I. Why Quantum Mechanics Makes Sense

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Abstract

We take it for granted that our physical environment communicates information, making things observable and measurable. However, there are very strong constraints on the fundamental physics of any universe that can do this. Measuring or communicating any kind of information always requires an appropriate interactive context, and these contexts are necessarily complex, involving other kinds of information determined in different contexts. This makes measurement hard to grasp theoretically, since every measurement depends on other kinds of measurements. Even so, we can identify some basic functional requirements for a physics that determines and communicates facts. These are sufficient to explain the peculiar features of quantum mechanics, combining the unitary evolution of superpositions with the mysterious "collapse" that occurs whenever the context allows new facts to be defined. Moreover, the precise determinism of classical physics can be understood on the same basis. It seems likely, in fact, that most of the complexity and fine-tuning we see in our most fundamental theories is needed to make any kind of information measurable.

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1 What Does it Take to Make Things Observable?

Classical physics describes a world that makes sense to us. There are always precisely definite facts about things and their relationships in space and time, whether or not these facts happen to be observed. Then given these facts, all interaction between things is exactly determined by a few simple mathematical laws. This gives us a very clear idea of how the physical world works, and it's verifiably correct to an extremely close approximation. So why should physics be so radically different at a more fundamental level, and vastly more complicated?

I suggest the answer lies in a basic feature of our interactive environment that's always been taken for granted – its ability to define and communicate information, making things observable and measurable. Unlike classical physics, quantum mechanics gives a central role to the interactive context in which a system is observed: very generally, there are determinate facts about a system just to the extent that the context makes those facts determinable. If a particle's momentum can't be measured in a given situation, for example, its momentum is indeterminate, existing in a superposition of all its possible values. So the question is, why should our most fundamental theory concern the conditions under which measurements can be made?

Unfortunately, the role of measurement is the least well-understood aspect of quantum theory. It's not at all clear, in the first place, what it means for something to exist in a superposition of possibilities. Then there's the question of how an actual result appears when a system is measured: not only is the theory silent about what kinds of interactions count as measurements, but the basic linearity of its equations should prohibit a "collapse of the wave-function" under any conditions.

The goal of this essay is show why this makes sense – why any universe that communicates information about things needs to be based on such a strangely complex and seemingly incomplete kind of physics. I'll argue that our difficulties in understanding measurement don't stem from anything weird about the quantum realm; rather, what makes quantum mechanics seem so bizarre is our failure to appreciate the basic facts about how things get measured.

These facts are easily summarized. The observable world consists of many kinds of information, and they all get measured in different ways, in different contexts. There's no one way of interacting with things that's common to all measurements. Moreover, setting up a context in which one kind of information can be measured always involves other kinds of observations, made in other contexts. Just to measure a distance in space, for example, something other than space also has to be observable. So I take this as a fundamental principle, and the basis for my argument: no information can ever be observed or measured except in the context of certain other kinds of information that are also observed and measured.[1]

Now physicists generally treat information as a dimensionless quantity – as a number of bits or qubits. Yet any information that can be defined or used in any way is always information of a particular kind, in the context of other related kinds of information. Even in pure mathematics, to define a number we also need to define another kind of information, i.e. the operations to be performed on numbers. A logical bit can only hold usable information if we can also specify its location in a string or storage-unit. In short, information is inherently contextual: it only exists where distinct kinds of information provide contexts for each other.

The physical world clearly bears this out. It's structured by a remarkably diverse array of measurable parameters: there are intervals in space and time, velocity and acceleration, mass and charge, energy and momentum, electromagnetic potentials, the speed of light, the gravitational constant and many more, including all the variables and constants of the Standard Model. None of these quantities is determinable by itself, or has any definable meaning apart from the others.

This contextual interdependence is at the root of our difficulty in conceptualizing measurement, at a fundamental level. The problem doesn't stem from anything peculiar to the quantum realm, but from the nature of information itself. The main reason measurement is hard to pin down, at a fundamental level, is that any context in which one parameter can be measured always involves other parameters, that need to be measured in other kinds of contexts.[2] If every measurement depends on information provided by other kinds of measurements, there can be no simple answer to the question of what constitutes a measurement, or what's required to make any particular kind of measurement possible. Measurement contexts obviously exist, but have no definite boundaries. Measurement can never be adequately conceived as a specific set of events in isolation, or as a chain of interactions that transfer data from an object to an observer. Any such description radically oversimplifies the situation, since it takes the existence of measurement-contexts for granted.[3]

At the level of classical physics, though, we can afford to ignore all this. At the macrocosmic scale, the web of interactions is extremely dense – it constantly communicates highly redundant information about things through many different channels at once. There are adequate contexts everywhere, so we can always find ways of measuring things as closely as we like. Complicated observations can be reduced to simple basic measurements: we determine how big something is just by putting a ruler next to it; we tell time just by checking a clock; we can measure mass just by setting something on a balance-scale. The interdependence of measurement-contexts never becomes an issue.

In quantum physics, on the other hand, we're right at the edge of what's measurable. Observations of quantum systems typically depend on a single interaction, like a particle hitting a detector. And here it turns out that contexts are crucial: determinate facts about quantum systems only exist when and where the context actually determines them. If there's any way to tell which path a particle takes, in a dual-slit experiment, then it takes a particular path; otherwise not – both paths are involved in a superposition. To make sense of this we need to conceive our factual reality as rooted in the inherently complex structure of interdependent measurement-contexts.

