# Three Questions About the Metaphysics of Chance

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**Abstract**

Probability, we are often told, is graded possibility. In this paper, I offer an analysis of the chances which turn up in physics from the perspective of modal metaphysics. In particular, I offer three questions which probe the nature of chance and possibility, delineating a total of eight viable views on the metaphysical nature of chance. I contextualize this taxonomy of views with some discussion on physical chance-laws, and in particular the physical chances which arise in quantum mechanics. Gestures are made towards various avenues for further inquiry.

## I.

## An Inventory of Physical Chance Laws

The formalism of probability is ubiquitous in the natural sciences. Despite its historical origins as a purely utilitarian tool developed to assist gamblers and investors in formulating risk assessments, probability and related notions have since found their way into our mathematical descriptions of the natural world. We often find ourselves saying "there is an 80% chance of rain," and we do not necessarily think of ourselves as merely offering advice to bettors. The extent to which probabilistic talk today permeates our natural language perhaps obscures the fact that we don't actually know what it is. What are we talking about when we talk about probability?

Philosophers typically distinguish two broad categories of probabilistic talk: chance, which is to say, *objective* chance or *physical* chance; and credence, which is taken to be an epistemic feature of an agent operating with less-than-complete information about the system she is analyzing. Credence, it could be compellingly argued, is well understood. Decision theory provides a detailed account of how credence arises as a necessary tool for rational decisionmaking under circumstances of ignorance, tracing its direct lineage to the origin of probability theory in games of chance. It is also quite intuitive how we would extend this logic beyond the traditional bounds of academic decision theory, understanding the more informal, everyday manifestations of credence (such as when we say "there is probably food at the event") as inputs into a deliberative process (such as whether to eat before going to the event). From another angle: we should expect an evolved being, who seeks her own survival and reproduction in contexts of ignorance, to have a hard-wired notion of credence.

Less consensus has been reached regarding the concept of physical chance, which will be the focus of this paper. It is a curious fact that the rules of physics that we have written down contain chances. What could this mean?

Please note a crucial distinction that I believe is often overlooked. There is the present-day *physics canon*, a set of theoretical and computational tools used by humans to analyze and manipulate the world. And then there are the bona fide *laws of nature*, which either govern the world or describe it perfectly, depending on your religion.[1] When we say that the rules of physics contain chances, we are talking about the former, because it unfortunately is all that we have access to. Statistical mechanics, fluid dynamics, quantum mechanics, and even some contexts in classical Newtonian physics all produce predictions of future events in probabilistic terms—not "X will happen" but "X is 40% likely and Y is 60% likely." Our inability to predict exactly whether X or Y will actually happen may in the end be only a feature of our collective ignorance, or it may be a genuine aspect of reality. Physicists and philosophers of physics are not so certain on

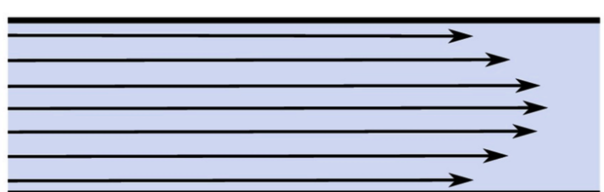
[1]The governance view asserts that laws constrain or create the world, while the Humean or "mere patterns" view asserts that the world simply is, and the laws describe it succinctly.

this point as traditional philosophers often make us out to be.[2]

My aim in this paper is not to argue for one particular interpretation of these chances in physical law, but to offer a taxonomy of what views are still viable, given all that we have seen. In this section I will run through a very quick inventory of where chance appears in physical law, and categorize all as either "emergent" or "fundamental." In §2, I will draw the analogy between probability and possibility, stressingly the inherently metaphysical nature of interpreting chance. My primary contribution is in §3, which offers a three-question taxonomy of metaphysical views on chance. §4 discusses this questionnaire in the context of quantum mechanical chances, and §5 suggests a few additional lines of inquiry regarding the nature and origin of the probability measure on each view. Let's begin.

Here is an example of a physical system which can be said to evolve unpredictably. There is a shallow stream of water working its way down a slight incline, over a bed of rocks and sticks and soil arranged in a particular way. A leaf drops onto the surface of the water several meters upstream of a boulder which briefly splits the stream into two paths. Will the leaf proceed down the left path or the right path?

If the stream is an oversimplified, smooth basin of water flowing linearly downhill in an environment of absolute stillness, the question is easy to answer. A leaf on the left half of the stream takes the left path, and one on the right half takes the right path. This is a *laminar* or *smooth flow*: a slight change in the initial conditions leads to a predictably small change in the future state of the system.

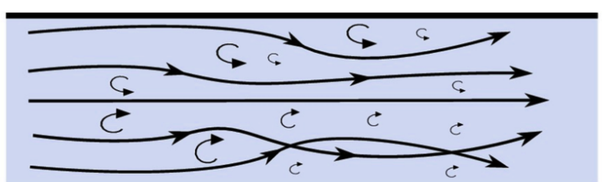


But if the stream is anything like a real, naturally-occuring stream, it is nearly impossible to answer this question with certainty. The flow of the water is highly complex,

[2] Quantum physics (and in particular radioactive decay) is often informally characterized as "proving" that there is genuine in-the-world chance. This is not so, as we will see in §4.

deflecting off every pebble and particulate, compressing and sloshing upward, possibly even developing eddies or frothing and interacting with the air and wind. Even if we understand the microscopical mechanical laws which govern all particles in the system (and we somewhat miraculously believe that we do), this knowledge is useless to us unless we know the exact position of every object at the initial time and have a supercomputer capable of running a program as complex as the world itself.

