Strong Determinism

Eddy Keming Chen*

March 5, 2022

> What I'm really interested in is whether God could have made the world in a different way; that is, whether the necessity of logical simplicity leaves any freedom at all.
>
> Albert Einstein, reported by Ernst Strauss

Abstract

A strongly deterministic theory of physics is one that permits with exactly one possible history of the universe. In the words of Penrose (1989), "it is not just a matter of the future being determined by the past; the *entire history of the universe is fixed*, according to some precise mathematical scheme, for all time." Such an extraordinary feature may appear unattainable in any realistic and simple theory of physics. In this paper, I propose a definition of strong determinism and contrast it with those of standard determinism and super-determinism. Next, I discuss its consequences for explanation, causation, prediction, fundamental properties, free will, and modality. Finally, I present the first example of a realistic, simple, and strongly deterministic physical theory—the Everettian Wentaculus. As a consequence of physical laws, the history of the Everettian multiverse could not have been different. If the Everettian Wentaculus is empirically equivalent to other quantum theories, we can never empirically find out whether or not our world is strongly deterministic. Even if strong determinism fails to be true, it is closer to the actual world than we have presumed, with implications for some of the central topics in philosophy and foundations of physics.

Keywords: determinism, super-determinism, laws of nature, causation, prediction, explanation, simplicity, Past Hypothesis, Wentaculus, Mentaculus, quantum foundations, arrow of time, empirical equivalence, limitation of knowledge, the consequence argument, free will, modal realism

*Department of Philosophy, University of California, San Diego, 9500 Gilman Dr, La Jolla, CA 92093-0119. Website: www.eddykemingchen.net. Email: eddykemingchen@ucsd.edu

Contents

1 Introduction

Determinism is a familiar notion that connects with some central topics in philosophy, such as free will, causation, and laws of nature. Super-determinism is not as familiar but much discussed in the foundations of physics literature. In contrast, strong determinism is less well known in both philosophy and foundations of physics.

In this paper, I focus on strong determinism. According to Penrose (1989), it is "not just a matter of the future being determined by the past; the *entire history of the universe is fixed*, according to some precise mathematical scheme, for all time" (emphasis original, p.432). While Penrose defines strong determinism in terms of *mathematical schemes*, I define it in terms of *fundamental laws*: a strongly deterministic theory of physics is one that, according to its fundamental laws, permits exactly one nomologically possible world; our world is strongly deterministic just in case it is the only nomologically possible world. Importantly, we expect fundamental laws to be simple, which explains why strong determinism is difficult to achieve. As Penrose points out, the idea expressed by Einstein and quoted in the epigraph may be strong determinism.[1]

As I explain, strong determinism goes beyond determinism and is distinct from super-determinism. It should be of interest to those who work in the intersection of philosophy and physics and may also be of general interest. If strong determinism is possible, it has significant consequences.

First, strong determinism can be regarded as a limiting case of determinism where the entire space of nomological possibilities is a singleton. A strongly deterministic theory enables the strongest kind of explanation provided by deterministic theories, as it eliminates all alternative nomological possibilities. If we discover that the actual laws are strongly deterministic, there is no longer any scientific question why our world is this way, beyond the question why the laws are what they are.[2] Because of the physical laws, the world has to be exactly as it is.

Second, strong determinism makes all counterfactuals (that are not counterlegals) vacuously true. On such a theory, then, according to counterfactual dependence theories of causation (or modified versions in the structural equations framework), we have the surprising result that every event in spacetime causes every other event. It raises vexing questions about the status of causal explanations in such a world.

Third, strong determinism enables the strongest kind of prediction; we can in principle deduce all the fundamental facts of the world from the fundamental laws alone, without any input from empirical observations (beyond those we need to confirm the laws). Still, strong prediction does not preclude meaningful notions of uncertainty (e.g. of self-location).

Finally, strong determinism has implications for current debates in metaphysics and philosophy of science. For example, it vindicates a nomic version of the Principle of Sufficient Reason (PSR), sheds new light on Lewis (1986)'s best-system account of laws, highlights the limits of Loewer (2020a)'s free-will compatibilism, and provides an improvement for Wilson (2020)'s quantum modal realism.

I start by defining strong determinism. Next, I discuss its consequences for explanation, causation, prediction, and current debates in metaphysics and philosophy of science. I provide two toy examples of strong determinism: the Lone-Particle World and the Mandelbrot World. They implement strong determinism by using constraint laws that determine a unique world. Is there a realistic example of strong determinism? I show that the Everettian Wentaculus is such an example. As far as I know, it is also the first. It implements strong determinism by using a

[1]This quote in the epigraph is from (Holton 1978, p.xii). However, given Einstein's interests in Spinoza's philosophy (Holton and Elkana 1982, p.309), it is conceivable that the quote is also related to *Ethics* 1P33 (translated by R. H. M. Elwes): "Things could not have been brought into being by God in any manner or in any order different from that which has in fact obtained." I thank Don Rutherford for pointing me to this passage in *Ethics*.

[2]Here I assume that in physics we try to discover fundamental laws and use them to scientifically explain the patterns in the world. Why the fundamental laws are what they is a metaphysical issue. On reformed Humeanism, they are what they are in virtue of the Humean mosaic. On minimal primitivism, they are primitive facts and have no deeper metaphysical explanations. See §2.

deterministic dynamical law and a simple law that specifies a unique initial state. The Everettian Wentaculus teaches us three lessons. First, a realistic example of strong determinism may not have all the features we naively expect of it. Second, under certain assumptions, it is empirically underdetermined whether our world is strongly deterministic. Finally, a strongly deterministic theory can be better in certain aspects than its deterministic counterpart. None of these proves that strong determinism is true, but they suggest that, at the very least, it is closer to the actual world than we have presumed.

By showing how it works in concrete physical theories and how it connects to important philosophical debates, I hope the readers will see that strong determinism is not a remote possibility that can safely be ignored but an important one that may well describe the world we live in, with consequences for a variety of topics in philosophy and foundations of physics.

2 Defining Strong Determinism

In this section, I explain what I take strong determinism to be and how it differs from standard determinism and super-determinism.

To begin, let us review the standard notion of determinism.[3] In his recent survey article, Hoefer (2016) provides the following (first-pass) characterization of determinism (emphases original):

Determinism$_0$ The *world* is *governed by* (or is *under the sway of*) determinism if and only if, given a specified *way things are at a time t*, the way things go *thereafter* is fixed as a matter of *natural law*.

Hoefer goes on to clarify the italicized phrases. As Hoefer notes, the word "thereafter" suggests that determinism in this sense is future-directed but not past-directed. Nevertheless, determinism can hold in worlds without a fundamental direction of time. For concreteness, I define the following:

- A possible world w: a four-dimensional spacetime and its material contents.
- The actual world α: the actual spacetime and its material contents.
- Material contents: material objects and their qualitative properties.[4]

[3]There are controversies about how to define determinism. Fortunately, we can set aside many of the nuances for the purpose of this discussion, which is to contrast determinism with strong determinism. See Earman (1986) for an informative survey. Some difficulties with defining determinism arise in general relativity, in boundary conditions at infinity, and in theories without a fundamental spatio-temporal structure. I do not get into such issues in this paper, but it should be clear that the definitions of strong determinism will be more robust than those of determinism, because the former only require a notion of the cardinality of models.

[4]Here I mean the *fundamental* material contents—the fundamental material objects and their fundamental properties. Examples include but are not limited to Newtonian point particles, their locations, masses, and charges; electromagnetic fields, their strengths, and directions; quantum states of the universe.

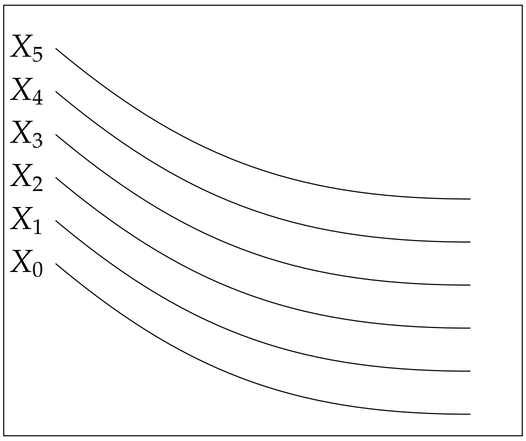

Figure 1: Schematic illustration of a deterministic theory T. Ω^T contains six nomologically possible worlds that do not cross in state space.

- Ω^T: the set of possible worlds that satisfy the fundamental laws[5] specified in theory T.
- Ω_α: the set of possible worlds that satisfy the actual fundamental laws of α, i.e. the set of all nomologically possible worlds.[6]

People who dislike possible worlds can replace them with mathematical models. I will return to the notion of fundamental laws at the end of this section.

Using the above notions and borrowing ideas from (Montague 1974, pp.319-321), (Lewis 1983, p.360), and (Earman 1986, pp.12-13), I define determinism as follows (also see Figure 1):

Determinism$_T$ Theory T is *deterministic* just in case, for any two $w, w' \in \Omega^T$, if w and w' agree at any time, they agree at all times.

Determinism$_\alpha$ The actual world α is *deterministic* just in case, for any two $w, w' \in \Omega_\alpha$, if w and w' agree at any time, they agree at all times.

Determinism is true just in case α is deterministic. My definitions correspond to what (Earman 1986, p.13) calls *Laplacian determinism*. The basic idea is that the nomologically possible worlds never cross in state space. By using four-dimensional spacetimes, such definitions are more suitable for relativistic contexts as well as worlds without a fundamental direction of time.[7]

Let us turn to strong determinism. I define it as follows (also see Figure 2):

[5]In this paper, I assume there are fundamental laws and they play important roles in scientific explanations. Fundamental laws correspond to the basic principles that govern (or optimally describe) the world. In theory T, its fundamental laws correspond to its axioms. Different choices of fundamental laws correspond to the axioms of different candidates for the final theory of physics or the Theory of Everything (TOE). The fundamental laws cannot be explained in terms of deeper principles (Weinberg 1992, p.18). From them we can derive theorems of great importance and explain all significant observable regularities. See also Chen and Goldstein (2021).

[6]Note that $\Omega_\alpha = \Omega^T$ only when T is the actual theory of the world, i.e. the axioms of T correspond

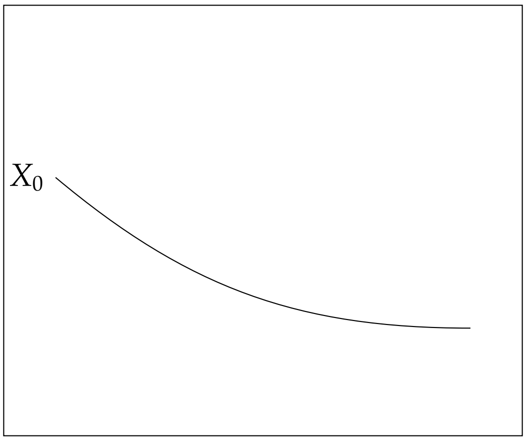

Figure 2: Schematic illustration of a strongly deterministic theory T. Ω^T contains exactly one nomologically possible world.

Strong Determinism$_T$ Theory T is strongly deterministic if $|\Omega^T| = 1$, i.e. its fundamental laws are compatible with exactly one possible world.

Strong Determinism$_\alpha$ The actual world α is strongly deterministic if $\Omega_\alpha = \{\alpha\}$.

Strong determinism is true just in case α is strongly deterministic. My notion of strong determinism corresponds to the idea that the entire history of the universe is fixed by the fundamental laws of nature alone.[8]

Under my definitions, strong determinism is stronger than determinism in a precise sense: strong determinism logically implies determinism but not vice versa.