We're used to imagining things the other way round: our observations are supposed to be based on an underlying objective reality. That certainly makes sense at the level of classical physics, and in all the other sciences, but it can't work at a fundamental level. No inherently determinate reality can function as the basis for an observable world. That's because the context in which anything becomes observable must also consist of observable information. So even if there were some definite factual reality at the bottom of things, it would be irrelevant to the context-structure that makes measurements possible. Since only what's observable can contribute to the contexts that make other kinds of things observable, the web of communicated information has to be able to define itself entirely in terms of itself, regardless of any underlying reality.[4]

What does it take to accomplish this? There's no easy answer to this question. But our current theories give us a remarkably detailed blueprint of such a self-defining system, which suggests that the functional requirements are both complex and extremely stringent. Our universe is incredibly rich in observable phenomena, and gives us many ways of measuring them. But any measurement is possible only because there are things that serve as reliable clocks and rulers and detectors, etc. – and such things only exist because of the great stability and exact uniformity of atomic structure. If there were no atoms, or if each atom had slightly different properties, or if atoms didn't connect in complicated ways to build quasi-rigid molecules, there would be no higher-level structure in the universe. In that case there could be no way to determine distances in space or time, or any other kind of physical information.

Now the quantum physics that stabilizes atomic nuclei and their electron-shells is not only profoundly complex, but also finely-tuned in many respects.[5] According to well-established theory, a universe could be based on almost exactly the same physics as ours, with only minor changes in a few basic constants, and never be able to produce any stable atoms. In such a universe, particles could have no determinable properties; neither space nor time nor any of the laws of physics would be observable, or even definable.

This doesn't mean that a universe has to support atoms just like ours, to measure and communicate facts. There could well be many other ways for an interactive environment to do this. But it does suggest that most of what we know about the base-level physics of our universe may be required for this particular self-defining system to work. That opens up a new approach to fundamental physics. The traditional goal has been to explain all observed phenomena on the basis of a single formal structure – an underlying theory that "unifies" quantum field theory with the relativistic theory of gravity. But if the universe is a system in which distinct interaction-contexts define different kinds of information, this ceases to make sense. What needs to be explained is how the various types of interaction support each other – what each contributes to the functionality of the system as a whole.

The present essay has a more limited goal, which is just to explain the peculiar dual dynamics of quantum theory, with its superpositions that preserve unitarity over time, but "collapse" wherever there's a context that can define a specific measurement result. The same argument also explains why the randomness and indeterminacy of the quantum realm can nonetheless support a precisely deterministic dynamics at the scale of classical physics. That is, I want to show why we need a contextual physics at a fundamental level, and why it needs to support a context-independent objective reality at a higher level.

2 The Dual Dynamics

That the physical world operates at two distinct levels is shown by the profound difference between quantum theory and classical physics. I've argued that the function of the deeper-level physics is to define and communicate the information that constitutes the higher-level reality. Accordingly, we'll conceive the fundamental structure as a web of measurement-contexts, where new facts are constantly being determined and passed on to set up more such contexts, in a self-perpetuating process. These measurement-contexts are complex, always involving several kinds of interactions, and since they're neither discrete entities nor fields, it's not obvious how they can be represented theoretically.[6] Nonetheless we know a great deal about them, in that we understand the kinds of situations we need to set up to be able to measure any observable parameter. Moreover, my goal here is to show that quantum mechanics already gives us a fully-developed description of this kind of foundational structure, though it hasn't been conceived in these terms.

What I want to focus on is the dual aspect of quantum dynamics. On the one hand there's the continuous evolution of quantum systems represented by deterministic equations; on the other hand, the seemingly unaccountable, discontinuous "collapse" that occurs when measurements are made. The whole content of the theory lies in the equations, so the "collapse" can be ignored for all practical purposes. However, the equations don't represent a definite factual reality. Rather, they represent systems as superpositions of possible states and interactions – or more precisely, as superpositions of possible measurement results in some specified context. But the equations provide no mechanism to select one particular outcome, collapsing the superposition and updating it with new information. When quantum systems interact, the equations tell us their superpositions become entangled in more complicated superpositions, preserving unitarity. No collapse should ever occur.

Nonetheless, measurements give results. Wherever there's a context that makes something about a system determinable, a particular fact appears. This is strange, not only because there's nothing in the equations to account for it, but also because these contexts are non-local in space and time. They can include arbitrarily distant events, and may not even involve any interaction with the system itself, as in the EPR scenario, where the spin-orientation of a particle is determined by interacting with another entangled particle at a spacelike-separate location. In a delayed-choice experiment, we don't decide what the measurement-context will be until the interaction we're concerned with has already taken place; even so, what happened in that interaction still turns out to depend on the context we choose later. Or in the quantum eraser version of the dual-path experiment, we set up a context that determines which path each particle takes, which should collapse the superposition. But if the which-path information is made inaccessible, the result is just as if no collapse had occurred. In every case, there get to be definite facts about quantum systems just insofar as the overall context makes those facts physically knowable.

