local* conception. This distinction is the focus of the next subsection.

3.2 Local vs Global Branching

As we have seen, global branching generates a problem through its apparent commitment to a non-local form of worldshaping causation. So, if we can avoid global branching, then we have a chance of sustaining the claim that EQM is causally local.

A prominent defence of local branching in EQM is found in the work of Chris Timpson and David Wallace (e.g. Timpson and Wallace this volume), Bacciagaluppi (this volume) and Blackshaw et al. (this volume). According to the local branching approach, branching is a dynamical process which is relativistically constrained in the usual way. It is constituted by decoherence, which in turn is a result of local force-mediated dynamical interactions (most relevantly for the usual examples, electromagnetic interactions). Decoherence then propagates outwards at (or nearly at) the speed of light, riding on the coat-tails of these interactions.

The local branching approach tells a compelling story about how quantum correlations between results of measurement on entangled systems at spacelike separation are to be explained. On the local branching picture, there simply is no joint outcome of these measurements until their forward light-cones intersect. Consequently, relative to the non-intersecting parts of the forward light-cones, there is no complete and determinate world incorporating both measurement outcomes. Instead we obtain 'mini-worlds', within which determinacy of outcomes extends up to the decoherence horizon but no further. There are never any spacelike-separated correlations to explain, and *a fortiori* there is never any need for non-local causal explanations of spacelike-separated correlations.

There is much to like about the local branching picture. However, Alyssa Ney (this volume) argues that the local branching approach is the wrong choice for Everettians. Ney's primary reason for doubt about local branching is that it clashes with a core idea of decoherence-based EQM: the 'functionalist' definition of Everett worlds as maximal effectively-causally-isolated patterns in the universal state. The mini-worlds of the local branching conception do not meet this criterion: they are not causally isolated, since they can and will grow to intersect other mini-worlds, at which point they will become determinate with respect to a steadily wider range of quantities. Nor are they world-like in the sense of being complete qualitative possibilities, since they are limited in spatial extent.

By itself, I don't find this objection compelling. Although the local branching picture does involve modifying the letter of some accounts of the ontology of emergent worlds in decoherence-based EQM – including in Wallace's "Everett and Structure" and some parts of his 2012 book – I don't see that it involves sacrificing any of the spirit of the original decoherence-based accounts. The mini-worlds which take centre stage in the local branching account are world-like at least to the extent that they are effectively causally isolated from other mini-worlds from which they have already branched; so there is clear continuity between them and the global worlds usually associated with the functionalist account of Everett worlds. And in any case, local branching theorists can still employ a more global notion of world, associated with the contents of the backwards light cone of any point. This would seem to give them all they worlds they need.

Though I don't take this brief discussion to be remotely decisive, local branching looks to me to have good prospects of evading Ney's objection from the functionalist definition of worlds. However, in addition to this primary objection, Ney adduces three further reasons for scepticism about the local branching picture. One of these further reasons[1] is in the vicinity of the objection from the functionalist definition of worlds, and – although Ney doesn't regard it as decisive – I think that it does actually present a more significant problem for local branching.

Ney notes that local branching is in potential tension with uses of self-locating probability to address the probability problem in EQM. These accounts of probability rely on self-locating contents, such that the probability of outcome X is identifiable with the squared amplitude associated with myself being in a world in which outcome X occurs. If worlds are mini-worlds, then most future-directed probabilities will lack subject-matters: the mini-world includes neither outcome X nor its alternative outcome Y, so I am determinately not in an X-world and determinately not in a Y-world. I explore this type of problem at length in Wilson (2011, 2013).

Some self-locating accounts of Everettian probability (e.g. Vaidman 1998) are unaffected by this concern, since they only consider backwards-looking probabilities: those which attach to events which are already in my past light cone but which are unknown to me. However, several more ambitious approaches to Everettian probability aim also at capturing forwards-looking objective probabilities. These more ambitious approaches include, for example: Saunders (2010), Wilson (2011, 2020), Sebens & Carroll (2018), Wilhelm (2022). But forward-looking objective probabilities are hard to sustain in the local branching picture: before the expanding decoherence horizon from Alice's experiment has reached Bob, there are no global possibilities with different outcomes for Bob's measurement, and so there is nothing for Alice to self-locate herself within.