This is a *turbulent flow*: the path of a leaf depends sensitively on initial conditions. Move the initial position of the leaf very slightly and its future trajectory will change dramatically. Compress a tiny patch of soil miles downstream and the trajectory will change dramatically. The region of the stream which feeds into the left path is fractal-like, infinitesimally interwoven with the region that feeds into the right — and its boundaries shift chaotically as time proceeds. To predict the system's behavior, in practice, we must make approximations, and we must project probabilistically. We may run hundreds or thousands of simulations of streams from different initial "microstates" (exact locations of all objects) that are consistent with the observed "macrostate" (approximate locations of objects, as best as we can measure). We don't know which microstate is the correct one, but if 80% of the microstates we try proceed down the left path, we can guess that the true microstate has an 80% chance of proceeding down the left path.



This example comes from fluid dynamics, but it is representative of the broader category of *emergent chances* in physical law. These are cases where we believe the actual fundamental natural law to be purely deterministic, but we do not know which exact microstate we are starting from. So we average over a "statistical ensemble" of similar microstates, and obtain a probabilistic answer. These probabilities are not fundamental, and we expect that an independent omniscient observer would be able to compute the exact future trajectory without hedging.

Two useful concepts associated with emergent chances are *chaos theory* and *the butterfly effect*. A chaotic system is one like the turbulent flow in fluid dynamics: a system whose trajectory is sensitively dependent on initial conditions. Examples from physics include weather patterns, a double pendulum, the $n$-body problem, billiard balls on an oval table, and many more. The butterfly effect is a common natural language description of such systems, indicating that a minuscule change in the state at time $t_0$ leads to dramatically different behavior at all times $t > t_0$. Wherever we have a chaotic system, the butterfly effect reigns, and emergent chances must be used to analyze the system practically.

Then there are *fundamental chances*. These are, at least hypothetically, chances that are genuinely baked into the nature of reality. We imagine that if we were to rewind the tape and play it back again, things would shake out differently. At least that is how such matters are often informally discussed; as we will see in §3 and §4, even this is not so certain. The canonical example of fundamental chances comes from quantum mechanics, which predicts the behavior of fundamental particles such as electrons and quarks. Given the exact position, momentum, spin, and so forth of any number of fundamental particles, and given a particular interaction between the particles, the formalism of quantum mechanics produces a numerical value that corresponds to the chance of that interaction occurring. We are not (as far as we know) making any simplifying assumptions or guesses about the initial conditions of the system, and yet the predictions are probabilistic. We are looking at one single microstate, and its future evolution is chancy.

What are we to make of this? Physicists and engineers do not spend too much time thinking about it: they simply use the probabilistic predictions to explain observed phenomena and to develop new machines and weapons. To a philosopher, though, the existence and unmatched predictive success of these fundamental chance laws is worth a moment's consideration. Perhaps there is something to be learned about the nature of possibility and questions of determinism by staring into microscopes.

## II.
## Chance and Modality

It is an unspoken background assumption in philosophical discussions of chance that probability is no more than graded possibility. I wish to make use of this analogy in this paper, but I must first take a moment to complicate it slightly.

The positive aspects of this analogy are self-evident. Modal claims and probabilistic claims are both claims made, roughly speaking, somewhere between true and false. You're not saying "Gina is going to be late" but you're also not saying "Gina isn't going to be late." You're saying she might be: there's a world where she will be and a world where she won't. In the case of probabilistic claims, you go the extra step of quantifying (somehow; see §5) the worlds where she's late vis-à-vis the worlds where she isn't.

The two theories also admit similar formal treatments. In modal logic we might write

$$\Diamond \text{ Gina will be late.} \tag{1}$$

to indicate that for some set of possible worlds $G$, there is a world $w \in G$ such that $w \models$ Gina will be late. Meanwhile, we write

$$P(\text{Gina will be late.}) = \tfrac{3}{5} \tag{2}$$

to indicate that for some set of possible outcomes $\Omega$, there are outcomes $x \in \Omega$ such that in $x$, Gina will be late; moreover, the set of all such $x$'s makes up precisely $\frac{3}{5}$ of $\Omega$. (More on that in a moment.) We could stress the underlying similarities further by adjusting probabilistic notation to accommodate modal logic:

$$\langle \tfrac{3}{5} \rangle \text{ Gina will be late.} \tag{3}$$

We can be a bit more precise with what we mean by "probability is graded possibility." What we mean is that probability theory is isomorphic to modal logic with an added measure $m : \Sigma_G \to [0,1]$. What exactly the metaphysical nature of this measure is is an open question. For now it suffices to say that each set of possible worlds in the modal frame is assigned a real number between zero and one, that this assignment is countably additive, and that the empty set is assigned a value of zero.