Proof: (a) Suppose strong determinism is true. Then α is strongly deterministic, i.e. $\Omega_\alpha = \{\alpha\}$. Trivially, for any two $w, w' \in \Omega_\alpha$, if w and w' agree at any time, they

to the fundamental laws governing α.

[7]As with Penrose, we often talk about determinism in the sense of "the future being determined by the past," which is futuristic determinism. However, a (fundamental) direction of time is not essential for defining determinism. Nevertheless, we can recover the more familiar notion of determinism by choosing a direction of time:

Futuristic Determinism$_T$ Theory T is *futuristically deterministic* just in case, for any two $w, w' \in \Omega^T$, if w and w' agree at any time, they agree at all later times.

We can similarly define:

Historical Determinism$_T$ Theory T is *historically deterministic* just in case, for any two $w, w' \in \Omega^T$, if w and w' agree at any time, they agree at all earlier times.

Moreover, we can define what it means for futuristic determinism or historical determinism to be true. Given a direction of time, determinism is equivalent to the conjunction of futuristic determinism and historical determinism.

[8]See also (Chen 2021, p.120). Adlam (2021) has independently proposed a similar account of strong determinism, which she calls *strong holistic determinism*. Both accounts are inspired by (Penrose 1989). Adlam's goal is to generalize definitions of determinism and conceptions of laws of nature beyond the "time-evolution paradigm" (the paradigm of physical theories that employ differential equations with initial value formulations and explanations of future states in terms of past states and the dynamical laws). I am sympathetic to that goal. See also Chen and Goldstein (2021). In contrast, my main focus here is to develop the idea of strong determinism, discuss its consequences for philosophical theories, and analyze its concrete realization in a simple theory—the Everettian Wentaculus.

agree at all times. Therefore, determinism is true. (b) Suppose determinism is true. Consider this model: $\Omega_\alpha = \{\alpha, \beta\}$ with α and β agreeing at no times. In this model, strong determinism is false because $\Omega_\alpha \neq \{\alpha\}$. ■

We are also ready to contrast strong determinism with super-determinism, a concept much debated in quantum foundations. According to Hossenfelder and Palmer (2020), a super-deterministic theory is a deterministic one that is Psi-epistemic, local, and in violation of Statistical Independence. Roughly speaking, a theory is *Psi-epistemic* just in case the wave function (Ψ) does not correspond to an object (or have an objective status) in the physical world; *local* just in case there is no "spooky action at a distance" in the sense of Einstein; *in violation of Statistical Independence* just in case the probability distribution of the fundamental physical variables is not independent of the detector settings. These requirements are not requirements for strong determinism. For example, a strongly deterministic theory can be a non-local theory in which Statistical Independence holds and the wave function corresponds to an object in the physical world.[9] Moreover, super-determinism by itself is insufficient for strong determinism: while a strongly deterministic theory has exactly one nomologically possible world, a super-deterministic one can have (infinitely) many. Hence, strong determinism and super-determinism are logically independent.

On my view, the notion of fundamental laws is central to the definition of strong determinism (and that of determinism).[10] Penrose (1989), in contrast, defines strong determinism as the entire universe being fixed by some precise mathematical scheme for all time. The notion of a mathematical scheme is broader than that of fundamental laws. Although fundamental laws presumably correspond to mathematical schemes, there are many mathematical schemes that do not represent laws. Hence, Penrose's idea of strong determinism is more inclusive than the one I have. For example, as I discuss in §5, Penrose regards the standard Everettian theory of quantum mechanics (with a universal wave function) as an example of a strongly deterministic theory, leading to unwelcome results and risking trivializing the distinction between determinism and strong determinism. In contrast, my account does not.

There is a lively debate about what, metaphysically speaking, fundamental laws of nature are. For concreteness, I summarize and focus on two ways of thinking about them.[11] The first is a Humean approach according to which they are merely systematizations of the material contents in spacetime:

Reformed Humeanism The fundamental laws are the axioms of the best system that

[9]The Everettian Wentaculus introduced in §5 may be interpreted as one such theory with all the features except perhaps non-locality. The question of non-locality in Everettian theories is a subtle issue. See (Allori et al. 2010, sect.5) for a discussion in the context of a many-worlds theory with a fundamental mass-density ontology.

[10]In this paper, I assume that there are fundamental laws of nature. Unless noted otherwise, in what follows, I use "laws" and "fundamental laws" interchangeably.

[11]See Carroll (2020), Hildebrand (2020) and Bhogal (2020) for more detailed surveys. My reason for focusing on these two is because they are two of the mostly science-friendly views in the literature, especially regarding the form of modern physical laws and the issue of the direction of time. See Chen and Goldstein (2021).

summarizes the mosaic and optimally balances simplicity, informativeness, fit, and degree of naturalness of the properties referred to. The mosaic (spacetime and its material contents) contains only local matters of particular fact, and the mosaic is the complete collection of fundamental facts. The best system supervenes on the mosaic.[12]

The second is an anti-Humean approach according to which laws govern and exist over and above the material contents (Chen and Goldstein 2021):

Minimal Primitivism Fundamental laws of nature are certain primitive facts about the world. There is no restriction on the form of the fundamental laws. They govern the behavior of material objects by constraining the physical possibilities.

The theoretical virtues invoked by the reformed Humean are still useful for the minimal primitivist:

Epistemic Guides Even though theoretical virtues such as simplicity, informativeness, fit, and degree of naturalness are not metaphysically constitutive of fundamental laws, they are good epistemic guides for discovering and evaluating them.

Both approaches are compatible with my definitions of determinism and strong determinism. Moreover, they are flexible regarding the form of the laws; both in-principle allow certain particular facts to be fundamental laws. For example, as I discuss in §5, both allow the Past Hypothesis of the low-entropy boundary condition of the universe to be regarded as a fundamental law.

Simplicity is important on both approaches. On reformed Humeanism, simplicity is one of the constitutive features of fundamental laws. On minimal primitivism, it is an epistemic guide for discovering and evaluating candidate fundamental laws.[13]

On my view, the reason determinism has real bite is because we expect actual laws to be simple.[14] It is significant when simple laws turn out to be deterministic. If we consider any mathematical formula regardless of its complexity, determinism is extremely easy to achieve and can be true of any world. The basic idea of determinism

[12]A key difference between reformed Humeanism and Lewis's Humeanism (Lewis 1973, 1983, 1986) is that the latter but not the former requires fundamental laws to be regularities. See (Chen and Goldstein 2021, sect.2) and (Chen 2022, sect.2.3) for more in-depth comparisons. On Humeanism, the mosaic is often required to be about local matters of particular fact.

[13]Some anti-Humeans may worry that accepting the principle of Epistemic Guides opens them up to an objection from Humeans: since the minimal primitivist laws can be anything, why think they are simple? However, Humeans are not in a position to make that objection, as they make a similar assumption about the mosaic. The Humean mosaic could be anything and yet Humeans assume it has various nice features such as supporting induction and allowing simple systematizations. This is an important issue deserving its own paper; I do not have the space here to discuss it further.

[14](Russell 1913, pp.22-24) and (Earman 1986, pp.22) also note that there is an important connection between determinism and simplicity, and it is mediated by the simplicity of the laws. In the end, however, (Russell 1913, p.23) seems to reject simplicity as the solution to the trivialization of determinism, but his proposed solution in terms of uniformity of nature (more specifically, time translation invariance) can be viewed as a specific version of the simplicity requirement.

is that worlds never cross in state space (Figure 1). But there are infinitely many mathematical functions on state space that can meet this condition. For an extreme example, we can consider an infinitary theory T^∞ whose axioms do not express simple equations. Instead, they directly specify the nomologically possible worlds of Ω^{T^∞} (say, by giving a list of particle locations at different times) such that *they never cross in state space*, rendering the theory deterministic by brute force. As long as $\alpha \in \Omega^{T^\infty}$, the theory can be true and its axioms can represent the fundamental laws obtaining in the actual world. No one bothers to write such theories down because their axioms are in general extremely complicated and are bad candidates for fundamental laws. It is an advantage of reformed Humeanism and minimal primitivism that they recognize the importance of simplicity, either as part of the definition of what laws are or as that by which we discover or evaluate them. Hence, when characterizing determinism, it is crucial to keep simplicity in mind. Without it, determinism is easy to achieve and says almost nothing about the world, which would trivialize the distinction between determinism and indeterminism.

Similarly, the reason strong determinism has real bite is because we expect actual laws to be simple. It is even more significant when simple laws turn out to be not just deterministic but strongly deterministic. For any deterministic theory (expressed in terms of differential equations), we can always consider an extra fundamental law that stipulates the exact initial microstate of the universe. Such a new law, together with the deterministic dynamics, will make the theory strongly deterministic: given the fundamental laws (which now includes the new one), only one world is possible. However, the axioms of such a theory will in general be extremely complicated. For example, consider a classical universe with N point particles of the same mass m governed by $F = ma$ with Newtonian gravitation. Add a new fundamental law specifying the complete microstate of the world at some time t_0, in terms of $6N$ real numbers:

$$X_0(t_0) = \{\mathbf{q_1}, \mathbf{q_2}, ..., \mathbf{q_N}; \mathbf{p_1}, \mathbf{p_2}, ..., \mathbf{p_N}\} \tag{1}$$

with $\mathbf{q_i}$ and $\mathbf{p_i}$ the exact position and the momentum of the i-th particle in the 3-dimensional physical space. The theory with (1) representing a new fundamental law will not be an attractive theory at all because it fails to be sufficiently simple.[15] On reformed Humeanism, the specification of the exact microstate at t_0 will not count as an axiom in the best system of such a universe. Its gain in strength is outweighed by its cost in complexity. On minimal primitivism, although there is no metaphysical prohibition against such a theory, the epistemic guides tell us to look for one that better balances simplicity and informativeness.[16] A sufficiently simple theory that still accounts for the variety of kinds of empirical phenomena would be a marvelous achievement. We are interested in whether such theories are strongly deterministic.

[15] One could try to coordinatize physical space so that (1) may look simple in that coordinate system. But the particular choice of the coordinate system will in general be highly complicated to specify.

[16] Other philosophical theories about laws that are silent about simplicity may come to a different conclusion here. On such theories, we might still ask why we prefer simpler laws, why we find simplicity attractive and a guide to our scientific theorizing, and why it works in practice. Moreover, if simplicity is also the reason why determinism is not trivial on such theories, it can play the same role when evaluating strong determinism.

3 Consequences of Strong Determinism

Strong determinism enables a strong type of scientific explanation and a strong type of prediction. Moreover, it has interesting ramifications for current debates in philosophy, such as those on fundamental properties, free will, and modality.

3.1 Explanation, Causation, and Counterfactuals

In this paper, I assume that fundamental laws are a key component to a successful scientific explanation in fundamental physics. Whether the laws are deterministic or strongly deterministic makes a difference to the kind of explanations we obtain from a physical theory. Here, I discuss the implications for (i) strong explanations, (ii) the Principle of Sufficient Reason, and (iii) causal explanations.

(i) *Strong explanations.* While determinism enables what I call *conditional explanations*, strong determinism enables *strong explanations*. For simplicity, consider again $F = ma$ with Newtonian gravitation (and appropriate boundary conditions), a familiar example of a deterministic dynamical law. Suppose it governs (or describes) a world of N point particles (with positions, momenta, and Newtonian masses) moving in a 3-dimensional Euclidean space. Its explanatory power lies in the fact that such a simple law accounts for a bewildering variety of phenomena, from falling bodies on Earth to the patterns of planetary motion. For any closed system in such a world, the law maps a state at a time uniquely to a state at another time. For the universe as a whole, the law accounts for a general temporal pattern (cf. Russell (1913)):

(A) If the state of the universe is S at t, then the state of the universe is $S' = f(S, t, t')$ at t', where f is a simple function.