This is true even where no actual measurement is involved. Wherever the physical context makes it possible to infer something about a system indirectly, the effect is the same as if that information had been observed. For example, there's no need to measure the momentum of an atomic electron to know that it lies within a limited range, since if its momentum were any greater it wouldn't stay bound to its nucleus. This contextual restriction has just the same effect as a measurement – for example, because the electron's momentum is determined to that extent, the uncertainty principle requires its position to be indeterminate within a corresponding range. This indeterminacy has important consequences: it plays a key role in stabilizing atomic electron-shells against the Coulomb force, which would pull the electrons into the nucleus if they could be that precisely localized.

The point is that the determinacy of facts about a quantum system doesn't necessarily depend on the presence of an observer, or even a measuring device. But it does depend on the ability of the interactive environment to determine those facts in particular contexts, and make them relevant to other contexts where other kinds of information are determined. This only makes sense if we think of facts as existing in the communicative environment, not in quantum systems by themselves.[7]

How can we describe the dynamics of this kind of environment, where facts are not just given in reality but have to be constantly redefined in the web of communications? The answer is quantum mechanics, with its dual dynamics of superposition and collapse. To demonstrate this, I first want to explain why a fundamental theory needs to represent systems as superpositions of possible measurement-results. I'll then show why quantum theory provides no mechanism for collapsing superpositions – why no additional physics is needed for the selection of particular outcomes, once a measurement-context is set up – and why the probabilities of the various possible outcomes are given by the Born rule.

3 The Physics of Possibility

The long debate over the meaning of the wave-function presents essentially two alternatives. The "ontic" position takes this function as describing a strange kind of objective reality, where systems exist in a superposition of possible states. In the "epistemic" approach it only represents our knowledge of these systems. But this dichotomy is misleading. I don't doubt that quantum theory tells us about what's out there in the world, not what's in our minds. But quantum systems have no definable reality in themselves, apart from the web of contexts that define and communicate their states. The base-level structure of the world is indeed the structure of what's knowable – what's physically determined about a system in a specific context – and these contexts can be different for different observers. But it doesn't depend on what anyone actually knows or believes.

What the wave-function represents is a special kind of situation, in which a certain set of outcomes are possible, and where the particular outcome that actually occurs makes a difference to what's possible in other such situations. This includes both the system and its context.[8] If instead we take the equations as describing quantum systems by themselves, it seems bizarre that a system can be in many different states at once, or follow many different paths. But there's nothing strange in considering a situation as a superposition of possibilities, some of them more likely than others. In fact, this is just how we ordinarily describe situations, by detailing the various things that might happen in them. Of course there's an important difference between quantum superpositions and the kinds of situations we encounter in the classical realm, in that they manifest cyclical patterns of interference between their possibilities. That's an issue I'll discuss in a separate essay, on the origins of our self-determining universe.[9]

Now one reason for our difficulty in conceptualizing quantum physics is that our traditional notions of possibility and probability are inadequate. Since we've taken it for granted that facts about reality are fundamental, we give possibility no significant role to play in the physical world. We generally think of possibilities just as facts that may or may not actually come about.[10] In the deterministic world of classical physics, possibilities and probabilities exist only in our minds, due to our limited ability to predict future events.

In quantum theory, however, possibility comes first. The equations represent the world entirely as a structure of possibilities, to which relative probabilities can be assigned. In any particular situation, the possibilities are very strongly constrained, both by the laws of physics and by the context of previously determined facts. These constraints, reflected in the wave-function, shape the situation by making many outcomes impossible, and making some possible outcomes more likely than others – the more likely ones being those that can come about in many different ways.[11] In general, the combination of laws and prior facts isn't adequate to determine a unique outcome; this happens only when a measurement is made. Even then, "collapsing" the superposition by measuring some parameter of a system only makes all its conjugate variables less determinate, per Heisenberg's principle – so a quantum system always remains in a superposition of possibilities.

To make sense of this we need to conceive possibility as a category in its own right, not as a secondary, provisional mode of factuality. Possibility means the same as indeterminacy – i.e. freedom, subject to constraint. Without constraints, possibility has no shape – that is, it can't be the possibility of anything in particular. Possibility evolves by being narrowed down – possibilities become more specific the more tightly they're restricted. So quantum theory describes the world as possibility, constrained by a diverse and complicated system of mathematical rules, operating on previously determined facts. They function to support a process in which new factual constraints are constantly being defined, so as to set up new situations that can keep this process going.

This way of conceiving the world as an evolving structure of possibilities is unfamiliar, but it's not at all in conflict with our ordinary experience.[12] At any moment in our daily lives we're in some situation where many things might happen, some of them more likely than others. Whenever something happens, that changes the possibilities and probabilities for what can happen next. We're used to thinking of this in terms of classical causality, where precisely determinate facts exactly determine everything that happens, so that possibility and probability have no role to play. But the picture I'm sketching here is really much closer to our experience of the world, where nothing is perfectly predictable. Our minds and even our sensory systems operate by anticipating what might be helpful or dangerous or interesting in the current situation. That is, we perceive our world mainly in terms of what might happen and how our situation might change. Possibility and probability come first; only secondarily do we step back and merely notice facts about things.