In the case of physical chances, the positive aspects of the analogy extend beyond notation and formal treatment to the semantic interpretation of claims and the metaphysical questions one might pose about the scenarios described by such claims. The modal claim (1) and the probabilistic claim (3) are both descriptive claims[3] asserted to be true not in one specifically identified world (a microstate) but in some of a large number of worlds that share large-scale features in common (a macrostate). One of these worlds is presumed to be "actual" in a sense which we will interrogate momentarily, while the rest differ substantively from the actual one yet bear some relation of similarity or accessibility to it. Perhaps they are exactly the physically possible worlds indistinguishable from the actual world, to a particular epistemic agent with a particular notion of indistinguishability, or those which *were* indistinguishable at a particular moment in the past. Or perhaps the accessibility relation is objective, a fact of reality or natural law, as opposed to a feature of an observer. These are metaphysically substantive questions which must be answered about both chance and modality, and it seems that the right questions to ask will be the same in both instances.

Before asking these questions, I would like to point out three negative aspects of the analogy between chance and modality, which is to say, three places where the translation process between the two fails. The first is what we may call the *bullseye problem*. In the case of physical chances, there may be a macrostate consisting of infinitely many microstates, and the measure assigned to a subset of microstates may be zero even if that subset is non-empty. For instance, consider a world consisting of two real numbers $x$ and $y$ chosen uniformly at random from the range $[0,1]$. The chance that $x = y$ is

[3]We will only be discussing descriptive claims in this paper; no "It is possible that one should revolt against oppressive governments" or any normative modal claims.

zero:

$$\langle 0 \rangle \ x = y \tag{4}$$

We might naïvely think to write this in modal terms as a claim of impossibility:

$$\neg\Diamond \ x = y \tag{5}$$

$$\Box \ x \neq y \tag{6}$$

and yet there clearly exist worlds in the frame in which $x = y$. This is a significant disanalogy which should be addressed in the context of metaphysical interpretations of physical chance.

The converse problem, which we may call the *long tail problem*, is troubling as well: there are macrostates (subsets of possible worlds) to which the probabilistic measure assigns a non-zero value, which we nonetheless would like to consider "impossible" or "necessarily false." In physics we often take the position and momentum of any particle to be given by a normal distribution or some other probability distribution with "long tails," that is, which is nowhere zero. This means that there is a non-zero chance that one of the electrons associated with a nucleus in my nose is presently located in Kamchatka. More troublingly, it assigns a far smaller but still non-zero chance that my entire nose is presently located in Kamchatka. In statistical mechanics, very small but non-zero probabilities are assigned to all sorts of outrageous scenarios, such as a puddle of water in a hot room unmelting into a perfect ice cube[4] or a car driven off a cliff exploding in precisely such a way that all of its debris particles gather back at the top of the cliff and click into place as an unscathed car. Obviously these scenarios in the "long tails" of probability distributions should not be considered "possible" on any traditional modal

[4]The microdynamical laws of physics are exactly time-symmetric, so any process which proceeds forward in time can also proceed identically backward in time. The set of forward paths associated with "reasonable" scenarios, such as an ice cube melting in a hot room, are just assigned far higher probabilities than the set associated with "unreasonable" ones.

reading, and yet they have non-zero probability.

A third and final disanalogy receives comparably little attention but is, I believe, still a notable weakness of the project. This is what we may call the *macrostate problem*. In discussions of chance, and in physics in particular, we often state claims that apply not to a particular microstate but to a macrostate of many individual worlds at once. For instance, the thermodynamic variable of entropy is often considered to not be a feature of any one world in isolation, but of a set of worlds with similar large-scale measurables (temperature, pressure, etc.). There is no way to convert such a claim from physics into modal talk, as there is no way in modal logic to state claims about multiple worlds at once. This could likely be rectified by a generalization of the notation used in modal claim-making, but it remains a disanalogy at the present moment which would prevent, for instance, a complete formal treatment of thermodynamics in terms of modality.

It will not be the focus of this paper to attempt to resolve these disanalogies; I simply felt it necessary to state them openly before proceeding to ignore them entirely for the remainder of the paper. We will now proceed as if chance and modality are for all practical purposes identical — not, I hope you'll agree, too outrageous of a simplifying assumption. With this in mind, we are prepared to pose the three questions which delineate metaphysical views on chance and possibility.

## III.
## Three Questions

For clarity and consistency, I will make use of a simple toy model throughout this section, which will allow us to abstract away the particularities of different chance events we have explored so far. In doing so, I run the risk of suggesting that all chance events are fundamentally alike, which I hope I have made clear is not the case. While all the chance events we are considering share certain core similarities — a unitary measure over at least two distinct possibilities, a time after which only one possibility is deemed to have actually transpired — they may be metaphysically quite dissimilar. Choosing a door in the Monty Hall problem may be substantively different from flipping a coin, and the path of an object in a turbulent flow may be substantively different from the outcome of a spin measurement on a fundamental particle. In a proper taxonomy of chance events, different events will likely be sorted differently.

It is my project at this time, however, to offer a *taxonomy of metaphysical views* about the nature of chances in fundamental physical law. These two taxonomies will of course consist in the exact same categories: given any final physical theory that is presumed to contain all facts of our physical reality, we may distinguish the metaphysical views by their answers to the question "what kind of chance events are the fundamental physical chances?" I wish to remain neutral at this time as to what the final physical theory actually is, or even if such a theory exists, and so I will focus on a toy model when posing the three questions. (I do not mean to suggest that the toy model resembles the genuine physical chances.) We will then consider whether all the resulting categories are plausibly self-consistent in the context of fundamental chances, and in §4 I will specifically focus on the case of chances in quantum mechanics.