We may say that the state of the universe at t' is explained by the state of the universe at t together with the deterministic laws. As such, the type of explanation has a conditional form: conditional on the state of the universe at t, deterministic laws explain the state of the universe at t'. Call it a *conditional explanation*.

In contrast, strongly deterministic laws (see Figure 2) can explain more. They underwrite conditional explanations such as above but also account for unconditional facts such as:

(B) The state of the universe is S at t.

The state of the universe at any time is completely explained by the laws alone. I call it a *strong explanation*, in contrast to the conditional ones afforded by merely deterministic laws. Strongly deterministic laws can explain even particular facts such as "This fundamental object is in this place at this time." If strong determinism is true, every fundamental fact about the physical universe can be explained by the laws alone. If fundamental laws are where scientific explanation ultimately stops, then strong explanation may be completely satisfactory, leaving nothing unexplained.[17]

[17] There is still the question why the fundamental laws are what they are. That question seems to lie outside the scope of paradigmatic scientific explanations.

In other words, if strong determinism is true, every fundamental fact becomes subsumed under the fundamental laws. Nothing is left to contingency, chance, or randomness. There is not even a "choice" about the microscopic initial condition of the universe. Given the laws, the world could not have been otherwise. To use the God metaphor: after choosing the fundamental laws, God has no more choice to make. If fundamental laws are where scientific explanations should ultimately rest, then strong explanation is the most satisfactory explanation of the universe there can be. In the words of Einstein, God could not have made the world in a different way; that is, the necessity of logical simplicity leaves no freedom at all.

(ii) *The Principle of Sufficient Reason (PSR).* There is an interesting and under-appreciated connection between strong determinism and Leibniz's PSR. Regarding determinism, Hoefer (2016) notes that its roots lie in the PSR:

> The roots of the notion of determinism surely lie in a very common philosophical idea: the idea that *everything can, in principle, be explained*, or that *everything that is, has a sufficient reason for being and being as it is, and not otherwise*. In other words, the roots of determinism lie in what Leibniz named the Principle of Sufficient Reason.

That is a plausible suggestion.[18] Although there are several non-equivalent formulations of the PSR, the basic idea, as Rodriguez-Pereyra (2018) summarizes, is that "there are no brute facts or truths, that is, there are no facts or truths for which no explanation can be given." On this characterization, strong determinism is closer to realizing PSR than determinism is. As I have argued, determinism only enables conditional explanations but not strong explanations. Even if every event can be

[18] Hoefer does not claim that Leibniz endorses determinism because of his PSR. But as far as I know, it is not a controversial reading of Leibniz. However, the textual evidence in Leibniz's writings is often entangled with Leibniz's views about the pre-established harmony, optimality, and monads. This issue is complicated partly because it is unclear what kind of determinist Leibniz is. See Adams (1994) for a book-length discussion about the connections of Leibniz's determinism, theism, and idealism. I mention some suggestive passages in Leibniz's *Philosophical Essays*, translated by Ariew and Garber (AG):

"I therefore think that there are only a few free primitive decrees that regulate the course of things, decrees that can be called laws of the universe, and which, joined to the free decree to create Adam [i.e. an initial event], bring about the consequence. This is a bit like needing few hypotheses to explain phenomena—something I will explain more distinctly in what follows... [I]f this world were only possible, the individual notion of some body in this world, which includes certain motions as possible, would also include our laws of motion (which are free decrees of God), but also only as possible. For, since there is an infinity of possible worlds, there is also an infinity of possible laws, some proper to one world, others proper to another, and each possible individual of a world includes the laws of its world in its notion." (AG 71)

"For everything is ordered in things once and for all, with as much order and agreement as possible, since supreme wisdom and goodness can only act with perfect harmony: the present is pregnant with the future; the future can be read in the past; the distant is expressed in the proximate." (AG 211)

"As for motions of the celestial bodies, and even the formation of plants and animals, there is nothing in them that looks like a miracle except their beginning. The organism of animals is a mechanism which supposes a divine preformation. What follows upon it is purely natural and entirely mechanical." (AG 344)

I thank Don Rutherford and Shelly Yiran Shi for pointing me to these passages and for helpful discussions about this issue.

explained by an earlier event together with the laws, mere determinism provides no explanation for *why the initial event is the way it is*. Deterministic laws are (in general) compatible with many distinct initial states of the universe. Perhaps Leibniz recognizes this when he writes:

> For we cannot find in any of the individual things, or even in the entire collection and series of things, a sufficient reason for why they exist... [H]owever far back we might go into previous states, we will never find in those states a complete explanation [*ratio*] for why, indeed, there is any world at all, and why it is the way it is. (AG 149)

We may formulate a nomic version of the PSR:

PSR$_{nomic}$ There is a nomic reason for every event in spacetime.

Here I define a nomic reason for an event as entailment from the fundamental laws. Determinism by itself is not sufficient for PSR$_{nomic}$, but strong determinism is. All events in spacetime, including the initial one, are completely entailed by strongly deterministic laws. The world started in the exact initial state because, according to the strongly deterministic laws, it has to.[19]

The vindication of PSR$_{nomic}$ is another characterization of the strong explanation provided by strong determinism. Naively, it is reasonable to expect that strongly deterministic laws also provide an explanation for every non-fundamental fact, such as the actual position of the table in front of me at a particular time. However, when we look at a realistic example of strong determinism, the naive expectation no longer holds.

(iii) *Causation and counterfactuals.* Proponents of causal explanations may raise a worry. In many scientific contexts, the notion of causality is central to explanations. Causality is sometimes characterized by a counterfactual dependence theory (or the related accounts in the structural equations framework).[20] As a first approximation, we say that event A is a cause for event C just in case C counterfactually depends on A:

$$(A \mathrel{\Box\!\!\rightarrow} C) \wedge (\neg A \mathrel{\Box\!\!\rightarrow} \neg C) \tag{2}$$

where $\Box\!\!\rightarrow$ denotes the counterfactual conditional. The counterfactuals in such models are not counterlegals, as the causal structure should not outrun the nomic one. A *prima facie* problem arises on a strong determinism because there are no counterfactual

[19]It is plausible that Leibniz has in mind a stronger version of PSR:

PSR$^{+}_{nomic}$ There is a nomic reason for every event, and there is a sufficient reason for the laws.

Even strong determinism is not sufficient for PSR$^{+}_{nomic}$, as a strongly deterministic theory gives no sufficient reason for the laws. A Humean account of law is not much help here, as Leibniz would reject the Humean explanation of the laws in terms of the mosaic. Leibniz thinks that "the ultimate and extramundane reason for things" is God (AG 150).

[20]See Menzies and Beebee (2020) for an overview. There are problems of taking such an account as the analysis of causation. But even so, the counterfactual dependence theory seems to capture an important aspect of causation for the purposes of deliberation, manipulation, and scientific modeling. I thank David Danks for discussions here.

possibilities (the nomological state space is a singleton). Consequently, on the standard semantics, the relevant counterfactuals are all vacuously true, rendering the surprising result that every event causes every other event. This raises the question whether we can even make sense of causation and counterfactuals in a strongly deterministic theory.

In my view, that is an interesting and open question. So far, strong determinism is not on the radar for most people working on causation, counterfactuals, and causal explanations. Working out a complete theory of such notions under strong determinism falls outside the scope of this paper. Here I list three options for further evaluation.

Option 1: We can accept that there is still a causal relationship, since the relevant counterfactuals are still true. Let $A(t_1)$ and $C(t_2)$ correspond to the states of the universe at any two distinct times t_1 and t_2. Given strong determinism, counterfactuals with $\neg A(t_1)$-antecedents and $\neg C(t_2)$-antecedents are vacuously true. Hence, $A(t_1)$ and $C(t_2)$ counterfactually depend on each other.[21] So far, the dependence is symmetrical. To understand the causal asymmetry of time, we may add a version of the Past Hypothesis (PH) as a fundamental law such that it applies to one temporal boundary of the world but not the other, and we may define a non-fundamental arrow of time as the distance away from the time that PH applies (as Albert (2000, 2015) and Loewer (2007a, 2012) suggest and as we do in §5). We may then define the direction of causation as the same as the direction of time. For example, if t_1 is closer to the time of PH than t_2 is, then $A(t_1)$ causes $C(t_2)$ but not vice versa.

Option 2: We can understand the relevant counterfactuals for causal modeling and explanation as involving not the universe as a whole but the subsystems of the universe. For example, we may construct non-trivial state spaces for the subsystems of the universe. One way to do so is by collecting ensembles of the subsystems and use them as the points of the state space for the subsystems. A related strategy exists in the Everettian theories where there are many different branches of the multiverse such that counterfactual possibilities can be modeled by variations in the different branches. See Wilson (2020) for a proposal.

Option 3: We may consider using counterlegals for causal modeling and allow causal variables to range over metaphysically possible but nomologically impossible states. This deviates from the usual practice of disallowing counterlegals, as we assume that the causal structure is fixed by the laws of nature. This is counter-intuitive, but since strong determinism is relatively new, perhaps some of our presuppositions should be revised.

3.2 Prediction

Whether the laws are deterministic or strongly deterministic also makes a difference to the kind of predictions we obtain from a physical theory. While determinism enables what I call *conditional predictions*, strong determinism enables *strong predictions*.

[21] Although $\neg A(t_1) \,\Box\!\!\rightarrow C(t_2)$, it is not the case that $A(t_1) \,\Box\!\!\rightarrow \neg C(t_2)$. Hence, it does not follow that $\neg A(t_1)$ causes $C(t_2)$.

Recall Laplace's demon:

> We ought to regard the present state of the universe as the effect of its antecedent state and as the cause of the state that is to follow. An intelligence knowing all the forces acting in nature at a given instant, as well as the momentary positions of all things in the universe, would be able to comprehend in one single formula the motions of the largest bodies as well as the lightest atoms in the world, provided that its intellect were sufficiently powerful to subject all data to analysis; to it nothing would be uncertain, the future as well as the past would be present to its eyes. The perfection that the human mind has been able to give to astronomy affords but a feeble outline of such an intelligence. (Laplace (1820), trans. Nagel (1961))

If the initial value problem that Laplace has in mind is for Newtonian gravitation theory, he should have included instantaneous velocities to the things that the intelligence must know. In the best cases, given the forces, instantaneous velocities, and the positions of all particles in the universe at some time (and certain mathematical boundary conditions at infinity), a Laplacian demon can deduce all past states and all future states of the universe. However, this deduction is conditional as it requires information about the contingent state of the world at some time. In other words, in such cases, determinism enables what I call *conditional predictions*:

Conditional Prediction Conditional on the state of the universe at some time (or states of the universe at some finite interval of time), one can in-principle deduce, using the fundamental laws, the state of the universe at any time.

In contrast, strong determinism enables what I call *strong prediction*:

Strong Prediction One can in-principle deduce, using the fundamental laws, the state of the universe at any time.

To deduce the state of the universe at any time, one just needs the fundamental laws and needs no contingent fact about the universe (beyond what one needs to confirm the fundamental laws). Such laws, if they are boundary-condition laws, may be about the state of the universe at some particular time. But if they are laws, the boundary conditions will be nomologically necessary, and we have good reasons to expect them to be simple, unlike typical microstates of the universe in a deterministic theory, which are nomologically contingent and complicated.