Likewise any measuring device must predefine a certain range of possible results. Every system of communication involves a set of possible signals and meanings from which actual messages can be selected. Both measurement results and meaningful messages narrow down the scope of subsequent possibilities, constraining them so that new possibilities can arise in new situations.[13]

At the level of classical physics, the combination of laws and facts is so constraining that it seems to eliminate possibility altogether, forcing things to happen exactly according to mathematical laws. Yet if we want to imagine such exact determinism working at a fundamental level, we have to overlook some fairly obvious problems. It's not just that it would take an infinite amount of information to define the position and momentum of a single particle. Even if we assume that's possible, the equations of classical dynamics can't actually determine trajectories for these particles. We know there's no analytic solution to Newton's equations for the motion of just three gravitating point-like masses, even if they could be isolated from any other influence. The more accurate equations of General Relativity have no known solution for just two bodies, unless we ignore the mass of one of them. It's merely fantasy to suppose that physical dynamics can be mathematically determined. Mathematics can only define trajectories perturbatively, by a process of successive approximation, while the physical world itself can obviously determine trajectories for huge numbers of particles, interacting in many different ways at once, and it does so in real time.

Quantum theory shows us how this is accomplished. This physics doesn't operate with infinitely exact information about things, and it doesn't compute trajectories. It applies constraints to set up complex structures of possibility, represented by wave-functions, and then lets actual outcomes be selected by chance. This is the dual dynamics at work. What we observe at the level of classical physics – the very precise synchronization of countless interacting trajectories – isn't achieved by making things obey mathematical laws. The laws are statistical, *post facto* rather than predetermining; they describe what happens when a particular complicated, many-leveled system of constraints is applied to huge numbers of aggregated quantum events. Fortunately, physicists have learned how to imitate this procedure with remarkable accuracy, using perturbation methods and other means of approximation. They've been able to compute results to compare with experimental data, giving us a very clear and detailed understanding of the many different kinds of constraints that make this process work.

Unfortunately, in the absence of any insight into the reason these constraints exist, theorists still tend to imagine the world as built on purely mathematical foundations. So despite the remarkable success of our theories in predicting the results of experiment, it seems wrong that this needs to be done by summing up terms in an infinite series of possibilities. They feel that exact, non-perturbative equations ought to be fundamental – which is one motivation for the long, so far unsuccessful quest for a deeper, more elegant mathematical basis that would underlie and unify all our current theories.

Here, on the other hand, the issue is not formal elegance or unification but functionality. The constraints represented in the laws and principles of our currently-known physics are what keep this information-defining system going. Whether or not there's any deeper common basis for all the known types of interaction, the differences between them are what's crucial to the functioning of our communicative environment. The system of very diverse constraints operates to ensure that certain special situations arise over and over again, where specific outcomes can be selected from a range of possibilities, creating new facts that create new measurement-contexts. The key question, to which we turn next, is how this selection happens.

4 The Collapse

Every measurement requires an adequate context. The point of this section is to show that wherever a context exists that can randomly distinguish a specific outcome and pass it on to other contexts, there's nothing more that's needed to bring about such a selection. I want to explain why there's no specific mechanism for wave-function collapse, and why this part of the dual dynamics doesn't show up in the equations.

To begin with, it makes sense that no particular type of interaction is responsible for the collapse. Any measurement-context involves many kinds of interactions, and depends on facts defined in other kinds of contexts, so that every measurement involves many different physical mechanisms. A single interaction can convey information in the right context, but no interaction ever communicates anything by itself.

Not only do measurements involve many interactions, but as Von Neumann demonstrated long ago, the linearity of the equations means that it makes no difference to the statistical predictions of the theory which interaction we consider as bringing about the collapse. The probabilities for the outcomes of a measurement depend on the context as a whole. If it seems baffling that the collapse can sometimes depend on something that happens far away, or on changes made to the measurement-context after a particle has already passed through a beam-splitter, it's because we mistakenly imagine measurement as a localized physical event. Measurements can never be strictly local in space or time, because their contexts always depend on other previous contexts, and a definite result appears only insofar as it gets registered, making a difference in some other context.

In short, measurement can't be defined at the level of individual quantum systems and interaction-events. Definite outcomes occur only in higher-level situations, where contexts define and communicate facts. When we talk about quantum particles, states and fields, we're not describing any definite reality that exists beneath the web of communicated information. These are short-hand ways of describing the structure of constraints on what's possible, in any given situation. The wave-function doesn't represent the micro-structure of reality, but the shape of possibility under these constraints, giving the probabilities for what will be observed when the situation changes so that a particular fact about the system becomes empirically definable. The collapse isn't something that objectively happens to a quantum system by itself. It's just a change in the situation that sets up a context where a specific outcome can be distinguished, and made relevant to other such contexts. As soon as a measurement becomes possible, a result automatically appears, randomly chosen from the set of alternative outcomes weighted according to their respective probabilities.

Why should this happen? If any of the possible outcomes included in the wave-function would satisfy all the relevant constraints of a given situation, why should one of them become the actual measurement result, while all the others become irrelevant? The short answer is that this is required by the laws of physics – specifically, the conservation laws. If we shoot a particle at a screen, for example, these laws require it to show up at some particular spot: the particle's charge, energy and momentum aren't allowed just to disappear, or get spread out over the entire screen. The deeper answer is that the laws of physics are set up this way because they're part of a self-sustaining process. The selection of a particular fact is needed, wherever the context allows this to happen, because that makes it possible to set up more such contexts in which other specific facts can be selected. We can think of it as a kind of spontaneous symmetry-breaking, in which the unitarity of the equations gets superseded by the random choice of particular outcomes, updating the equations. This is the fundamental process that sustains the observable world.