From my point of view, this problem for local branching is the most compelling. If our metaphysics of branching fails to secure a coherent general account of probabilistic reasoning, then it is a non-starter as an interpretation of quantum theory. Probabilistic considerations of this kind are the basis on which I have previously endorsed global branching, as part of a broader defence of *diverging* EQM – an approach to which I now turn. Countenancing the possibility of a diverging structure of parallel worlds opens up new routes to the preservation of causal locality in EQM.

[1] The other two arguments are as follows. First, Ney argues that it is not required to support claims to causal locality and underwrite the argument for locality for EQM; she offers instead a picture of global branching which is still grounded in local decoherence-generating interactions. Secondly, Ney notes that local branching relies on decoherence, even though some Everettians (e.g. Deutsch, Vaidman) deny that decoherence has any substantive role to play in explicating EQM.

3.3 Overlap vs Divergence

The Everettian treatments of branching reviewed up to this point have shared a presupposition concerning the mereological structure of Everett worlds: worlds overlap, in the sense that they share parts – have segments in common – prior to branching. This reflects the widely-used 'splitting worlds' metaphor for EQM. But an alternative mereological picture is available. According to this alternative, Everett worlds diverge; distinct worlds have no segments in common at any time. This pairs instead with the 'parallel worlds' metaphor.

Divergence has been promoted on various grounds as an interpretive strategy for Everettians – by me (2011, 2012, 2013, 2020), by Saunders (2010), and by Wilhelm (2022). Divergence provides a clear semantics for future-directed discourse (Saunders 2010; Wilson 2011, 2012). It thereby resolves the problem of future-directed probabilities (Wilson 2013, 2020; Wilhelm 2022). It avoids Doomsday-argument-style epistemological objections to EQM based on counting observer-stages (Wilson 2017, 2020). In the present context we can canvass another potential benefit. Does divergence resolve problems associated with locality in worldshaping causal explanation in EQM? My answer may come as no surprise: yes, it does.

The problem with worldshaping causation was that measurements have non-local effects in virtue of splitting the world. In making a measurement, Alice increases the number of distinct Alices. In order to preserve a 1-1 correlation between Alices and Bobs, it seems the number of Bobs needs to increase too. Under divergence, this mismatch problem does not arise in the first place: the number of Alices and Bobs in general remains constant through measurements.

Where does this leave us? Local branching avoids nonlocal causal explanations, but it cannot handle ascriptions of the full range of forward-directed probabilities (Wilson 2011). Global branching without divergence does not avoid nonlocal causal explanations (Sebens and Carroll 2018). Divergence does better than either package: it avoids non-local causal explanations while also handling future-directed probability in full generality. On divergence, but not on the local-branching-with-overlap approach, we can for example make sense of wondering whether there will be a meteor strike on Earth after our own demise but within the lifespan of our grandchildren.

Though brief, I hope this discussion has served to motivate divergence as a promising approach to the question of local causal explanation in EQM. In the next section, I aim to fill out the positive proposal by showing how the diverging picture combines causal explanations with non-causal explanations, reconciling global branching with causal locality.

4. Worldbound Causation and Transworld Grounding

Under divergence, quantum systems do not split at all, so there is no need for any causal mechanism for splitting of worlds – whether global or local. Although there are branches, there is no branching in any literal sense – no case where a single thing multiplies into two things – there is only qualitative divergence, where two distinct things which matched up to some time cease to match after that time. In short, divergence yields no worldshaping causation whatsoever.

Divergence is part of the family of decoherence-based approaches to EQM. Accordingly, and in line with the functionalist account of worlds discussed in the previous section, there is no event causation between events in different diverging worlds: decoherence suppresses to negligible levels the physical interactions which could sustain causation. However, nothing in the divergence picture is inherently hostile to event causation per se: we can (and, if EQM is correct, we constantly do) give causal explanations of the event-causation kind between events within individual quantum worlds. As a result, divergence fits with a view of causation as an invariably in-world matter: necessarily, if A causes B, then A and B are events in the same Everett world.

Counterfactual dependence, objective probabilities and dispositional notions such a manipulability are all in-world matters from the divergence perspective. I make this argument in extended form in my book *The Nature of Contingency* (Wilson 2020). For present purposes, the essential idea is that these notions are constitutively linked to physical contingency, and physical contingency should be understood within EQM in terms of variations across worlds. Everett worlds, as part of the reductive base for physical contingency, are not themselves subject to physical contingency. Here it may be helpful to compare the situation with the block-universe view of change: instants of time, as part of the reductive base for change, are not themselves subject to change (Smart 1964).