Strongly deterministic laws are predictively powerful. Naively, it would seem to leave no room for uncertainty. Moreover, we might expect them to solve many of our practical problems. To predict the outcome of the next election, merely deterministic laws are not much help as conditional prediction requires us to know the exact microstate of the universe at some time (say, the present moment). Although it is in-principle possible for us to collect all the complicated microscopic facts of the universe, it is unrealistic; our time in the universe is too short to collect enough data for such a task. Non-computability given the initial data may present additional problems for creatures like us. In contrast, strong prediction is unconditional. We do not need to know the microstate of the universe at the present time to make the prediction. Given just the fundamental laws, we already can in principle deduce the state of the universe in, say, 2024 and predict the outcome of the next election with perfect accuracy. In this sense, a Laplacian demon will have unlimited predictive power. Hence, we may naively expect a strongly deterministic theory to solve many of our practical problems. However, we are not Laplacian demons. When we look at a realistic example of strong determinism (§5), the naive expectation no longer holds. What can be predicted from the laws and what is epistemically and practically relevant to us sometimes diverge. There can still be meaningful notions of uncertainty (e.g. of self-location) in strongly deterministic worlds (§5.3.2).

3.3 Other Ramifications

The importance of strong determinism is further illustrated by applying it to contemporary debates in metaphysics and philosophy of science. I discuss three such examples. (Readers whose interests lie outside metaphysics may skip this subsection.)

3.3.1 Fundamental Properties: Lewis on Naturalness.

The first example is from the landmark paper of Lewis (1983). One of Lewis's main arguments for postulating the existence of perfectly natural (metaphysically fundamental) properties is to avoid trivializing the best-system account of laws (BSA):

> We face an obvious problem. Different ways to express the same content, using different vocabulary, will differ in simplicity...Given system *S*, let *F* be a predicate that applies to all and only things at worlds where *S* holds. Take *F* as primitive, and axiomatise *S* (or an equivalent thereof) by the single axiom $\forall x F x$. If utter simplicity is so easily attained, the ideal theory may as well be as strong as possible. Simplicity and strength needn't be traded off. Then the ideal theory will include (its simple axiom will strictly imply) all truths, and *a fortiori* all regularities. Then, after all, every regularity will be a law. That must be wrong. (Lewis 1983, p.367)

In the same paragraph, the predicate *F* is characterized in two different ways[22]:

(F1) *F* applies to all and only things at worlds where *S* holds, which includes the actual world.

(F2) *F* applies to all and only things at the actual world.

[22]Here I am indebted to discussions with Jonathan Schaffer, Ted Sider, and members of the Rutgers metaphysics reading group in 2020.

Lewis initially defines F as (F1). However, he needs the logically stronger (F2) to argue that $\forall x F x$ strictly implies all truths.[23] Given the characterization in (F2), the deductive system S axiomatized as $\{\forall x F x\}$ is compatible with exactly one world. That is, $|\Omega^S| = 1$. Hence, S is strongly deterministic on my definition. If S is the best system of the actual world, strong determinism is true.

It is a generic feature of strong determinism that all truths and all regularities about the material contents of the universe are entailed by the fundamental laws. Consequently, on Lewis's BSA, in such a universe all such truths will be laws, albeit not all fundamental laws (which, according to (Lewis 1983, p.368), is reserved for the axioms of the best system). To say that this must be wrong already presumes that strong determinism is impossible. If strong determinism is possible, the collapse of the distinction between laws and mere regularities is to be expected. Once we understand strong determinism and accept its possibility, we need to revise Lewis's influential argument, as it would be unsound.[24]

I propose a revised argument, with changes italicized:

> Given system S, *let F be a predicate that applies to all and only things at the actual world*. Take F as primitive, and axiomatise S (or an equivalent thereof) by the single axiom $\forall x F x$. If utter simplicity is so easily attained, the ideal theory may as well be as strong as possible. Simplicity and strength needn't be traded off. *This makes the actual world strongly deterministic, regardless of what the actual world is like. Then, after all, strong determinism is necessarily true (or true at least in all worlds where the BSA holds).* That must be wrong.

Here, the crucial premise is that strong determinism is metaphysically contingent and the BSA must not regard it as necessarily true. Lewis can then argue that we should postulate "perfect naturalness" to solve the problem. But the real problem is different from the one in Lewis's original formulation—the collapse of the distinction between laws and mere regularities.

3.3.2 Free Will: Loewer on Compatibilism

The second example is from a recent paper by Loewer (2020a) on free will and determinism. Loewer provides an ingenious reply to Van Inwagen (1983)'s Consequence Argument, based on a new theory of counterfactuals and the "Mentaculus account" of the temporal asymmetry of influence.[25] They are inspired by recent works in the

[23](Loewer 2007b, p.319) and (Sider 2011, p.21) adopt the characterization in (F2). One way to understand Lewis in this paragraph is to read the first as a general case and the second as a special case; he moves from the general case to the special one for the sake of a *reductio*. I thank Alessandro Torza for alerting me to this possibility.

[24]There are other worries about Lewis's argument. For example, his criterion for strength is logical strength and may be inappropriate for scientific theories (Loewer 2007b); his sufficient condition for derived laws may be too permissive (Gómez Sánchez 2020); his ranking method for best systems is mistaken (Torza 2020). But I shall not focus on them here.

[25]See Dorr (2016) for a similar account of counterfactuals that is not explicitly based on the Mentaculus. The following discussion may also be relevant to Dorr's account but I do not have the

foundations of statistical mechanics and especially the Mentaculus theory, which includes fundamental dynamical laws (such as the deterministic $F = ma$ with the force laws), a fundamental law specifying a low-entropy boundary condition (called the *Past Hypothesis*), and a probability distribution over microstates compatible with the Past Hypothesis (called the *Statistical Postulate*).

Let us focus on two key premises in Loewer's version of the Consequence Argument that he calls PAST and LAWS (where "$\Box\!\!\rightarrow$" denotes the counterfactual conditional):

PAST I have no influence over the past state at time t: there are no alternative decisions d_1 and d_2 possible for me at t such that $d_1 \Box\!\!\rightarrow s_1$ and $d_2 \Box\!\!\rightarrow s_2$, where s_1 and s_2 are incompatible states of affairs that pertain to times prior to t.

LAWS I have no influence over the laws at time t: there are no alternative decisions d_1 and d_2 possible for me at t such that $d_1 \Box\!\!\rightarrow L_1$ and $d_2 \Box\!\!\rightarrow L_2$, where L_1 and L_2 are incompatible laws.

Together with the premise of determinism and a principle that connects influence to free will, they are supposed to entail that I have no free will. As a compatibilist about free will and determinism, Loewer responds by rejecting PAST but retaining LAWS: I have (only microscopic) influence over the past of the universe but I do not have influence over the laws. It is a principled response motivated by a substantive philosophy of science (the "Mentaculus vision"). In the context of the reply, Loewer interprets the laws as fundamental laws and the states of affairs as the (nomologically possible) microstates of the universe.

There are many aspects of Loewer's response but I want to focus on its relevance to the theme of this paper: Loewer's compatibilism, though promising in the case of determinism, is in tension with strong determinism. One of Loewer's insights is based on the fact that, in the Mentaculus theory, there are distinct nomologically possible microstates compatible with the same macrostate at any time. According to Loewer, I have influence over the past state at t such that, if I had done otherwise than what I actually do, the microstate of the world at time prior to t would have been another microstate.[26] Loewer provides reasons for endorsing the other counterfactual that if I had done otherwise, the laws would not have been different. For example, even if s_1 and s_2 were incompatible microstates that counterfactually depend on my decision, they would be compatible with the same (Mentaculus) laws. However, if the Mentaculus theory is false and strong determinism is true, there will be exactly one nomologically possible microstate of the universe at any time. In that case, the fundamental laws are compatible with exactly one past state at any time prior to t. If I now had influence over the past state, I would now have influence over the laws.[27]

space to discuss it here.

[26]Loewer's reasoning seems to assume determinism and the condition that counterfactuals are evaluated with respect to worlds where determinism is true.

[27]Here is another way to see the tension. Given the epistemic possibility of strong determinism, reasonable assumptions about counterfactuals, and either option for the metaphysics of laws (§2), we

One might respond by simply assuming the deterministic (but not strongly deterministic) Mentaculus theory. But the argument above is quite general as it only requires that strong determinism is (in the appropriate sense) possible. One might then try to dismiss the argument by stipulating the impossibility of strong determinism. But that misses the point here. First, it would require some justification. Second, if it were justifiable, we would still have learnt something interesting: Loewer's compatibilism is compatible with determinism but incompatible with strong determinism. We may wonder: how should one generalize Loewer's compatibilism when strongly deterministic theories are allowed? When we consider (in §5) the empirical equivalence of the Mentaculus with a strongly deterministic theory (the Everettian Wentaculus), this question becomes more urgent. I will return to this point.[28]

3.3.3 Modality: Wilson on Quantum Modal Realism

The third example is Wilson (2020)'s quantum modal realism. Wilson proposes a bold and fascinating reintepretation of Lewis's modal realism about possible worlds in terms of Everettian (many-worlds) quantum mechanics. On the latter theory, the universal wave function gives rise to many emergent worlds. Wilson suggests that we understand metaphysically possible worlds as Everett worlds (the decohered branches of the universal wave function), and that we regard contingency as variation across Everett worlds.

A natural worry is that not all contingencies are contained in the actual universal wave function. For example, even though the Schrödinger equation deterministically evolves an initial wave function (and by decoherence gives rise to a branching

can show that, possibly (for all we know it could be the case that), if PAST is false, then so is LAWS.

Informal Proof: Suppose the laws under consideration are strongly deterministic. For simplicity, we restrict our attention to worlds where strong determinism is true. Suppose PAST is false. There are two alternative decisions d_1 and d_2 possible for me at t such that $d_1 \mathrel{\Box\!\!\rightarrow} s_1$ and $d_2 \mathrel{\Box\!\!\rightarrow} s_2$, where s_1 and s_2 are incompatible microstates of the universe at a time prior to t. By assumptions, $s_1 \leftrightarrow L_1$ and $s_2 \leftrightarrow L_2$, where $\rightarrow$ denotes the strict conditional (suitably restricted) and L_1 and L_2 are incompatible strongly deterministic laws. Let us assume that $(A \mathrel{\Box\!\!\rightarrow} B) \wedge (B \rightarrow C) \vDash A \mathrel{\Box\!\!\rightarrow} C$. (Here we only need to assume this principle is correct in non-counterpossibile contexts. In full generality, it might (given other plausible principles) make all counterpossibles vacuously true. I thank Sam Elgin for pointing this out. I also thank Daniel Rubio for helpful discussions about the logic of counterfactuals.) So, there are two alternative decisions d_1 and d_2 possible for me at t such that $d_1 \mathrel{\Box\!\!\rightarrow} L_1$ and $d_2 \mathrel{\Box\!\!\rightarrow} L_2$, where L_1 and L_2 are incompatible laws. Hence, LAWS is false. ■

[28]There is another reason that a defender of the Mentaculus theory should not dismiss strong determinism. In one way, it strengthens the Mentaculus vision that inspires Loewer's compatibilism. Part of the Mentaculus vision is to argue, as Loewer and Albert have done, that we should regard the temporal asymmetry of causation as grounded in the Past Hypothesis. Arguments from Elga (2001), Frisch (2005, 2007), and Fernandes (2013) suggest that on the Mentaculus I sometimes have causal influence of the past (for examples influence over the existence of Atlantis). So one might conclude that the Mentaculus account grounds only a weaker asymmetry of causation than ordinarily held. On Maudlin's characterization, on the Mentaculus account the asymmetry of causation holds "only as a matter of *preponderance*: causes *mostly* or *typically* precede their effects, but some effects precede their causes" (Maudlin 2007, p.176). However, if strong determinism is true, I have no influence of the past (assuming I have no influence of the laws). Though this is an improvement, it gives rise to a new problem: by the same analysis, I have no influence of the future. I return to this point in §5.3.4.

structure), the initial wave function is nomologically contingent, i.e. not fixed by the fundamental laws. If nomological contingency (variation in nomologically possible worlds) is a form of contingency that Wilson aims to capture, then quantum modal realism falls short. Wilson anticipates this worry:

> One place in which arbitrariness might seem to remain within quantum modal realism is in the initial quantum state of the universe. Since quantum modal realists model contingency as variation across Everett worlds, there can be no contingency in an initial state that these worlds have in common... If it were to turn out that the true initial quantum state of our universe has arbitrary-seeming features that lack any apparent theoretical explanation, that would be prima facie evidence against quantum modal realism–since it would suggest a source of contingency in reality that goes beyond quantum contingency. But at present there is no reason to believe this is how things will turn out. (Wilson 2020, p.28)

I disagree with Wilson's last claim. The standard deterministic laws of Everettian quantum mechanics do not pick out a unique initial (pure) quantum state of the universe. Current cosmological research does not give us reason to expect that it does.[29] We have good reasons to think that there is nomological contingency for the initial wave function and that it is not nomologically necessary, at least in standard deterministic versions of Everettian quantum mechanics.