The toy model is a coin flip which comes up Tails. There is a fair coin, with faces Heads and Tails, which is flipped once at time $t_{\text{flip}}$, and lands with the Tails face up. It is difficult to specify the scenario (for instance, what is meant by a "fair coin") without implicitly taking a stance on the three questions I am about to ask. The relevant points, though, should be intuitively clear: there are two possibilities, which we call Heads and Tails; before $t_{\text{flip}}$ both are said to have a $\frac{1}{2}$ chance; after $t_{\text{flip}}$ the Tails event is said to be the actual outcome and Heads is not. We are not concerned with the symmetries of the coin or anything like that. It may just as well be an $x$-spin measurement on a $z$-spin up electron, or an outcome of a close gubernatorial election. I just need a test case. Don't overthink it.

Here are the three questions. I have given each question a name and each answer a one-character identifier for ease of reference. The first two questions have already arisen in numerous guises in the literatures on metaphysics and the foundations of physics, while I have never found the third taken seriously in secular academic writing. I see no reason to exclude conceivable views at this time, and thus I have chosen to include the third question even if my expected audience may find it uninteresting or absurd.

**(1/2)**

**The question of actuality:**

*Is the actual outcome metaphysically real*
*in a way that the non-actual outcome is not?*

(1) Yes (2) No

In our toy model, we may expand the two options as follows:

(1) There is a single metaphysically real world, in which the coin flip came up Tails. Perhaps it *could have* come up Heads, but it didn't. There is no sense in which the coin flip came up Heads "somewhere else" or "in another world" or anything like that. The scenario in which the coin came up Heads was a fictional scenario we imagined prior to the event. This may have been a useful fiction for us to imagine. That doesn't make it real any more than our imagining talking dogs makes dogs talk. The coin came up Tails and it did not come up Heads.

(2) There is a world in which the coin came up Tails and a world in which the coin came up Heads and we happen to inhabit the world in which the coin came up Tails. The "actual" outcome is a purely indexical term, like "here" or "now," and in our world the term "actual outcome" refers to Tails. There are people quite like you and me who inhabit a world where the coin came up Heads, and for them the term "actual outcome" refers to Heads. From an outside perspective there is no way to metaphysically privilege one world as "real" and the other as "fictional."

The character (1) indicates that there is one world like ours, and (2) indicates that there are two or more worlds like ours.

**(E/A)**

**The question of determinacy:**

*Prior to the event, was there a fact of the matter*

*about which outcome would be the actual one?*

(E) Yes (A) No

(E) Facts are not located in time. Humans travel through time, learning more facts as we do, but we should not take this to mean that the facts we have not yet learned are not yet facts. The coin was always going to come up Tails, because the evolution of the universe is fundamentally deterministic, even if our current best models of it are not. An independent omniscient observer could in theory tell us the outcomes of all future coin flips, too. Lived experience is like watching a movie: you may not know what happens next, but it is already written. Chance, even fundamental physical chance, is irreducibly epistemic.

(A) Before the coin was flipped, it was simply not yet determined which way it would come up. The chance event was just that: a chance event. It could have gone Heads and it could have gone Tails. You didn't know it would be Tails and I didn't know it would be Tails because it was genuinely unknowable before $t_{\text{flip}}$ that it would be Tails. Even an independent omniscient observer couldn't have told us it would be Tails, because it wasn't yet that case that it would be Tails; it was just the case that there was a 50-50 shot either way. There is genuine, absolute chance, baked into the fundamental laws of nature.

The character (E) stands for epistemic, and (A) stands for absolute.

**(*/∅)**

**The question of intention:**

*Does any form of intention, desire, design, or plan*

*play a role in which event actually occurred?*

(*) Yes (∅) No

(*) While it is certainly possible that we live in a cold, uncaring universe, the physical facts do not require it. A chance event is an event that is in some good sense underdetermined, and each instance of underdetermination leaves an open door. Each coin flip, each lottery pick, each weather pattern, each genetic mutation, each election: open doors. What is the nature of the process which subsequently determines the outcomes? For the chancy processes taking place inside our skulls, there certainly seems to be intention in this process. Why, then, are we ridiculed for imagining that the chance events outside our skull are similar?

(∅) There is of course *room* for a supernatural intention in chancy processes, some sort of benevolent yet tightly constrained divinity enacting its grand plan by guiding the results of coin flips. But why on Earth should we believe this? There isn't evidence for such a view and never could be, so we ought to stick to the minimal ontology which reproduces all observed phenomena. Yes, it's comforting to imagine there's intention in all of it, and it's a natural human instinct to impute anthropomorphic features to the world around us. Ultimately, though, before we start telling our stories, all that's out there is genuine, cold, hard chance.

The character (*) suggests some extra feature of reality, while (∅) denotes nothing.

The eight categories generated by all combinations of possible answers to these three questions may each be denoted by stringing together the answer characters in order, with ∅ omitted. For instance, **1A*** and **2E** are two such categories. We will use this notation for the remainder of the paper.