In contemporary philosophy of science, the notions of counterfactual dependence, objective probabilities, and manipulability are frequently linked to causation in some constitutive manner: suitable patterns of these notions are, at the very least, diagnostic of causal connections (see e.g. Woodward 2003, Strevens 2008). Accordingly, the applicability of these notions within (but only within) Everett worlds supports the idea that events within (but only within) Everett worlds can causally explain and be causally explained. Universal-state-level and set-of-worlds-level explanatory connections do not stand in the appropriate connections to counterfactual conditionals, to objective probabilities, or to manipulability to qualify as causal.

Once we identify causation as in-world only, there is no longer any direct conflict between EQM and causal locality. The causal relations between events should instead be regarded as grounded in non-causal patterns at the level of the underlying space of worlds, and the underlying quantum state. But how does that go? Why does the space of Everett worlds have the structure it does? The answer to this question, I suggest, can be factored into three parts.

1. The unitary quantum evolution generates a complex, structured, physical system – for concreteness, call it this object the *universal quantum state*.
2. The universal quantum state grounds (Wilson 2022) or instantiates (Wallace 2012) a pattern of decoherent worlds.
3. Patterns holding across the space of decoherent worlds thus have a *common ground* in features of the universal wavefunction (Ismael and Schaffer 2020).

The first step can be compared to printing a photo, and the second step to cutting it into interlocking jigsaw pieces. At the third step, explanations of why individual worlds have the features they do can be analogized to explanation of why individual jigsaw pieces have the patterns they do. We can predict a piece's shape from shapes of nearby pieces. But ultimately, this is parasitic on a deeper explanation. Explaining the shape of an individual jigsaw piece requires saying how the picture was printed, and how the pattern was cut. The analogy is of course not perfect, since printing and cutting are causal processes; but the basic explanatory structure of the causal jigsaw case carries over to the case of diverging EQM.

The particular character of the non-causal explanations of worlds approapriate in the diverging setting will depend on further details of the fundamental-level ontology, and of the dynamics that is matched with that ontology. Within the broad church of EQM, we encounter several different candidate ontologies: e.g. wavefunction realism, spacetime state realism, mass density views. These have different implications for the metaphysical dependence structure which underlies the existence of a set of emergent Everett worlds: in effect, Everett worlds emerge differently according to the different ontological proposals. But since all causal relations are wholly inside those worlds, these different modes of emergence make no difference to the causal structures which they instantiate.[2]

However exactly these non-causal explanations are developed within a diverging picture, the general upshot is the same. Causation is an emergent, non-fundamental phenomenon about which Everettians are in a position to give a variety of different theories. EQM provides rich resources for

[2] For additional discussion of how worlds emerge in diverging EQM, see Wilson (2022).

this theorizing, in terms of the set of Everett worlds and the squared-amplitude measure over them. One attractive possibility for modelling in-world causation is a sophisticated probabilistic theory of causation (see e.g. Glynn 2011), analysing causation in terms of chance-raising where the chances are the quantum squared amplitudes. Another possibility is to draw on the contemporary interventionist implementation of the tradition of counterfactual theories of causation (see e.g. Woodward 2003), an approach which would analyse the notion using Everett worlds as the space of counterfactual alternatives. I discuss the different options for Everettian analyses of in-world causation in a little more detail elsewhere (Wilson 2020, p.58-60). But we don't need to choose between them here. It suffices for present purposes that causal relations are wholly in-world; we can set aside the question of exactly which in-world structure they should be identified with.

5. In-World Violations of Causal Principles?

One cloud remains on the horizon. Although I have argued that diverging EQM can avoid worldshaping causation in a principled manner, by limiting causation to (relativistically acceptable) worldbound event-event links, the resulting in-world causal structures are significantly sparser than the causal structures posited by many interpretive approaches. This raises the so-called 'causal problem of entanglement' for the view: some patterns of correlations are left causally unexplained.

Näger (2019) gives a self-contained presentation of the causal problem of entanglement. It arises because our standard principles of causal inference, when applied to EPR-style scenarios in which Bell correlations are observed, deliver the verdict that those correlations reflect a causal relationship. In particular, it seems that causal structures within individual Everett worlds violate the causal Markov condition (CMC), a backbone of contemporary causal modelling:

> **CMC**: a variable is independent of all variables which are not its effects, once we conditionalize on its direct causes.