However, a strongly deterministic Everettian theory can solve that problem in Wilson's proposal. In §5, I explain how to construct such a theory, called the *Everettian Wentaculus*. In that theory, the problematic kind of contingency is eliminated, and even the arbitrariness becomes tolerable. There is exactly one nomologically possible initial condition of the Everettian multiverse and thus exactly one nomologically possible history of the multiverse. This answers the original worry about nomological contingency (though there is still the worry for Wilson's account about how to model variations of different sets of nomological possibilities; see Harding (2021) for a discussion). In this regard, the Everettian Wentaculus is a better foundation for Wilson's quantum modal realism.

The three examples above suggest that strong determinism can be an important testing ground for evaluating philosophical theories.

4 Two Toy Examples

For a more concrete understanding of strong determinism, let us consider some examples. In this section, I discuss two toy examples that implement strong determinism through constraint laws that determine a unique world. Despite being unrealistic, they illustrate several consequences discussed in §3. In the next section, I discuss a more realistic physical theory.

[29] For example, the model proposed by Ashtekar and Gupt (2016), in the context of loop quantum cosmology, is compatible with an infinity of different initial wave functions of the universe.

4.1 The Lone-Particle World

Consider a two-dimensional Aristotelian spacetime with an absolute spatial center x_0 and a lone particle whose only property is position. Suppose it is governed (or optimally described) by this fundamental law:

$\mathbf{L}_1$ There exists only one particle, and it is is located at x_0 at all times.

Since the law is compatible with exactly one world—the world where one particle is always at x_0 and nothing else exists, the theory is strongly deterministic. (Let us suppose there cannot be haecceitistic differences.) This world is a strongly deterministic world. However, even though it is strongly deterministic, we do not regard the law as particularly interesting.

The law does not explain much, because there is not much to be explained. The world has no temporal variation. The only variation that distinguishes it from a completely empty spacetime is a stationary particle. Our concept of explanation may not even apply in this case, as we are used to talking about explanations of complicated phenomena in terms of simple laws. Explanations are illuminating insofar as there is a significant contrast between the complexity of the phenomena and the simplicity of the laws. Here, the law and the phenomena are more or less equivalent—they are both extremely simple.

The law does not predict much, because there is not much to be predicted. First, there is not enough structure for a predictor to exist. We can talk about the particle predicting its own trajectory in the Aristotelian spacetime, but that would be a caricature of prediction. Second, even if the particle is using the law to predict its own trajectory, it would not have much practical value. The particle does not have any practical problem to solve.

Fortunately, not all examples of strong determinism is like the lone-particle world.

4.2 The Mandelbrot World

Let us consider a more interesting toy example, where there is a significant contrast between the complexity of the phenomena and the simplicity of the laws. The example is from the study of fractal geometry and complex dynamical systems. Here I follow the discussion in (Chen and Goldstein 2021, sect. 3.2).

To begin, let us consider the Mandelbrot set in the complex plane (Figure 3), a striking example of the fractal structure, specified by the simple rule that a complex number c is in the set just in case the function

$$f_c(z) = z^2 + c \tag{3}$$

does not diverge when iterated starting from $z = 0$. For example, $c = -1$ is in this set but $c = 1$ is not, since the sequence $(0, -1, 0, -1, 0, -1, ...)$ is bounded but $(0, 1, 2, 5, 26, 677, 458330, ...)$ is not.

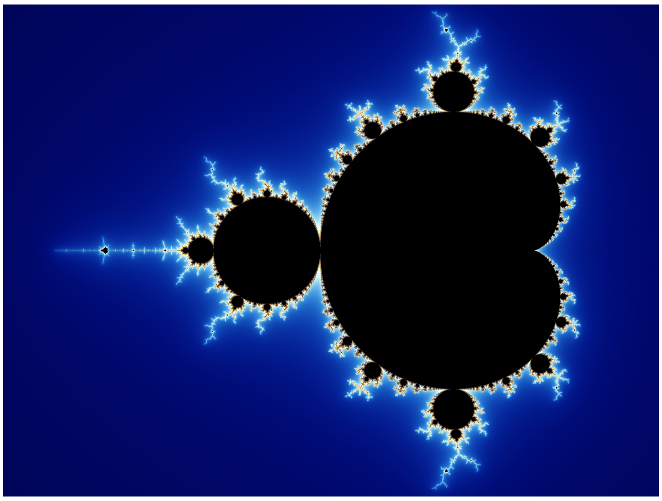

Figure 3: The Mandelbrot set with continuously colored environment. Picture created by Wolfgang Beyer with the program Ultra Fractal 3, CC BY-SA 3.0, https://creativecommons.org/licenses/by-sa/3.0, via Wikimedia Commons

Here, the pattern on the complex plane is surprisingly intricate and rich. When we zoom in, we see sub-structures that resemble the parent structure. When we zoom in again, we see sub-sub-structures that resemble the sub-structures and the parent structure. And so on. Interestingly, they closely resemble, but they are not exactly the same. As we zoom in further, there will always be surprises waiting for us. Each scale of magnification will reveal something new.[30] There is a puzzling pattern to be explained.

Now, let us endow the Mandelbrot set with physical significance. We regard the Mandelbrot set on the complex plane as corresponding to the distribution of matter over a two-dimensional spacetime, which we call the Mandelbrot world. We stipulate that the fundamental law of the Mandelbrot world is the rule just described. The fundamental law is compatible with exactly one world.[31] On my definition, the Mandelbrot world is strongly deterministic.

What about explanations in the Mandelbrot world? First, unlike the previous example, given just the pattern in the Mandelbrot world we may not expect it to be generated by any simple law. It would be a profound discovery in that world to learn that its remarkable structure is generated by the law based on the very simple function $f_c(z) = z^2 + c$. The fundamental law provides a striking explanation of the pattern that leads us to say "Aha! Now I understand." This also echos Penrose's emphasis on unexpected simplicity:

> Elegance and simplicity are certainly things that go very much together. But nevertheless it cannot be quite the whole story. I think perhaps one should say it has to do with *unexpected* simplicity, where one imagines

[30] For helpful visualizations, see (Penrose 1989, ch.3).

[31] It is worth noting that the patterns of the Mandelbrot world are not fine-tuned, as they are stable under certain changes to the law. For example, as (Penrose 1989, p.94) points out, other iterated mappings such as $f_c(z) = z^3 + iz^2 + c$ can produce similar patterns.

> that things are going to be complicated but suddenly they turn out to be very much simpler than expected. It is not unnatural that this should be pleasing to the mind. (Penrose 1974, p.268)

Second, the explanation provided by the law does not appear to be a causal or a temporal one. There is no obvious counterfactual dependence, causal or temporal ordering of events. The simple rule determines the whole world altogether. On reformed Humeanism, this simple rule is the axiom in the best system that summarizes the distribution of matter in spacetime. The axiom scientifically explains the mosaic by giving a unified account of the phenomena (Loewer 2012). On minimal primitivism, the axiom expresses the fundamental law that constrains the mosaic as a whole, even though it does not produce the mosaic moment by moment. On both accounts, the explanation provided by the laws need not be dynamic explanations (those that unfold in time). Unlike the example discussed in the next section, the Mandelbrot world does not have a natural structure to define a metaphysically derivative arrow of time or arrow of causation.

What about predictions in the Mandelbrot world? As the fundamental law is non-dynamical, it does not enable the usual kind of prediction with time-evolution equations. The spacetime does not have a natural foliation into equal-time hypersurfaces, so there is no obvious notion of temporal sequences that the law acts on. Metaphorically speaking, the law treats each spacetime point individually and decides whether to place something on it. Given the law alone, a Laplacian demon can deduce everything about the world, by plugging each spacetime location (represented by a complex number) into the formula. Unfortunately, the Mandelbrot set may not be decidable in the sense of permitting a computer algorithm to calculate the exact distribution of matter in finite time (Penrose 1989, p.128) . Hence, for computationally limited creatures like us, the law may not be calculation-friendly. The calculation of the exact distribution of matter may take infinite time. (Nevertheless, since the complement of the Mandelbrot set is semi-decidable, we can in finite time obtain *some* truths about the world.) The toy example illustrates that strong determinism does not always entail high predictive power that would be practically useful to us.

In the next example, we see that strong prediction may fail to be useful to us for a reason different from undecidability.

5 A Realistic Example

For a realistic example of strong determinism, I turn to the Everettian Wentaculus, a theory of quantum mechanics in a time-asymmetric universe. It implements strong determinism by using a deterministic dynamical law and a simple boundary-condition law that specifies a unique initial state of the world.

5.1 The Everettian Wentaculus

To begin, let us review some facts about the Everettian (many-worlds) theory of quantum mechanics. In its standard formulation, it is a deterministic (but not strongly deterministic) theory that aims to solve the *quantum measurement problem* and provide a consistent description of quantum phenomena. At any time, the state of the world is completely described by the universal wave function (Ψ_t). The time evolution of Ψ_t is given by the deterministic Schrödinger equation: $i\hbar\frac{\partial}{\partial t}\Psi_t = \hat{H}\Psi_t$. Fixing Ψ_0 suffices to fix the state of the world at any time.

What is the quantum measurement problem that it tries to solve? Recall Schrödinger's famous thought experiment. If the wave function is the complete description of the system with a cat in the box, and if it always obeys the Schrödinger equation, then the state of the system will, after some time, always be a superposition of the cat being alive and the cat being dead. That contradicts the assumption, suggested by observation, that after the experiment the cat is in a definite state: either alive or dead.

Everettian quantum mechanics solves the measurement problem by embracing the non-definiteness: yes, the cat is in a superposition of alive and dead, albeit in different "branches." The branches decohere from the universal wave function and correspond to different emergent worlds (that for all practical purposes do not interfere with each other). Since the observers will also experience branching, the observer in any particular branch will only observe a particular state of the cat in that branch. Everettian quantum mechanics denies that an outcome is definite *simpliciter*; instead, it is definite relative to a particular branch of the wave function. On this picture, there is an emergent multiverse associated with the universal wave function.

Let us distinguish between *fundamental worlds* and *emergent worlds* in Everettian quantum mechanics. Each fundamental world (whose state at a time is represented by the universal wave function) corresponds to a multiverse of (infinitely) many emergent worlds (whose states are represented by decohered branches of the universal wave function). Fundamental worlds correspond to curves in a state space called the Hilbert space. The theory is deterministic because those curves do not cross. The nomologically possible worlds refer to the fundamental worlds compatible with the fundamental laws.

The success of Everettian quantum mechanics requires solutions to two difficult problems: (1) to provide a satisfactory ontology on which our experiences supervene, and (2) to justify the Born rule of probability in quantum mechanics. It is controversial whether the two problems have been successfully solved. For the purpose of this paper, I set aside my doubts and grant that they have.[32] (As a first approximation, one may regard the Born rule probability as self-locating probability of where the agent is in the emergent multiverse. But this postulate is compatible with the determinism of the fundamental dynamics characterized by the Schrödinger equation.)