Note: all I have really done so far is provide a taxonomy of chance events. One may reasonably believe, for instance, that the event of revealing the color of the top card of a deck is **1E** (since the card is determined before you flip it) while also believing that the color a ball lands on in a roulette wheel is **1A** (since the physical system is chaotic). This is a perfectly interesting taxonomy, and may find other philosophical applications. For our purposes, though, we will be interested only in a single application: the taxonomy of metaphysical views about fundamental chances.

Imagine we are handed a final physical theory which perfectly describes the natural world. The theory contains a time-evolution law, which relates the worldstate at one time to the worldstate at another. Imagine that this time-evolution law is underdetermined. More specifically, imagine the theory is such that, given a worldstate $w(t_{\text{pre}})$ at time $t_{\text{pre}} < t_{\text{flip}}$, there are exactly two worldstates $w_1(t_{\text{post}})$ and $w_2(t_{\text{post}})$ at time $t_{\text{post}} > t_{\text{flip}}$ consistent with the laws of nature, and that each has a $\frac{1}{2}$ chance of obtaining, and moreover that no information present in the world prior to $t_{\text{flip}}$ is at all correlated with which outcome actually obtains.[5] What would you make of this? How would you characterize what exactly it is that happens at $t_{\text{flip}}$?

Your answers to the questions of actuality, determinacy, and intention in the case of these fundamental physical chance laws characterizes, I argue, your metaphysical view of possibility (subject to the assumption that you accept the provided theory as precisely valid). Note that your answers to these three questions are not in fact correlated with any possible measurements that can be made; how, for instance, could you determine whether there is intention in the outcomes of chance events by observing large numbers of them? No, all possible predictive claims are already contained in the theory that has been handed down. The three questions are, in other words, purely interpretative, extra-empirical, descriptive questions, about how we choose to tell the story of the physical theory once we have decided what it mathematically is.

Are all eight views plausibly self-consistent? For the remainder of this section, I will go through the options in the context of this question. Ultimately, I believe the answer is yes, and I find that many if not all of the eight boxes are recognizable views on possibility. Some are, as previously mentioned, uncommon in academic settings, and in particular I expect that many academic philosophers will find the * views unappealing. Nonetheless, I personally find that a perfectly reasonable argument can in theory be made for any of

[5] Of course, the insistence on a binary decision with equal probabilities assigned to each outcome is only one overly simple example of what a fundamental chance-law could look like. This is meant to maintain continuity with the coin-flip model, and the metaphysical questions are I believe identical regardless of the cardinality of the set of outcomes and the probability measure over them. In §4 we will turn to the chance-laws of quantum mechanics, a genuine contender (to some) for a final theory.

the combinations.

**1E** and **1A** are perhaps the most standard, recognizable views of the bunch; most contemporary "naturalist" views of scientific realism (with the exception of Everett/many-worlds views, discussed in §4) would fall into one of these categories. **1E** posits a single, deterministic world that is fixed from the initial conditions of the universe. Anything that looks like chance, in a **1E** world, is purely a feature of our own ignorance, and if we knew more about the present state of the universe we would cease to be uncertain about its future states. By contrast, **1A** is non-deterministic, and it is the case that nature "plays dice," so to speak. **1E** can be thought of as the high aspiration of Newtonian and pre-20th century physics, while **1A** is the view that many scientists have taken since the advent of quantum mechanics. Neither view permits a strong, incompatibilist free will.

The **2** views are less common in academia but highly prevalent in fiction and in many traditional belief systems. They have also, in the second half of the 20th century, found notable Western-naturalist treatments in David Lewis's modal realism (Lewis 1986) and Hugh Everett's many-worlds interpretation of quantum mechanics (Everett 1957). Lewis has called **2A** a "branching" view and **2E** a "divergence" view. In **2A**, your present self genuinely splits into two selves when the flip occurs, and there is not yet a fact as to which self "you" will proceed to be after the flip. In **2E**, there are two separate worlds that are physically identical at the present moment but will diverge at the time of the flip, and you are just ignorant at present as to which of the two you are in. Again, any free will in these theories would have to be an emergent feature of purely random events.

These four ∅ views are summarized in the following table.

| | **1** | **2** |
|---|---|---|
| **E** | one deterministic world | many distinct worlds (divergence) |
| **A** | one chancy world | many branching worlds |

One might think that **E** and ***** are mutually inconsistent: how, after all, could there be intention in something that is not truly chancy so much as a revelation of an already-decided fact? In **1E***, there would have to be intention or design present in the initial conditions of the universe, which is then revealed to us as the deterministic time-evolution laws proceed. **2E*** is a bit trickier to square, but I believe an argument could still be made. As all the deterministic worldpaths are equally real, the plan would have to be specific to *you*, the you that is on the particular path that you are on, and the plans for your counterparts would have to be different. As the intentionality in either **1E*** or **2E*** is located at the beginning of time, so to speak, or perhaps outside of time, **E** and ***** in combination would be associated with notions of fate or destiny, and may sometimes be characterized by their own adherents as theistic. Free will would have to constrained by such predestination; perhaps our free choices are taken to be facets of the eternal divine intention. At this point we are winding through views that would require far more elaboration to be made viable, but I am simply hoping to sketch how one might try to stake a claim in any of these territories.