I suggest Everettians should embrace failure of the CMC in a quantum setting, and seek to explain away any sense of impropriety. There is in fact a tradition of regarding the rejection of CMC in quantum theory as a methodologically virtuous instance of naturalized metaphysics: perhaps quantum physics, on the best available interpretation, simply teaches us that CMC is false. This line of thought has been traced by Cartwright (1999) and by Glymour (2006); Glymour in fact suggests that the real puzzle is instead why CMC systematically holds in application to ordinary classical macroscopic settings.

I suggest that friends of diverging EQM who want to preserve causal locality should endorse the Cartwright-Glymour approach of rejecting CMC in quantum settings. This does not mean giving up on the project of systematizing causal inference: the in-world causal explanations encompassed by the divergence metaphysics can instead be captured by the framework of *quantum causal models*. Influential recent proposals for systems of quantum causal models include Allen et al. (2017) and Shrapnel (2019). These approaches introduce a quantum analogue of the CMC, and show that it is respected in Bell experiments even where the classical CMC is violated. The standard CMC is recovered in cases where effects due to quantum entanglement can be neglected.[3]

The final ingredient in the overall explanatory picture I envisage would then be an account of why CMC fails in the quantum setting: that is, of why diverging worlds include correlations which cannot be explained causally. *Why* do we need to move from ordinary causal models to quantum causal models? I think that divergence-based Everettians are in a strong position to provide a schematic explanation of this sort. Causation is not fundamental, and the fundamental-level facts give rise to a pattern of in-world facts which are non-causally constrained by their integration into a larger structure – the Everettian multiverse. In such a setting, we should expect to see entangled systems displaying in-world correlations which have common-ground explanations but which lack any common cause explanation. It is precisely in cases of this sort that the CMC ceases to be applicable as a principle of causal inference. While this explanatory sketch remains to be filled out, I think it is a promising one.

6. Conclusion

My primary aims in this chapter have been to clarify the metaphysical choice-points facing Everettians with respect to causal locality, and to articulate a new account of local causal explanation in EQM which is built around a diverging metaphysics of worlds. From the discussions which have ensued, we can draw three conclusions for the contemporary debate over causal locality in EQM.

First conclusion: local branching, of the kind advocated by by Blackshaw et. al (this volume), Bacciagaluppi (this volume) and Timpson and Wallace (this volume), is not the only way to secure causal locality in EQM. Diverging EQM offers a well-motivated alternative strategy for eliminating non-local worldshaping causation and thereby for recovering causal locality. In the diverging setting, causal explanation bccomes a wholly in-world matter.

[3] See also Muthukrishnan (this volume) for an alternative approach to quantum causal models.

Second conclusion: diverging EQM does enable physical explanations to be given of Bell correlations, but these will be non-causal common ground explanations. A pattern at the level of the whole space of Everett worlds grounds patterns of correlations in individual Everett worlds. There are no causal explanations holding between individual events at spacelike separation.

Third conclusion: the argument from locality for EQM is partially vindicated, since diverging EQM provides a clear path to eliminating non-local causal explanation which is unavailable in the context of non-Everettian interpretations of quantum theory. The vindication is only partial, because locality comes at a cost: the CMC cannot be sustained in full generality. But the cost is affordable: quantum causal models provide a fully functional alternative to classical causal models.

The overall upshot of this chapter is that Everettians have available to them multiple viable metaphysical frameworks consistent with the preservation of causal locality. The choice between these frameworks must be made on independent grounds; that is work for another day.[4]

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References

Bacciagaluppi, G. (this volume). "The Relativity of Branching", in *Everett and Locality*, ed. A. Ney. New York: Oxford University Press.

Blackshaw, N., Huggett, N, & Ladyman, J. (this volume). "Everettian Branching in the World and of the World", in *Everett and Locality*, ed. A. Ney. New York: Oxford University Press.

Brown, H., & Timpson, C. (2002) "Entanglement and Relativity", in *Understanding Physical Knowledge* eds. R. Lupacchini & V. Fano. CLUEB.

Cartwright, N. (1999). *The Dappled World: A Study of the Boundaries of Science.* Cambridge: Cambridge University Press.

Colyvan M., Garfield, J,, and Priest, G. (2005). "Problems with the argument from fine-tuning", *Synthese* 145(39): 325–338.

Friederich, S. (2021). "Fine-Tuning", in *The Stanford Encyclopedia of Philosophy (Winter 2023 Edition)*, eds. E. Zalta & U. Nodelman.