The Everettian theory of quantum mechanics, as formulated, is time-symmetric in

[32] I invite the readers to do the same. But for those who cannot, they can perhaps view what follows as a conditional argument given the assumptions. For relevant discussions, see Saunders et al. (2010).

its fundamental postulates and does not adequately explain the apparent (thermodynamic) temporal asymmetries, such as the melting of ice cubes, the dispersion of gas, and the diffusion of heat. There are infinitely many wave functions compatible with Everettian quantum mechanics such that they fail to give rise to the thermodynamic asymmetry of time.[33]

To explain the asymmetries, we can adopt the Boltzmannian proposal. For concreteness, let us modify Albert and Loewer's Mentaculus theory and add the Past Hypothesis to Everettian quantum mechanics as a fundamental boundary-condition law.[34] In the quantum case, the Past Hypothesis is now a constraint on the macrostate realized by the initial wave function of the universe: it has low quantum Boltzmann entropy. More precisely, the initial wave function lies inside a low-dimensional subspace, denoted by $\mathscr{H}_{PH}$, the Past-Hypothesis subspace. In symbols:

$$\Psi_0 \in \mathscr{H}_{PH} \tag{4}$$

The size of $\mathscr{H}_{PH}$ is given by the logarithm of its dimension ($\log \dim \mathscr{H}_{PH}$) and its quantum Boltzmann entropy given by its size multiplied by the Boltzmann constant (k_B).[35] The Past Hypothesis constrains the thermodynamic entropy of the world "at the beginning of time." Given this constraint, we impose a Statistical Postulate: every wave function is equally likely as any other. (More precisely, we postulate a uniform probability distribution of wave functions compatible with $\mathscr{H}_{PH}$ with respect to the normalized surface area measure on the unit sphere in $\mathscr{H}_{PH}$.) Let us call the theory with the following fundamental laws *the Everettian Mentaculus*:

The Everettian Mentaculus

M1. The Schrödinger equation.

M2. The Past Hypothesis.

M3. The Statistical Postulate.

On this theory, it is plausible that with high likelihood, the universal wave function will, for the overwhelming majority of times, increase in thermodynamic entropy until it reaches the maximum entropy. While Everettian quantum mechanics solves the quantum measurement problem, the Everettian Mentaculus solves, in addition, the problem of the (thermodynamic) asymmetry of time.

The Everettian Mentaculus is deterministic but not strongly deterministic. The Past Hypothesis constrains the initial wave function but does not pick out a unique one. Given the fundamental laws (M1-M3), the history of the multiverse could have

[33]For an overview of the thermodynamic asymmetry of time, see (Callender 2011).

[34]The Past Hypothesis was originally suggested in (Boltzmann 1964)[1896] and Boltzmann (1897) (although he seems to favor another postulate that can be called the *Fluctuation Hypothesis*) and discussed in (Feynman 2017)[1965]. For recent discussions, see (Albert 2000), (Goldstein 2001), (Callender 2004, 2011), (Lebowitz 2008), (North 2011), (Loewer 2020b), (Goldstein et al. 2020), and Chen (2020b). The memorable phrase 'Past Hypothesis' was coined by Albert (2000).

[35]For an overview of Boltzmannian quantum statistical mechanics, see Goldstein et al. (2020).

been different, corresponding to different choices of the initial wave function inside $\mathscr{H}_{PH}$. Interpreting the Past Hypothesis as a fundamental law seems incompatible with certain non-Humean accounts of laws that require them to be regularities or dynamical. But it is compatible with reformed Humeanism and minimal primitivism. Just like the Schrödinger equation, the Past Hypothesis can be an axiom in the best system or a fundamental fact that constrains the behavior of fundamental objects. The reason for regarding the Past Hypothesis as simple is that the particular low-entropy boundary condition (corresponding to $\mathscr{H}_{PH}$) is expected to be simple to characterize.[36] The Past Hypothesis is informative because it partly explains the thermodynamic asymmetry of time.

Let us go further and construct a strongly deterministic and simple Everettian theory. Since the Everettian Mentaculus is a quantum theory, and since quantum mechanics allows us to consider both pure states (represented by wave functions) and impure states (represented by density matrices), I propose a new theory, called *the Everettian Wentaculus*.[37] On this theory, the state of the world at t is completely described by a universal density matrix (W_t). The time evolution of W_t is given by the deterministic von Neumann equation: $i\hbar\frac{d\hat{W}(t)}{dt} = [\hat{H}, \hat{W}]$, which generalizes the Schrödinger equation. Fixing W_0 suffices to fix the state of the world at any time. Moreover, instead of postulating a uniform probability distribution over initial density matrices compatible with the Past Hypothesis subspace $\mathscr{H}_{PH}$, I postulate a particular density matrix—the natural and the canonical one corresponding to the subspace, i.e. the normalized projection. In symbols:

$$\hat{W}_0 = \frac{I_{PH}}{\dim \mathscr{H}_{PH}} \tag{5}$$

with I_{PH} the projection operator onto $\mathscr{H}_{PH}$ (the identity operator restricted to $\mathscr{H}_{PH}$). This is called the *Initial Projection Hypothesis* (Chen 2018). It is as simple as the Past Hypothesis. I propose we regard it as a fundamental law that selects a unique initial quantum state of the universe.[38] To summarize, the Everettian Wentaculus contains two fundamental laws:

[36]For some discussions about the simplicity of the Past Hypothesis, see (Albert 2015, p.5), (Loewer 2012, p.129), and (Callender 2004, p.205). A simple example of the Past Hypothesis (in classical spacetime) is the Weyl curvature hypothesis: the Weyl curvature vanishes near any initial singularity (Penrose 1979, p.630). See Ashtekar and Gupt (2016) for a generalization of Penrose's idea to loop quantum cosmology. For different types of the Past Hypothesis, see (Chen 2022, sect.3).

[37]The Wentaculus framework is introduced in (Chen 2018) and further developed in (Chen 2019, 2020a,c, 2021, 2022).

[38]Contrast the Initial Projection Hypothesis with the Simple Past Hypothesis of Wallace (2011). The former may be viewed as a special case of the latter, so the two are compatible. However, justifying the entropic behavior of the particular mixed state does not require us to commit to the full scope of Wallace's Simple Dynamical Conjecture, which (in my view) may be too ambitious in its insistence that *all* simple initial states and distributions be entropic (as they evolve forward in time). In fact, we can rely on the usual (less ambitious) Boltzmannian arguments to derive a corollary that the particular mixed state is entropic.

The Everettian Wentaculus

W1. The von Neumann equation.

W2. The Initial Projection Hypothesis.

The Everettian Wentaculus is strongly deterministic, since it is compatible with exactly one fundamental world. Given the fundamental laws (W1&W2), the history of the multiverse has to be what it is; it could not have been different, on pain of violating the laws. Even though the density matrix is often regarded as denoting our ignorance of the underlying pure state, on the proposed theory the density matrix of the universe is the fundamental state of the world that gives rise to an emergent multiverse.

On an intuitive level, we can say that the multiverse of the Everettian Wentaculus has "more branches" than that of the Everettian Mentaculus. The Everettian Wentaculus multiverse has all the branches that the Everettian Mentaculus one has and more. Speaking loosely, all the nomological possibilities of the Everettian Mentaculus multiverse will be embedded somewhere in the actual Everettian Wentaculus multiverse. However, on the Everettian Wentaculus, there is no fundamental nomic contingency or possibility beyond the actual fundamental world. If notions of contingency, chance, probability, and counterfactual make sense in this world, they have to be emergent at the level of branches and subsystems in the multiverse. It is important to appreciate that the theory does not contain any notions of probability or typicality at the fundamental level of physics. Hence, this is a proposal that completely eliminates the Statistical Postulate in fundamental physics.[39]

5.2 Worry: Too Easy?

At this point, one might naturally wonder: exactly what has been achieved? It seems too easy, so there must be something wrong. Strong determinism is obtained by replacing a set of choices (initial conditions) with exactly one choice. If that is all, can't we do it much more easily in the Everettian Mentaculus, by just stipulating a particular initial microstate Ψ_0, thereby fixing the entire history of the multiverse? More generally, for any deterministic theory, can't we just stipulate exactly what the initial microstate has to be and obtain a strongly deterministic theory? Does that mean every deterministic theory is (or at least can be) strongly deterministic?[40]

Thinking through these worries can help us appreciate what has been achieved. What sets the Everettian Wentaculus apart is the simplicity of its fundamental laws.

[39]This proposal achieves something similar to that of Albert's conjecture of GRW quantum shuffling (Albert 2000, ch.7) and Wallace's Simple Dynamical Conjecture (Wallace 2011, 2012). However, the Everettian Wentaculus does so more conservatively, without relying on *new* conjectures.

[40]There are two other worries worth mentioning at this point: (1) what if we take the probability distribution on the classical phase space as fundamental and make classical mechanics strongly deterministic? (2) what about the arbitrariness in setting the boundary of the initial Past-Hypothesis subspace? Due to space constraint I do not discuss them here, but see Chen (2020c, 2022).

It is a surprising and important discovery that our empirical experiences can be adequately described by a strongly deterministic and *simple* theory.

I already discussed an example of a strongly deterministic classical mechanics at the end of §2. The reply was that the additional postulate (1) would be too complicated to be a good candidate for a fundamental law. For the standard Everettian quantum mechanics and the Everettian Mentaculus, the reply is the same. We can consider an additional postulate that specifies the exact wave function Ψ_0 at t_0. Such a postulate will in general be as complicated as (if not more complicated than) its counterpart in the classical universe. The theory will no longer be an attractive one with simple axioms (expressing either the best summary or the minimal primitivist laws that govern the quantum world).

It is highly non-trivial to find a strongly deterministic and *simple* theory. Before the Wentaculus, as far as I know, no one has considered a simple boundary-condition law that pins down a unique microstate.[41] The Past Hypothesis of the Mentaculus theory is a simple boundary-condition law but is compatible with infinitely many microstates.

The Everettian Wentaculus is the first realistic and simple strongly deterministic theory of the quantum world. Given the Initial Projection Hypothesis, we have a simple boundary-condition law that specifies a unique microstate. Given also the von Neumann equation, we have a theory that allows exactly one nomologically possible history of the world (multiverse).[42] In contrast, the Bohmian Wentaculus, with W1-2 plus a density-matrix version of the guidance equation, is not strongly deterministic. In the Bohmian theory, the quantum state is not everything; the initial particle configuration is not pinned down by the Initial Projection Hypothesis.

Recall that Penrose defines strong determinism in terms of a "mathematical scheme" while I define it in terms of fundamental laws. This difference manifests in our different judgments regarding the standard Everettian theory. Penrose writes:

> As a variant of strong determinism, one might consider the many-worlds view of quantum mechanics (cf. Chapter 6, p.381). According to this, it would not be a *single* individual universe-history that would be fixed by a precise mathematical scheme, but the totality of myriads upon myriads of 'possible' universe-histories that would be so determined. Despite the unpleasant nature (at least to me) of such a scheme and the multitude of problems and inadequacies that it presents us with, it cannot be ruled out as a possibility. (Penrose 1989, p.432, emphasis original)

On Penrose's view, standard Everettian quantum mechanics already is strongly

[41]The No-Boundary proposal of Hartle and Hawking (1983) pins down a unique wave function of the universe. However, it is unclear to me whether they intend it to be a simple law or merely a characterization of the (nomologically contingent and complicated) wave function of the universe.