**1A*** is the view I would associate with the common usage of the term "free will." Here there is a single path that occurs, and there are numerous decision points at which an intentional choice is made as to how that path will proceed. All physical chance events are guided, so to speak, and the guiding which take place within your skull may be referred to in total as your self or soul. I suppose one could even choose a middle ground between ***** and $\emptyset$ in which some chance events are chosen and others are truly random, if one wants it to be the case that humans have free will in a way that plants and thunderstorms do not. **2A*** similarly involves freely chosen physical events located in time, though here it is the case that whenever you freely choose one path, there is another you elsewhere who freely chose the other path.

While some of these eight options may be dismissed as dualist or metaphysically rich by ontologists who have, in Quine's famous phrasing, "a taste for desert landscapes" (Quine 1948), I hope I have stressed sufficiently that all of these views are empirically identical and none can be ruled out by the scientific method alone.

## IV.
## Peculiarities of the Quantum Case

We now leave behind the simplified toy model of fundamental physical chances we have been employing up to this point and turn to quantum mechanics, a physical theory which (in its "textbook" formulation) contains fundamental chance events.

The picture of reality used in quantum field theory is, very roughly, something like this. Fundamentally what there is is not particles, but wavefunctions. One can think of a wavefunction intuitively as a density cloud over physical space. When we speak informally of an "electron" existing at a point in space, what we are really referring to is a very dense bunching of the electron cloud around that point. Thus particles are imprecise objects with fuzzy boundaries, much like "adulthood" or "Europe" or "bald." In fact, two electrons are not truly distinct from each other; they are two peaks in the electron wavefunction, with a continuous gradient between them.[6] There can even be *negative* density in the electron cloud, which manifests as antiparticles. The contours of the density cloud shift over time, continuously and deterministically, as described by the Schrödinger equation, but (without considering interactions such as electromagnetism, which are outside the scope of this paper), the sum total "amount of electron" present in the universe remains constant over time.[7]

Here is where chances come in. When we check experimentally whether there is an electron in a particular region of space, the apparatus always tells us that there is or there isn't. The wavefunction formalism suggests that there should sometimes be a total

[6]When two electrons cross paths, there is not a fact of the matter as to whether they passed through each other or deflected off each other.

[7]Strictly speaking, what I am calling the wavefunction is the square of the magnitude of the wavefunction, $\int |\psi|^2 =$ constant. The true wavefunction $\psi$ would have to be described as assigning a density as well as a phase angle $\theta$ to each point; the phase angle determines (roughly) whether two clouds passing through each other will add or subtract.

density of 0.2 electrons in the region, but we always find that there is 0 or 1. Moreover, we find that if we repeatedly check a region which we expect to have 0.2 electrons, we find an electron exactly 20% of the time.[8] (Weird, right?)

This doesn't appear to be a fluke. After the measurement, the game is changed: the wavefunction proceeds to evolve as if there was exactly 1 electron in the region at the time of measurement (or 0, if we measured no electron). On the simplest, most naïve reading of this event, our act of measurement has caused a spontaneous discontinuity in the wavefunction, instantaneously changing its density in the observed region from 0.2 to exactly 0 or 1. This is called the Copenhagen interpretation, and while many physicists adopt this story (it works perfectly well for making predictions, after all), philosophers of physics hope to find a more plausible or satisfying interpretation.

Variants of what I have called the **1A**, **1E**, **2A**, and **2E** metaphysical views of chance have all appeared in the literature on foundations of quantum mechanics. (The question of intention is largely left out of discussion but presumably always taken to be answered $\emptyset$.) Due to the particular nature of quantum theory, each of these views has additional bullets to bite, so to speak, beyond those in the above toy model. This is known as the "measurement problem": it is provably the case that an interpretation of quantum mechanics cannot simultaneously satisfy a small number of common ontological desiderata while still producing all the predictions of the theory. I will now give a brief overview of what these additional "bullets" are, in each of the four cases. If quantum mechanics or something similar to it turns out to be the so-called final theory, any metaphysical view of chance will have to bite one of these bullets.

The **1A** metaphysical view corresponds to a number of similar interpretations referred to as *collapse interpretations*. The simplest collapse interpretation is the naïve Copenhagen interpretation described above, in which observation truly does cause an in-

[8] For some reason, radioactive decay appears to be the most common formulation of these physical chances in philosophical discourse. Radioactive decay is governed by the weak interaction, one of the four fundamental interactions in the standard model. Whether an interaction will occur in a unit time is assigned a probability amplitude, much like the one assigned to finding a particle in a region of space. Thus whether a radioactive particle will decay within the next hour is, on the standard model, a fundamentally chancy event.

stantaneous physical collapse of the wavefunction. A more robust form of this approach is the GRW theory, which posits that each individual "particle" has an infinitesimally small absolute chance of collapsing (spontaneously contracting its density cloud to be almost wholly contained in a very small region of space) per unit time (Ghirardi et al. 1986). Because our measurement apparatus necessarily contains an unthinkably large number of individual particles, which all become entangled[9] in the act of measurement, measurement causes collapse *incidentally*. The bullet to bite here is that there must be spontaneous discontinuities in the time-evolution of the universe, rather than the smooth, deterministic evolution described by the Schrödinger equation.