If this seems hard to grasp, it's because we're used to thinking in terms of classical physics, where all events are causal transitions from one determinate state to another state, occurring through specific types of interaction. We often use this same sort of language to describe quantum events as well, but here it can't be taken literally. Quantum states are complex structures of constraints on the information that's potentially available in the interactive environment. When the environment changes, so do the states. And the changes that constitute any measurement necessarily involve many kinds of interaction, most of which don't directly engage the system being measured.

The bottom line is that at a fundamental level, observing and measuring aren't physical events, in the usual sense. As noted above, it's a fantasy to suppose that a world of interaction as complex as the one we live in could operate according to causal mathematical laws applied to exact, intrinsically definite states. In quantum theory the laws of physics don't work like this – they don't force things to happen in a predetermined way. Ultimately, everything happens at random – but only those random events that happen to "obey" all the relevant laws and factual constraints can be observed, or have any determinate character. Facts only become observable in the context of prior facts, insofar as they help set up new contexts that make other facts observable. The laws of physics are just *de facto* constraints that happen to keep this system going. Nothing enforces them, nor are they given *a priori*, based on mathematical principles. They merely reflect the conditions that let interacting systems keep on creating the contexts that define those systems.

What quantum physics shows us is that the solid, stable and precisely reliable world of classical physics is the statistical result of a great many random interactions, subject to the condition that only observed events can contribute to the contexts that make other events observable. The collapse happens just because it can happen, in certain very special kinds of situations, and insofar as it does, it makes it possible for more such situations to arise.

This explains the seeming paradox that the fundamental laws of physics are merely statistical. Taken individually, quantum events are random; aggregated at a higher level, they fall into mathematically predictable patterns. That's because the higher-level structure is what's needed for the communicative environment to function. It's the uniform structure of atoms and molecules and the regularity of their interactions that provides the basis for our world of definable information. The deeper level of individual particles and interactions can't be defined so precisely, and doesn't need to be.

Likewise, the fine-tuning of many aspects of fundamental physics is unproblematic, in this picture. There's no reason to assume that the values of all physical constants should reflect deep mathematical patterns. These values too are randomly selected, subject to the basic constraint that they support the ongoing self-definition of the communicative environment. Among other things, that requires all observable events to happen according to laws that are reliably the same in every context, so that facts can be communicated between different points of view throughout the observable world.

It also requires that the environment keeps on communicating a coherent body of facts that are reliably the same from all points of view. It has to maintain a common and consistent historical background for defining current events – that is, a shared objective reality into which all newly determined facts must fit, so that further facts can continue to appear. At the quantum level, the specific outcomes of any situation are left to chance, but there always has to be a specific outcome, to the extent the current context can define one. And that outcome has to be consistent not only with the laws of physics but with all relevant facts defined in other associated contexts.

5 The Born Rule

To confirm this picture, let's think about the Born rule. The wave-function assigns a probability to each possible outcome of a measurement, but we call it a "probability amplitude," since according to the rule, the actual probability of a particular outcome is essentially its amplitude squared.[14]

This way of computing probabilities would seem peculiar if we imagined the wave-function as describing the actual state of a quantum system in itself, and the collapse as an actual physical event in which that state changes. In that case there's no clear reason why we should use squared amplitudes instead of normal probabilities for predicting measurement outcomes. But at the quantum level, there are no facts about things apart from the contexts that determine them. The wave-function describes the structure of information that's potentially determinable in a given situation, and a measurement is any change in the situation that lets a particular outcome be communicated to other contexts. So what the Born rule gives is not the probability of a change in the system by itself. Rather, it's the probability that a certain fact about the system will be consistently observed in all other contexts to which that information becomes relevant, even though there's no given underlying reality to which that information refers.

How should we compute such a probability? We begin with the amplitude given by the wave-function, reflecting the initial probability of one specific outcome being randomly selected in a measurement.[15] For this to become an objective fact, it has to be confirmed by some other observation – which could be a second measurement of the same system, or a measurement made on another entangled system, or any other observation that can independently verify this fact. In the absence of any underlying reality, the results of both measurements are random, and the probability that both of them will happen to produce the same outcome is the amplitude for that outcome squared. Hence the Born rule. It merely reflects the fact that one particular outcome has to be agreed upon, to maintain the functionality of the environment – but that agreement has to be achieved by a random selection in both observations.

Why do we consider only two measurements? Because no matter how many other observations might be made that reflect this outcome, they all need to give consistent results for it to function as objective fact. We don't keep on multiplying by the amplitude again and again for every new measurement, as if each one might have a different outcome. But it doesn't matter which two measurements we consider as the initial ones, that just happen to get the same result independently, by chance. The Born rule reflects an agreement that arises within the entire environment to which the result is relevant – but again, an agreement that's achieved through mutually random selection.[16]

At the level of classical physics, every observable event involves huge numbers of such agreements, all constrained to agree with each other in various ways. This great redundancy gives us a world in which the properties of things can seem intrinsically well-defined, independent of any context; rules that are merely statistical, at a fundamental level, can seem precise and deterministic. Even so, physicists have found ways to demonstrate on a macroscopic scale the very different character of the underlying physics – for example, in the EPR scenario. Here measurements are made of the spin-orientations of two entangled particles, which have been separated so there can't be any causal connection between the measurements made on each particle.[17] Each measurement involves the random selection of a specific outcome, and yet the two outcomes are found to be correlated by the usual quantum rules.