[42]It is worth briefly explaining the classical counterpart of this postulate: we stipulate that the state of the classical system is given by not a point but the ρ function on phase space that corresponds to what we ordinarily call the "probability distribution." However, this move makes the classical theory worse, by making it into a many-worlds theory or a stochastic theory. In contrast, this move makes the Everettian theory better. See Chen (2020c, 2022).

deterministic, presumably because the actual universal wave function and the Schrödinger equation suffice as a mathematical scheme that fixes the history of the world (multiverse). In my view, that is problematic for two reasons. First, it seems to trivialize strong determinism, rendering it a suitable target of the worry described earlier. After all, already in classical mechanics, the world history is fixed by the dynamical laws and the initial classical microstate (1). It seems that any deterministic theory (whose dynamical laws are expressed as differential equations) contains a mathematical scheme that fixes the world history and is therefore strongly deterministic. Second, this view is in conflict with the usual interpretation that standard Everettian quantum mechanics allows many different (nomologically possible) initial wave functions. The reason we come to different judgments regarding the standard Everettian theory is because of our different definitions of strong determinism. I do not know how to precisify the notion of "a precise mathematical scheme" in a way that avoids trivializing strong determinism. For that reason, I think it is better to define strong determinism in terms of fundamental laws.

5.3 Consequences

Let us examine the consequences of strong determinism in the context of Everettian Wentaculus.

5.3.1 Explanation, Causation, and Counterfactuals

What do explanations look like on the Everettian Wentaculus? On this physical theory, there is exactly one nomologically possible world—the actual one. Given the fundamental laws, the world (multiverse) has to be how it is.[43] Hence, on the scientific level, the entire history of the multiverse is strongly explained by the Everettian Wentaculus. This may be the ideal kind of scientific explanation on reformed Humeanism and on minimal primitivism. It also satisfies PSR_{nomic}.

As discussed in §3.1, this seems in tension with certain conceptions of causation and counterfactuals. Such notions are often explicated by appeal to alternative possibilities: to understand causal relationships and counterfactual dependences, we appeal to what the actual world could have been. The Everettian Wentaculus tells us that, at the fundamental level, there are no alternative possibilities.

Nevertheless, alternative possibilities may be understood at the non-fundamental level of branches and emergent worlds. (This corresponds to Option 2 in §3.1(iii).) If Wilson (2020) is right, then the Everettian theory in general and the Everettian Wentaculus in particular have the structure to ground a non-fundamental notion of alternative possibilities, which may be sufficient to ground a meaningful notion of causation and counterfactuals for most ordinary contexts. Recall that the universal

[43]In the sense of metaphysical possibility, the fundamental laws could have been different. But given the earlier assumptions (§2-3), that does not raise an additional puzzle for scientific explanations. At the scientific level, we start from the fundamental laws and do not try to explain them further. If some laws can indeed be explained in terms of other physical theories, then that is evidence the laws are not yet fundamental.

density matrix gives rise to an emergent multiverse due to decoherence. For example, there will be branches where Suzy throws a rock and the window breaks and ones where Suzy does not throw a rock and the window does not break.[44] If this approach can be successfully developed, notions of counterfactuals and causation may still be accommodated even if the strongly deterministic Everettian Wentaculus is true.

5.3.2 Prediction

What about predictions on the Everettian Wentaculus? Since the fundamental laws are strongly deterministic, strong prediction is available in the multiverse. Hence, a Laplacian demon can deduce the entire history of the multiverse from the laws alone, without any input about contingent matters of fact.

Whether the entire world is computable depends on whether W1 and W2 are computable. However, even granting their computability, there is another obstacle to the usefulness of strong prediction for situated agents such as ourselves. In Everettian theories, since every possible outcome of each experiment is realized in some branch, there needs be an account for the Born rule probability that situated observers can use. Everettians try to solve this problem by appealing to either decision theory or self-locating uncertainty, placing the source of such probability in the agents rather than the nomological structure of the world.[45] The goal is to justify (both qualitatively and quantitatively) the Born-rule probability so that we can make sense of how outcomes of measurement do in fact confirm Everettian quantum mechanics. I granted earlier that the probability problem(s) can be solved, otherwise Everettian quantum mechanics is already subject to decisive refutation. Insofar as we consider Everettian quantum mechanics a live empirical hypothesis (which many people do), we have to presuppose that it makes sense to talk about Born-rule probability, either through how much I prefer certain rewards or through how likely I am located in a particular branch of the multiverse.

However, the solutions to the probability problem(s) may hinder the usefulness of strong prediction. Even if the world is strongly deterministic, there is (by assumption) still a meaningful sense of uncertainty and probability. Either I will act as if I am uncertain or I will lack information about which branch I am on. Either way, prediction of the particular outcome of experiment will be effectively probabilistic, in accord with the Born rule. Hence, even though strong prediction is available, at the level of practical action and deliberation, predictions will remain effectively probabilistic.

This point may generalize to other quantum theories. Already in standard Bohmian mechanics, determinism of the fundamental laws is compatible with

[44] There is another way to model contingency in a world without fundamental contingency. As (Pearl 2009, pp.419-20) acknowledges, when you describe the whole universe using interventionist models, causality disappears. See also (Woodward 2016, sect. 10). However, there are many identical (or similar) subsystems of the world that for which causality still exists even if it disappears at the universal level.

[45] See Vaidman (2021) for a survey; for an example of the decision-theoretic approach, see Wallace (2012); for an example of the self-locating uncertainty approach, see Sebens and Carroll (2016).

absolute uncertainty—"when a system has wave function ψ we cannot know more about its configuration X than what is expressed by $|\psi|^2$" (Dürr et al. 1992, p.885). Now, consider a hypothetical Bohmian theory that implements strong determinism by postulating a simple and compelling law that picks out not just a unique initial quantum state (W2) but also *a unique initial particle configuration*. As long as the simple law does not pick out an atypical configuration (displaying quantum non-equilibrium), there can be unpredictability due to absolute uncertainty and the dispersion in the dynamical equation (Dürr et al. 1992, pp.885-86). Our predictions in such a world will still be effectively probabilistic, in accord with the Born rule ($|\psi|^2$). In this case, our uncertainty can also correspond to that of self-location (in space and time)—we may be uncertain about which subsystem we are in.[46]

5.3.3 Empirical Equivalence

Assuming that the Everettian problem(s) of probability can be solved, Everettian theories are empirically equivalent to textbook quantum mechanics, insofar as the latter makes unambiguous predictions. Moreover, Everettian theories are empirically equivalent to their Bohmian counterparts, as both assign the same Born rule probabilities to measurement outcomes. Furthermore, spontaneous collapse theories of GRW can be made approximately empirically equivalent to Everettian theories. Hence, the Everettian Mentaculus, the Bohmian Mentaculus, the Bohmian Wentaculus, and the Everettian Wentaculus are all empirically equivalent. They are also approximately empirically equivalent to the GRW Mentaculus and the GRW Wentaculus.

Given their empirical equivalence, in a time-asymmetric quantum world like ours, we cannot find out whether strong determinism is true or false by experiments or observations alone.[47] This is true regardless of what technological advances we make in terms of the measurement instruments. The question of strong determinism will forever be empirically underdetermined.

One might respond by pointing out that our definition of *interesting* strong determinism already appeals to the super-empirical virtue of simplicity. After all, any deterministic theory is empirically equivalent to an *uninteresting* strongly deterministic theory that turns out to be complicated (by stipulating the exact microstate such as in (1) or Ψ_0). In response, a stronger point can be made. We might have thought that there is no sufficiently simple theory that can account for our empirical experiences and be strongly deterministic. But it turns out that there is. Moreover, it may even be simpler and better than the standard deterministic theories.[48]

This is interesting even for people, such as myself, who do not think that the probability problem has been solved in Everettian theories. First, it shows that

[46] I thank Sheldon Goldstein for the insight.

[47] I thank Jeff Barrett for discussions about this point.

[48] For arguments that the Wentaculus theories are simpler and better than the Mentaculus theories, see Chen (2020a,c, 2022).

whether our world is strongly deterministic turns on conceptual questions about the meaning of probability. Second, it turns out that it is quantum mechanics but not classical mechanics that is hospitable to strong determinism. This stands in sharp contrast to the traditional belief that the quantum world is more indeterministic.

5.3.4 Other Ramifications

(i) *Fundamental properties.* Given the concrete example in this section, we can return to Lewis's argument for perfectly natural properties. If the Everettian Wentaculus is the best system of the actual world, then the best system entails all truths and *a fortiori* all regularities about the mosaic. Then, after all, every regularity will be a law. Surely that is exactly to be expected of such a world. The collapse of the distinction between lawful and accidental regularities is not a problem in itself.[49]

The real problem for BSA (with unrestricted language), as we have noted before, is that not all worlds are strongly deterministic. If the world turns out to be such that the best system is given by the Bohmian Wentaculus or the Everettian Mentaculus, then it is not the case that there is only one nomologically possible world. What Lewis should have said is that, without a restriction on language, BSA will make every world strongly deterministic. Hence, there can be a role for the fundamental (perfectly natural) properties to play, but their role is to avoid making strong determinism metaphysically necessary.

(ii) *Free will and modality.* In §3.3.2, I discussed the relevance of strong determinism to Loewer's compatibilism about free will and determinism. The upshot is that it is in tension with strong determinism. Now we can consider a generalization of Loewer's compatibilism to strong determinism. Loewer proposes that we retain PAST but reject LAWS. Inspired by Wilson (2020)'s strategy of modeling contingency as variation across branches in the multiverse, we may modify Loewer's proposal as follows. Instead of over microstates of the world (multiverse), we may consider our past influences over branch-relative microstates of the world. Consider a revised version of PAST:

PAST′ I have no influence over the past branch-relative state at time t: there are no alternative decisions d_1 and d_2 possible for me at t such that $d_1 \mathrel{\Box\!\!\rightarrow} s_1$ and $d_2 \mathrel{\Box\!\!\rightarrow} s_2$, where s_1 and s_2 are incompatible branch-relative states of affairs that pertain to times prior to t.

An advocate of Loewer's compatibilism can reject PAST′ without rejecting LAWS. One can do so on the strongly deterministic Everettian Wentaculus, because rejecting PAST′ is compatible with retaining PAST. On this approach, I do not have influence over the past state of the multiverse but I do have influence over the past branch-relative state. If I had raised my arm, I would have come from a different branch than the one I am on. Hence, the compatibilist may concede to van Inwagen that I have

[49] In the Everettian Wentaculus, we might make sense of branch-relative regularities such that the distinction still holds. There are non-fundamental and branch-relative descriptions of the mosaic such that not all regularities are laws.

no free will in the sense of influencing the future state of the multiverse, but I still have free will in the sense of influencing the branch-relative future, i.e. which future branch will be mine. The question is whether this sense of free will is sufficient to accommodate the conception of free will that the compatibilist wants. However, it is worth noting that it is an open question how to think about freedom and agency in a multiverse context. So perhaps it is not unreasonable to expect that some of our intuitions will have to be revised.[50]

6 Conclusion

Strong determinism holds when the actual world is the only nomologically possible world. There are many reasons to be interested in strong determinism. As illustrated by the Lone-Particle World and the Mandelbrot World, it enables strong explanations and strong predictions. It also raises vexing questions about the status of causation and counterfactuals. The Everettian Wentaculus, the first realistic and simple strongly deterministic theory, teaches us that strong determinism may well be true but does not always have the features we naively expect of it.[51]

Even if strong determinism fails to be true, it is closer to the actual world than we have presumed, with implications for a variety of topics in philosophy and foundations of physics. Thus, it would be a mistake to regard it as impossible. This paper has explored only some aspects of strong determinism; it has much more to teach us. Regarding determinism, Earman (1986) writes:

> [D]eterminism wins our unceasing admiration in forcing to the surface many of the more important and intriguing issues in the length and breadth of the philosophy of science. (p.21)

Strong determinism is admirable for the same reason.