The **1E** metaphysical view corresponds to *Bohm's interpretation*, also called *Bohmian mechanics*. On this view, there are wavefunctions, but there are also *bona fide* particles; the particles are guided by their wavefunctions like a cork in a stream (Bohm 1952). Thus when we check a region of space which should have 0.2 electrons, it does indeed have a volume of 0.2 of the electron wavefunction, but the actual point-electron guided by this wave is either in the region or it isn't. The chances are purely epistemic, reflecting the observer's uncertainty as to the initial locations of all the particles, and the guiding equation has particles move towards dense patches of the cloud in such a way that a 0.2 region will always have a 20% chance of containing a particle. Unfortunately, this condition requires that the guiding equation be non-local: the motion of a particle depends not just on the wavefunction density in its immediate surroundings, but the locations of all other particles in the universe. This is the bullet to bite in Bohm/**1E**: the laws of physics are non-local, and causation occurs instantaneously at great distances.

The **2A** metaphysical view corresponds to *Everett's interpretation*, also called the *many-worlds interpretation*. We take a definite mental state (like the type we typically consider ourselves to be experiencing) to be the product of definite particle locations (Everett 1957). The experimenter's experience of "measuring 1 electron" is delineated,

[9] In quantum theory, the laws of interactions between particles are encoded as relationships between wavefunctions. If one particle's wavefunction collapses, any "entangled" particle in a physical relationship with it will become tightly constrained, thus also undergoing effective collapse.

then, by a set of possible particle configurations inside her skull consistent with such a mental state. Without positing collapse or definite particle locations, the raw wavefunction formalism suggests that her brain is not in a single definite configuration, but rather a density cloud of different configurations, 0.2 of which correspond to the experience of "measuring 1 electron." The Everett interpetation takes this picture seriously, accepting that the true, complete physical state of the universe is not one in which we have definite mental states, but rather exist in many mental states at once, superposed on top of one another. This is considered by many to be too big a bullet: physical processes, including scientific experiments, cannot be said to have definite outcomes.

The **2E** metaphysical view is not associated with a canonical interpretation of quantum mechanics, though it had an early defender in Einstein and has recently been pushed by (Sebens 2015). On this reading, the wavefunction does not describe a single physical state of reality but rather an ensemble of many states composed of particles at definite locations, with the wavefunction now serving the non-fundamental role of a sort of summary or density function over the ensemble of states. We take our experience of reality to be a single member of this ensemble. The states each evolve in time in such a way that the sum total of all states obeys the Schrödinger equation. The bullet? In order for this to work out, there must be interaction between worlds; that is, the time-evolution of an individual world depends on the density of other worlds in similar states.

These four categories of interpretation, and the apparent problems with each, are summarized in the table below.

| | **1** | **2** |
|---|---|---|
| **E** | Bohmian mechanics<br>*non-local causation* | ensemble views<br>*interaction between worlds* |
| **A** | collapse (e.g. GRW)<br>*discontinuous time-evolution* | Everett/many-worlds<br>*no definite events* |

Let me try to drive home just how odd this predicament is. Let's assume, for the moment, that the predictions of quantum mechanics are generally correct throughout space and time, and not just coincidentally correct in all the cases we've tested them. Then, if there is one real world, it is either the case that causation operates instantaneously across large distance, or that physical matter moves discontinuously in space. Non-locality, discontinuity, or there are multiple physically real worlds like ours.

## IV$\frac{1}{2}$.
## A Brief Note on Intention

The question of intention is generally ignored in philosophy of physics, but it is worth saying a few words about it at this time. If one hopes it is the case that there is some form of intention (divine, human, supernatural, or however else) present in the universe, this option is not denied to us by quantum mechanics. The fundamental chance events present in the formalism may be considered on any of these four interpretations to either be genuinely chancy ($\emptyset$), or to have an intelligent guiding (*). Such guiding of the fundamental chance events would be sufficient, due to their ubiquity, to account for a genuinely libertarian free will, divine intervention or predestination in many physical matters, or both. I will quickly and non-rigorously illustrate this point, assuming a **1A**/collapse interpretation for simplicity.

As discussed in §1, many common physical systems are "chaotic" or "turbulent," which is to say, highly sensitive to initial conditions. This is known in common speech as the butterfly effect. Weather patterns, for instance, are highly chaotic, such that today's weather depends on the precise arrangement of water particles at the frothy sea-air interface in nearby bodies of water two weeks ago: a slightly different microstate evolves into a greatly different macrostate. The dynamics of two water molecules in sea spray colliding off of one another is dependent on the degree of electric attraction between the two, which depends on the precise locations of their valence electrons. According to GRW theory, these electron locations are not definite until they become entangled with a sufficient number of other particles, at which point a spontaneous chance event decides whether they are this way or that. If one takes a **1A*** view, one could ascribe this control over valence electrons, and thus over rain patterns, to God, a water spirit, or whatever else one likes. This extends, of course, to any large-scale weather phenomena governed by chaotic physical systems: hurricanes, volcanic eruptions, earthquakes, etc.