This simply confirms what is also shown in many other experiments, that the collapse is never a strictly local event. Facts are only determinable in the context of other facts, defined in other contexts, and the selection of any outcome requires coordination with many other outcomes to maintain the consistency of the environment. Almost always, though, such non-local coordination is apparent only in the submicroscopic quantum domain; it takes much ingenuity and effort to demonstrate it on the scale of direct experience, as in the EPR situation. Ultimately though, this coordination has to come about by chance. As noted above, no mathematically deterministic system can define precise trajectories for countless particles, interacting in many ways at once. Our physical world accomplishes this by letting everything happen at random, while the only combinations of events that can be observable are those that happen to sustain a self-consistent environment of objective facts, operating according to universal rules that continually create new measurement-contexts.

This picture seems strange to us, perhaps even unbelievable, since this kind of dynamics is the opposite of the precise determinism that prevails on the scale of human experience. If it were not for the abundant evidence of quantum physics, no one would ever have imagined that a world could function like this, or that all the complex phenomena that constitute our universe could arise from entirely random processes. But the evidence is there. Moreover, we know of a completely different kind of natural process that's also able to maintain astonishing levels of functional complexity on the basis of random events, to be discussed in the following section.

The key point here is that the collapse – the random choice of a particular outcome – is based on the statistical weighting of amplitudes for each possible result, but the actual probability of an outcome doesn't refer to the result of any measurement by itself. It refers to the emergence of a spontaneous agreement that arises between many random outcomes in many other contexts. And while the result of any observation taken by itself is simply random, the selection of an outcome by such an agreement is doubly random – as evidenced by the Born rule. Yet this kind of agreement is what's needed to support an objective reality that can keep on producing new facts. A random selection made in any one context can only participate in our observable universe if it happens to be consistent with all other relevant facts that appear in other contexts, even though there's no causal connection underlying such correlations.

6 Natural Selection

I've been describing measurement as a recursively self-sustaining process, in which random events are constrained in order to keep on making new measurements possible. Events that don't help sustain the world of observable phenomena don't need to be prevented or suppressed – they just don't matter, since they can't be observed or make any definite difference to what's observed.[18]

This invites comparison with another recursive process that's much better known and much easier to envision – the process of biological reproduction that's responsible for the evolution of life on Earth. That process operates very differently from the measurement process, but there are many significant analogies between the two, beginning with the fact that they both make use of random selection to support the production of amazingly complex and finely-tuned functional systems. To help clarify the picture I'm developing of the physical process, I want to outline briefly both how it differs and how it's similar to the biological one.

Biology is, of course, based on physics. Life is possible because molecular structure is precisely uniform, so that even extremely complex molecules interact in reliably repeatable ways. Before the emergence of living organisms, though, only very simple molecules could exist, because complex systems are always much easier to break up than they are to build. For this reason molecules containing more than a dozen or so atoms are rare in the non-living universe. But there is one way, in nature, to overcome this physical limitation. If some kind of system can reliably make copies of all its component molecules and replicate itself in multiple versions before it gets broken up by the environment, then there are almost no limits to the level of ordered complexity such a system can achieve.

The problem is, physics and chemistry don't provide any easy way for this to happen. As a result, self-replicating systems are also very rare in this universe. On the other hand, if by chance such a system comes to exist, in some unusual physical environment, then so long as it keeps on making copies of itself it will automatically evolve. Random events will selectively promote the proliferation of those variants that happen to be best at reproducing themselves, and also at adapting to other environments, while the less successful variants will disappear. Over a few billion years, this process has been able to produce the astonishing diversity of living organisms on this planet, every one of them radically more complex than any other kind of physical system.

Now selection in quantum physics works very differently from Darwinian natural selection, because the underlying functionalities are so different. Biology depends on the well-defined and exactly uniform information built into the structure of molecules: its key functionality is the copying of such information through chemical interactions that catalyze the building of new molecules. On the other hand, there are no basic processes in physics that simply replicate given information. The underlying functionality in physics is more fundamental: it's not a matter of copying information to preserve it over time, but about making information definable and observable in the first place.

In both cases, though, what makes these processes special is that to the extent they succeed, they pass on the information that's needed to keep the same process going. This is obvious in biology, but less so in physics, because measurement-contexts are not discrete identifiable objects, like organisms, and they never replicate themselves – contexts generally contribute information to set up other kinds of contexts. Moreover, the self-sustaining process in which contexts determine and communicate facts doesn't result in a gradual, incremental development of more and more complex systems, as happens with the evolution of life. In fact, it does just the opposite. Physical information can only be reliably defined and communicated if the same basic structures of interaction apply everywhere, throughout all space and time. Since this radical consistency is crucial to sustaining the process, the result of random selection in measurement is always to keep on redefining the same changeless system of physical laws and objective historical facts.

Nonetheless there's a similar kind of dual dynamics at work, in both measurement and reproduction. They both depend on a very complex, tightly-controlled system involving many kinds of interactions – defined on the one hand by the universal laws of physics, and on the other by the particular genetically-encoded operating instructions that get passed down from one generation to the next, in each biological species. And in both cases, the other side of the dynamics – natural selection – is not only random, but has no definite character at all. In biology, natural selection refers to any kind of event that in any way affects the reproductive success of an organism – which could be anything from a random mutation in a single molecule to a global geological disaster. In physics, the collapse that selects a specific measurement result can be brought about by any kind of change in the environment that makes some parameter of a system determinable, whether directly or indirectly.