Acknowledgement

An earlier version of this paper was presented at the Lake Arrowhead Conference of the California Quantum Interpretation Network in September 2021 and the Quantum Foundations Seminar at the University of Surrey in October 2021. I thank the participants in both events, especially Jim Al-Khalili, Jeff Barrett, Craig Callender, David Glick, Mario Hubert, Matthew Leifer, Alyssa Ney, Simon Saunders, Lev Vaidman, and Ken Wharton. I am also grateful for helpful discussions with Eugene

[50]This move has an additional welcome feature. As discussed in fn.28, people (such as Frisch) who object to the possibility that I can have causal influence over the past may be less worried about the account here, as the influence I have over past are over branch-relative self-locating states and not the state of the world.

[51]Is strong determinism a theoretical virtue? That is a hard question. Some might endorse the following principle: other things being equal, strong determinism makes a theory better. But the interesting and open question is exactly when other things are equal. It would be more fruitful to regard it as one of the many good-making features a theory may have.

Chua, David Danks, Sam Elgin, Mathias Frisch, Sheldon Goldstein, Barry Loewer, Daniel Rubio, Alessendro Torza, James Weatherall, and Alastair Wilson. I thank Don Rutherford and Shelly Yiran Shi for discussions about the connections between Leibniz's PSR and determinism. I benefited immensely from the research assistance of Shelly Yiran Shi, who provided detailed comments on multiple drafts of this paper.

References

Adams, R. M. (1994). *Leibniz: determinist, theist, idealist*. Oxford University Press.

Adlam, E. (2021). Determinism beyond time evolution. *arXiv preprint arXiv:2110.07656*.

Albert, D. Z. (2000). *Time and chance*. Cambridge: Harvard University Press.

Albert, D. Z. (2015). *After physics*. Cambridge: Harvard University Press.

Allori, V., Goldstein, S., Tumulka, R., and Zanghì, N. (2010). Many worlds and Schrödinger's first quantum theory. *British Journal for the Philosophy of Science*, 62(1):1–27.

Ashtekar, A. and Gupt, B. (2016). Initial conditions for cosmological perturbations. *Classical and Quantum Gravity*, 34(3):035004.

Bhogal, H. (2020). Humeanism about laws of nature. *Philosophy Compass*, 15(8):e12696.

Boltzmann, L. (1897). Zu Hrn. Zermelos Abhandlung „Über die mechanische Erklärung irreversibler Vorgänge ". *Annalen der Physik*, 60:392–398.

Boltzmann, L. (1964). *Lectures on gas theory*. Berkeley: University of California Press.

Callender, C. (2004). Measures, explanations and the past: Should 'special' initial conditions be explained? *The British Journal for the Philosophy of Science*, 55(2):195–217.

Callender, C. (2011). Thermodynamic asymmetry in time. In Zalta, E. N., editor, *The Stanford Encyclopedia of Philosophy*. Metaphysics Research Lab, Stanford University, fall 2011 edition.

Carroll, J. W. (2020). Laws of Nature. In Zalta, E. N., editor, *The Stanford Encyclopedia of Philosophy*. Metaphysics Research Lab, Stanford University, Winter 2020 edition.

Chen, E. K. (2018). Quantum mechanics in a time-asymmetric universe: On the nature of the initial quantum state. *The British Journal for the Philosophy of Science*, doi.org/10.1093/bjps/axy068.

Chen, E. K. (2019). Quantum states of a time-asymmetric universe: Wave function, density matrix, and empirical equivalence. *Master's Thesis, Department of Mathematics, Rutgers University, New Brunswick. arXiv:1901.08053.*

Chen, E. K. (2020a). From time asymmetry to quantum entanglement: The Humean unification. *Noûs*, pages 1–29.

Chen, E. K. (2020b). The Past Hypothesis and the nature of physical laws. In Loewer, Barry, W. E. and Weslake, B., editors, *Time's Arrows and the Probability Structure of the World*. Harvard University Press, forthcoming.

Chen, E. K. (2020c). Time's arrow in a quantum universe: On the status of statistical mechanical probabilities. In Allori, V., editor, *Statistical Mechanics and Scientific Explanation: Determinism, Indeterminism and Laws of Nature*. Singapore: World Scientific.

Chen, E. K. (2021). The cosmic void. In Bernstein, S. and Goldschmidt, T., editors, *Non-Being: New Essays on the Metaphysics of Nonexistence*. Oxford University Press.

Chen, E. K. (2022). Fundamental nomic vagueness. *The Philosophical Review*, 131(1).

Chen, E. K. and Goldstein, S. (2021). Governing without a fundamental direction of time: Minimal primitivism about laws of nature. In Ben-Menahem, Y., editor, *Rethinking Laws of Nature (forthcoming)*. Springer.

Dorr, C. (2016). Against counterfactual miracles. *The Philosophical Review*, 125(2):241–286.

Dürr, D., Goldstein, S., and Zanghì, N. (1992). Quantum equilibrium and the origin of absolute uncertainty. *Journal of Statistical Physics*, 67(5-6):843–907.

Earman, J. (1986). *A primer on determinism*, volume 32. D. Reidel Publishing Company.

Elga, A. (2001). Statistical mechanics and the asymmetry of counterfactual dependence. *Philosophy of Science*, 68(S3):S313–S324.

Fernandes, A. (2013). Time, flies, and why we can't control the past. In Barry Loewer, Eric Winsberg, B. W., editor, *Time's Arrows and the Probability Structure of the world*. Harvard University Press, forthcoming.

Feynman, R. (2017). *The Character of Physical Law*. Cambridge: MIT press.

Frisch, M. (2005). Counterfactuals and the past hypothesis. *Philosophy of Science*, 72(5):739–750.

Frisch, M. (2007). Causation, counterfactuals, and entropy. In Price, H. and Corry, R., editors, *Causation, physics, and the constitution of reality: Russell's republic revisited*. Oxford University Press.

Goldstein, S. (2001). Boltzmann's approach to statistical mechanics. In Bricmont, J., Dürr, D., Galavotti, M. C., Ghirardi, G., Petruccione, F., and Zanghì, N., editors, *Chance in Physics*, pages 39–54. Berlin: Springer.

Goldstein, S., Lebowitz, J. L., Tumulka, R., and Zanghì, N. (2020). Gibbs and Boltzmann entropy in classical and quantum mechanics. In Allori, V., editor, *Statistical Mechanics and Scientific Explanation: Determinism, Indeterminism and Laws of Nature*. Singapore: World Scientific.

Gómez Sánchez, V. (2020). Crystallized regularities. *Journal of Philosophy*, 117:434–466.

Harding, J. (2021). Everettian quantum mechanics and the metaphysics of modality. *The British Journal for the Philosophy of Science*.

Hartle, J. B. and Hawking, S. W. (1983). Wave function of the universe. *Physical Review D*, 28(12):2960.

Hildebrand, T. (2020). Non-humean theories of natural necessity. *Philosophy Compass*, 15(5):e12662.

Hoefer, C. (2016). Causal Determinism. In Zalta, E. N., editor, *The Stanford Encyclopedia of Philosophy*. Metaphysics Research Lab, Stanford University, Spring 2016 edition.

Holton, G. (1978). *The scientific imagination: Case studies*. Cambridge University Press.

Holton, G. and Elkana, Y. (1982). *Albert Einstein: Historical and cultural perspectives*. Princeton University Press.

Hossenfelder, S. and Palmer, T. (2020). Rethinking superdeterminism. *Frontiers in Physics*, 8:139.

Laplace, P.-S. (1820). *Théorie analytique des probabilités*. Paris: V. Courcier.

Lebowitz, J. L. (2008). Time's arrow and Boltzmann's entropy. *Scholarpedia*, 3(4):3448.

Leibniz, G. W. (1989). *Philosophical Essays*. Hackett, Indianapolis. Translated by Roger Ariew and Daniel Garber.

Lewis, D. (1973). *Counterfactuals*. Blackwell, Oxford.

Lewis, D. (1983). New work for a theory of universals. *Australasian Journal of Philosophy*, 61:343–77.

Lewis, D. (1986). *Philosophical papers II*. Oxford: Oxford University Press.

Loewer, B. (2007a). Counterfactuals and the second law. In Price, H. and Corry, R., editors, *Causation, Physics, and the Constitution of Reality: Russell's Republic Revisited*. Oxford University Press.

Loewer, B. (2007b). Laws and natural properties. *Philosophical Topics*, 35(1/2):313–328.

Loewer, B. (2012). Two accounts of laws and time. *Philosophical Studies*, 160(1):115–137.

Loewer, B. (2020a). The consequence argument meets the Mentaculus. In Barry Loewer, Eric Winsberg, B. W., editor, *Time's Arrows and the Probability Structure of the world*. Harvard University Press, forthcoming.

Loewer, B. (2020b). The Mentaculus vision. In Allori, V., editor, *Statistical Mechanics and Scientific Explanation: Determinism, Indeterminism and Laws of Nature*. Singapore: World Scientific.

Maudlin, T. (2007). *The Metaphysics Within Physics*. Oxford University Press, New York.

Menzies, P. and Beebee, H. (2020). Counterfactual Theories of Causation. In Zalta, E. N., editor, *The Stanford Encyclopedia of Philosophy*. Metaphysics Research Lab, Stanford University, Winter 2020 edition.

Montague, R. (1974). *Formal Philosophy: Selected Papers of Richard Montague*. Yale University Press, New Haven.

Nagel, E. (1961). *The Structure of Science*. Harcourt, Brace, and World.

North, J. (2011). Time in thermodynamics. *The oxford handbook of philosophy of time*, pages 312–350.

Pearl, J. (2009). *Causality*. Cambridge University Press.

Penrose, R. (1974). The role of aesthetics in pure and applied mathematical research. *Bull. Inst. Math. Appl.*, 10:266–271.

Penrose, R. (1979). Singularities and time-asymmetry. In Hawking, S. and Israel, W., editors, *General relativity*, pages 581–638. Cambridge: Cambridge University Press.

Penrose, R. (1989). *The Emperor's New Mind: Concerning Computers, Minds, and the Laws of physics*. Oxford: Oxford University Press.

Rodriguez-Pereyra, G. (2018). The principles of contradiction, sufficient reason, and identity of indiscernibles. In Antognazza, M. R., editor, *The Oxford Handbook of Leibniz*, pages 204–215. Oxford University Press.

Russell, B. (1913). On the notion of cause. *Proceedings of the Aristotelian society*, 13:1–26.

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

Sebens, C. T. and Carroll, S. M. (2016). Self-locating uncertainty and the origin of probability in everettian quantum mechanics. *The British Journal for the Philosophy of Science*, 69(1):25–74.

Sider, T. (2011). *Writing the Book of the World*. Clarendon Press, Oxford.

Torza, A. (2020). Laws of nature and theory choice. *Manuscript*.

Vaidman, L. (2021). Many-worlds interpretation of quantum mechanics. In Zalta, E. N., editor, *The Stanford Encyclopedia of Philosophy*. Metaphysics Research Lab, Stanford University, fall 2021 edition.

Van Inwagen, P. (1983). *An essay on free will*. Oxford: Clarendon Press.

Wallace, D. (2011). The logic of the past hypothesis. manuscript.

Wallace, D. (2012). *The Emergent Multiverse: Quantum theory according to the Everett interpretation*. Oxford: Oxford University Press.

Weinberg, S. (1992). *Dreams of a Final Theory: The Search for the Fundamental Laws of Nature*. New York: Pantheon.

Wilson, A. (2020). *The nature of contingency: Quantum physics as modal realism*. Oxford University Press, USA.

Woodward, J. (2016). Causation and Manipulability. In Zalta, E. N., editor, *The Stanford Encyclopedia of Philosophy*. Metaphysics Research Lab, Stanford University, Winter 2016 edition.