While computational neuroscience has not yet advanced to the level where the exact physical dynamics of brain activity is known, it is quite likely that a sufficiently complex neural network is a chaotic system. A neuron, after all, will fire if and only if it receives above a threshold amount of voltage from incoming neural connections. For a neuron near the firing threshold, it seems plausible that quantum fluctuations in electron density in the dendritic tree could push it over the threshold or hold it under, causing or preventing a cascade of neural firings and thus altering the subsequent large-scale behavior of the brain and body. If one grants some form of control over these fluctuations to a supernatural soul or life force, one could easily locate an incompatibilist free will within these contexts of underdetermination in physical law. This would not have been possible if something like Newtonian physics had turned out to be the final theory.

## V.

## On the Nature of the Measure

One final pertinent metaphysical question, on which this paper is unfortunately far too short to offer any meaningful treatment, is the nature of the probabilistic measure. More pointedly, we may consider a new scenario identical to our toy coin-flip model but with a weighted coin that has a $\frac{2}{3}$ chance of turning up Tails. What is the difference, metaphysically speaking, between this and the $\frac{1}{2}$ case?

A few words may be quickly said on this point; I am unfortunately out of space and time to flesh these ideas out to their fullest extent. It is my hope to explore this question further in the future.

On the **A** theories, the probabilistic measure must be a *bona fide* feature of reality, such that the $\frac{1}{2}$ case truly describes a different world than the $\frac{2}{3}$ case. On **1A**, there must be some primitive notion we may call *brute chance*, which acts dynamically in the way we think it does. The coin is flipped, and there is an irreducible, out-in-the-world, $\frac{2}{3}$ chance of getting Tails; this is substantively different from there being a $\frac{1}{2}$ chance, and remains so even after the outcome of the flip is determined. Similarly, **2A** would have to involve there being a measure among worlds, which is simply a fact of the many-world reality and cannot be explained by more primitive facts which do not make reference to this world-measure. In either case, we must introduce some new primitive notion of a measure on possibilities, and this introduction will require a detailed formal treatment and defense.

The **E** views are somewhat simpler to accommodate, but I believe work must still be done to spell out what exactly is the difference between the $\frac{1}{2}$ and $\frac{2}{3}$ scenarios. Here, since chance is taken to be purely epistemic, a feature of our ignorance, the assigned numerical values are merely features of our predictive model, as opposed to features of the actual world itself. The choice of $p$ is optimized for good performance, so to speak. In the **1E** case, this will mean that chances are frequentist: we assign the probability $p$ to the coin flip's coming out Tails if, across all instances of the coin being flipped, from the beginning of time to the end, the proportion of flips which come out Tails is $p$. This is simply the choice which is decision-theoretically rational. On **2E**, chances must be what we may call *multifrequentist*: they correspond to the proportion of coin flips coming up Tails across all flips *in all worlds*. Thus we are more comfortably able to assign probabilities to one-time chances than in the **1E** case.

On either of these **E** views, a final riddle remains, to which I have no satisfactory answer at the present moment. Even given the frequentist or multifrequentist information about the outcomes of $n$ flips on the whole, how are we ever justified in assigning a chance to any one fip in particular? Imagine, for the **1E** case, we are told that a certain coin will be flipped 300 times, and that it will come up Tails 200 of those times. How are we to know, on a given flip, which of those instances we are about to witness? We seem to require a *a priori* principle of indifference, which many in the philosophy of physics are not willing to simply grant. Similarly, in **2E**, we may know that the flip comes up Tails in 200 of 300 worlds, but how can we be justified in apportioning our credences equally among the 300 worlds? How can we be justified in any apportionment of credences whatsoever? It seems, on this superficial analysis, that we still require an appeal to an earlier brute chance event. We require there to be some chancy event, taking place before we were born, at which point we were "assigned" one of the 300 worlds, and that we were equally likely to receive any of the 300 assignments . . . whatever that might mean!

The * variations on each view do not make matters easier; in fact, they add more questions to be answered. Whatever the nature of the intention guiding chance events, what is the relationship between such "planning" and the numerical chances? Is God constrained, so to speak, to have 50% of all coin flips come up Tails, but it is up to Him which are which? A constrained-intention view of this sort would have to be careful about how much leeway is afforded to the planner. For instance, we could not have it that all of the ethically high-stakes coin flips are chosen to maximize human flourishing, and the remainder of the flips are chosen to round out the score. In such a case, we would be able to predict the outcome of coin flips far better than 50-50 by evaluating the impact of each outcome. Thus a proponent of a * view (particularly a **1*** view) must spell out the relationship between the metaphysical intention and the physical chance measure.

These are all questions which I believe can in theory be answered satisfactorily by a partisan who commits to one view. My goal here has not been to take any one stance and expand it to its fullest potential, but only to offer a roadmap for others who wish to do so. My hope is that the taxonomy I have offered in this paper is useful in this regard, for framing and organizing debates on the metaphysical nature of chances.

# References

Bohm, D., 1952: A suggested interpretation of the quantum theory in terms of "hidden" variables. *Physical Review*.

Everett, H., 1957: "relative state" formulation of quantum mechanics. *Reviews of modern physics*.

Ghirardi, G., A. Rimini, and T. Weber, 1986: Unified dynamics for microscopic and macroscopic systems. *Physical Review D*.

Lewis, D., 1986: *On the Plurality of Worlds*. Wiley-Blackwell.

Quine, W. V. O., 1948: On what there is. *Review of Metaphysics*.

Sebens, C., 2015: Quantum mechanics as classical physics. *Philosophy of Science*.