What makes both these processes work is that the tightly-controlled side of the dynamics is a structure of variant possibilities. A species can evolve because it consists of many individual organisms, each one carrying a particular version of the species genome that can potentially be reproduced. At the level of individual organisms, it's mainly a matter of luck which ones happen to succeed in reproducing their genes, so over short time-periods and in small populations, genetic change from one generation to the next is largely random. At a higher level, though, the cumulative result of random selection over time is to promote each species' adaptation to its environment, favoring the species that evolve most rapidly. This involves changes to thousands of genes in response to countless different environmental factors. But since evolution happens through random selection, the tremendous complexity of interrelated changes it responds to doesn't present any obstacle to the process.

In physics, the controlled side of the dynamics is described by the wave-function, representing a physical situation as a superposition of all the possible facts that it could pass on to other contexts, if and when a measurement occurs. At the level of individual measurements the outcomes are essentially random, but because of phase-interference between possibilities, and because many different possibilities can lead to the same outcome, the aggregate results of many measurements give a highly predictable statistical distribution of outcomes. On the scale of our ordinary experience, this gives us the precise dynamics of classical physics. And again, since the underlying selection is random, the tremendous complexity of the higher-level situations doesn't present any problem. Trajectories determined by this process of natural selection can take account of many different kinds of interaction with countless other systems all going on at once.

In both biology and physics there's a basic functional unit – the living cell and the atom. Everything in biology depends on the self-replication of individual cells, the basic building-blocks for all forms of life, which also perform a great variety of subsidiary functions. Atoms too are not only building-blocks for every kind of material structure, but also function as tiny measuring-rods and clocks, providing universal standards of distance and frequency. They detect photons with specific energies, store information over time in the energy-levels of their electron-shells, and communicate with other atoms, both nearby and very far away. The observable world is at bottom a world of signals exchanged between atoms, just as the living world is made of interacting cells.

Both atoms and cells are complicated, finely-tuned systems, with many functional components that all need to operate in precisely reliable ways. Yet the deepest levels of interaction in each case are largely random. The interaction of molecules in a cell, as between sub-atomic particles, is essentially chaotic. The system works nevertheless, because all this uncontrolled interaction averages out statistically to keep the process going. This happens not because of any preordained law, but just because where it doesn't happen, the system ceases to contribute to the ongoing process. A cell that fails to reproduce itself makes no difference to the further evolution of life. Physical events that don't support the exact reliability of atomic interaction can't be observed, or contribute to making other things observable.

Every organism on earth descends from a very long line of ancestors, back to the beginning of life, every one of which succeeded in reproducing itself. In physics, only information that's successfully defined in some local context and passed on to other contexts can make any difference to anything. So here too, everything that happens in the observable world is the result of a long history of accidents, back to the beginning, each one of which made some definite difference to the context in which other events could make a difference. All the regularities of physics come about because only things that help make other things measurable can make any contribution to this history.

Because both these self-sustaining processes are so profoundly complex, what's hardest to understand about them is how they came into existence in the first place. In biology, at least we have a fossil record of an evolutionary process that gradually produced more and more complicated forms of life – although the earliest cells for which we have evidence were already far more advanced than the first self-replicating systems could have been. In physics, the historical record shows us no such process of gradual change in the finely-tuned system of laws and principles that makes measurement possible – so we face a much greater conceptual challenge in envisioning how this system could have emerged from simpler kinds of self-defining systems. This is a question we'll take up in a separate essay, on The Origins of Determinate Information. To prepare that discussion, the reader should turn first to an essay on Your Present Moment in Spacetime, which considers how our other foundational theories – Special and General Relativity – help support the physics of measurement and communication.

7 Conclusion

The underlying question I'm raising here is this: how and why does our physical environment convey information? The key point I've made is that no kind of interaction does this by itself. Observing any parameter requires a context in which other parameters are also observable, and those require other kinds of interaction-contexts. This means that the base-level structures that support a self-defining universe are necessarily diverse and complicated. However, to a great extent we know what these structures are, in our own universe. So the task we face is essentially a matter of reverse engineering. If we can be clear about what this system of physics does, we can figure out how it works.

I suggested in section 1 above that most of what we know about the base-level physics of our universe may be needed to support the possibility of measurement, since every kind of measurement depends on the very complex structure of atoms and their nuclei. This raises the prospect of developing a detailed explanation of the Standard Model and gravitational spacetime, perhaps along the lines suggested by the "archaeological" analysis proposed in the accompanying essay on The Origins of Determinate Information. But it also raises an important question: how can we consider atomic structure to be fundamental, since we know that there were no atoms for the first 300,000 years of cosmic history? My entire argument is built on the assumption that there can be no determinate information apart from a physical context that actually determines it. How can this be reconciled with our well-established cosmological theory, based on the assumption that all the basic structures of physics were in place almost from the beginning, long before there was any possibility of measuring or communicating any kind of information?

I'll address that question in the essay on Origins. Meanwhile, note that we're dealing with the physical world on two levels, that operate very differently: the level of empirically observed facts, and the level of quantum interaction that's responsible for creating and sustaining the world of facts. Now one basic condition for the existence of observable facts is that the same set of physical laws must always apply, everywhere, at all times. Our empirical cosmology describes the factual universe, and projects the past history of that universe based on this assumption of changeless universal laws. This works out very well, giving an account that explains a great deal about the state of the universe today. On the other hand, it can't explain how or why the laws came to be as they are, or why our universe is based on this specific set of observable parameters. That requires another approach, appropriate to the level of quantum theory. So the question of the origins of the cosmos needs a different kind of answer on each level; my task will be to show how both answers can make sense without contradicting each other.