Glymour, C. (2006). "Markov Properties and Quantum Experiments", in *Physical Theory and its Interpretation: Essays in Honour of Jeffrey Bub*, eds. W. Demopoulos & Itamar Pitowsky.

Glynn, L. (2011). "A Probabilistic Analysis of Causation", *The British Journal for the Philosophy of Science* 62(2): 343-392.

Heider, F., & Simmel, M. (1944). "An experimental study of apparent behavior", *The American Journal of Psychology* 57: 243–259.

Ismael, J., & Schaffer, J. (2020). "Quantum Holism: Nonseparability as Common Ground", *Synthese* 197 (10): 4131-4160.

Price, H. & Wharton, K. (2021). "Entanglement Swapping and Action at a Distance", *Foundations of Physics* 51: 105.

Leftow, B. (2012). *God and Necessity*. Oxford: Oxford University Press.

Lewis, D. (1986). *On the Plurality of Worlds*. Oxford: Blackwell.

McQueen, K., & Vaidman, L. (2019). "In defence of the self-location uncertainty account of probability in the many-worlds interpretation", *Studies in History and Philosophy of Modern Physics* 66: 14-23.

McQueen, K., & Waegell, M. (this volume). "Real Locality", in *Everett and Locality*, ed. A. Ney. New York: OUP.

Morris, T. & Menzel, C. (1986). "Absolute Creation", *American Philosophical Quarterly* 23(4): 353-362.

Muthukrishnan, S. (this volume). "Many Worlds as Anti-Conspiracy Theory: Locally and causally explaining a quantum world without finetuning", in *Everett and Locality*, ed. A. Ney. New York: OUP.

Näger, P. (2019). "The Causal Problem of Entanglement", *Synthese* 193(4): 1127-1155.

Ney, A. (forthcoming). "The argument from locality for many worlds quantum mechanics", *Journal of Philosophy*.

Ney, A. (this volume). "Branching Everywhere and All at Once", in *Everett and Locality*, ed. A. Ney. New York: OUP.

Saunders, S. (2010). "Probability in the Everett Interpretation", in *Many Worlds? Everett, Quantum Theory and Reality,* in eds. S. Saunders, J. Barrett, A. Kent & D. Wallace. Oxford: Oxford University Press.

Sebens, C., & Carroll, S. (2018). "Self-Locating Uncertainty and the Origin of Probability in Everettian Quantum Mechanics", *The British Journal for the Philosophy of Science*, 69(1): 25-74.

Shrapnel, S. (2019). "Discovering Quantum Causal Models", *The British Journal for the Philosophy of Science* 70(1): 1-25.

Smart, J. J. C. (1964). *Problems of Space and Time.* New York: Macmillan.

Strevens, M. (2008). *Depth: An Account of Scientific Explanation.* Cambridge: Harvard University Press.

Timpson, C., & Wallace, D. (this volume). "Locality in the Everett Interpretation: Ontology vs. Dynamics", in *Everett and Locality*, ed. A. Ney. New York: Oxford University Press.

Vaidman, L. (1998). "On schizophrenic experiences of the neutron or why we should believe in the many-worlds interpretation of quantum theory", *International Studies in the Philosophy of Science* 12(3): 245-261.

Wallace, D. (2012). *The Emergent Multiverse: Quantum Theory According to the Everett Interpretation.* Oxford: OUP.

Wilhelm, I. (2022). "Centering the Everett Interpretation", *Philosophical Quarterly* 72(4): 1019-1039.

Wilson, A, (2011). "Macroscopic Ontology in Everettian Quantum Mechanics", *Philosophical Quarterly* 61(243): 363–382.

Wilson, A. (2012). "Everettian Quantum Mechanics without Branching Time", *Synthese* 188(1): 67-84.

Wilson, A. (2013). "Objective Probability in Everettian Quantum Mechanics", *The British Journal for the Philosophy of Science* 64(4): 709-737.

Wilson, A. (2017). "The Quantum Doomsday Argument", *The British Journal for the Philosophy of Science* 68(2): 597-617.

Wilson, A. (2020). *The Nature of Contingency: Quantum Physics as Modal Realism.* Oxford: Oxford University Press.

Wilson, A. (2022). "Fundamentality and Levels in Everettian Quantum Mechanics", in V. Allori (ed.) *Quantum Mechanics and Fundamentality: Naturalizing Quantum Theory between Scientific Realism and Ontological Indeterminacy*. Springer.

Woodward, J. (2003). *Making Things Happen: A Theory of Causal Explanation.* Oxford: Oxford University Press.