Traditionally, physics dealt only with the level of given facts; its ultimate goal was to account for all the complexities of the universe on the basis of a simple, unified mathematical foundation. This ambition proved fruitful up to the advent of the Standard Model, but since then its prospects have dimmed – it seems hardly conceivable now that a unified theory could be in any sense simple. But in any case, how much could such a theory tell us? If we could show that all the basic interactions derive by spontaneous symmetry-breaking from one underlying structure, that still gives us no way to explain why that highly symmetrical structure should have been there at the beginning; nor would it help us understand the remarkable diversity and finely-tuned complexity of our physical world today. Whether or not all these kinds of interaction are ultimately the same, what's more important are the profoundly different roles they play in sustaining a communicative environment.

My proposal is that we should embrace the messiness and diversity of our empirically established physics, and of measurement-processes in particular. The goal shouldn't just be a more elegant and unified formal theory, but a way of understanding why these many kinds and levels of complex structure are needed for a universe like ours to work. I want to show there's a clear path toward explaining the basic features of quantum mechanics, relativity and classical physics by considering the functional requirements of a world of determinable facts. If this approach can succeed, we have at our disposal a vast resource of knowledge to draw on in investigating why this system needs to operate with such a wealth of complex structure, and how such an astonishingly creative system could have come to exist.

Notes

1. To be clear, the context in which any measurement of one kind of information takes place always includes other instances of the same kind of information, obtained in similar contexts, as well as other kinds of information from other contexts. To measure a length requires reference to other lengths, but also to observations of physical objects that exhibit these lengths.

   See "On Finding Meaning in the Language of Physics" submitted to the Foundational Questions Institute 2015 essay contest. This discusses the radical "semantic closure" of this mathematical language, in that all the observable parameters in physics are necessarily defined in terms of other observable parameters.

2. This isn't obviously true for all measurements. Simple measurements can seem to involve only one parameter, as when we measure length of an object against lengths marked out on a ruler, or when we determine the mass of an object by weighing it against another object on a balance scale. But as noted below in this section, the existence of measuring rods, clocks and balance scales involves all the parameters of atomic physics. Measurements can seem simple only because the background of mutually-supporting contexts can be taken for granted.

3. For an empirical analysis of the complex features of measurement-contexts in the quantum domain, see Barbara Drossel and George Ellis, "Contextual Wavefunction Collapse: An integrated theory of quantum measurement," 2018 New J. Phys. 20 113025, iopscience.iop.org/article/10.1088/1367-2630/aaecec/pdf, section 5.4. The present essay argues from a more general consideration of the requisites of measurement, to reach a more radical conclusion regarding the "collapse" that is not incompatible with the views of Drossel and Ellis.

4. I'm not arguing that it's always invalid to base a theory on hypotheses about an unobservable reality. In general it's quite reasonable to explain what we observe based on plausible assumptions about things that aren't directly observable. My argument is that fundamental physics can not be just a matter of explaining observed phenomena; we also need to understand how anything gets to be observable. This depends entirely on the ability of different kinds of observable information to provide contexts for each other.

5. Fine-tuning shows up in many seemingly unrelated aspects of atomic physics and cosmology – see Luke Barnes, "The Fine-Tuning of the Universe for Intelligent Life", arxiv.org/abs/1112.4647. But the idea that our universe might be finely-tuned for the sake of intelligent life – or any form of life – is peculiar. For one thing, the mechanisms of biology are also finely-tuned in many ways, but the reason for this is clear in biology itself: without the complex mutual adjustment of many different molecular cycles and higher-level processes, self-replicating organisms could not exist. Few biologists believe that the evolution of life was directed toward producing the kind of intelligence

that only one species has. But there's just as little reason to believe that the complexities of the physical world were directed toward creating life – since there are so many other things that physics supports, nearly all of which are far more prevalent in the universe than living beings.

The goal here is to investigate a specifically physical reason why physics needs to be complex and finely-tuned: if it were not, nothing would be measurable or in any way determinable. But I'm not suggesting that the laws of physics have to be exactly as they are in order to support observable information. Not everything in physics seems to be finely-tuned; there's evidently some leeway in the construction of our universe. And it's possible that universes structured very differently from ours might be able to define and communicate a different set of measurable parameters.

6. There are however some recent efforts to develop a theory of contexts – see Barbara Drossel and George Ellis, "Contextual Wavefunction Collapse: An integrated theory of quantum measurement," 2018 New J. Phys. 20 113025, iopscience.iop.org/article/10.1088/1367-2630/aaecec/pdf. This paper presents mathematical models for the various levels of interaction involved in typical measurement arrangements, arguing that the unitarity of the quantum equations necessarily breaks down when a quantum system is in contact with higher-level systems that must be described in classical terms. For another interesting approach see Alexia Auffèves and Phillipe Grangier, "A Generic Model for Quantum Measurements," 2019 Entropy 21(9):904, arxiv.org/abs/1907.11261, "Contexts, Systems and Modalities: a new ontology for quantum mechanics" (2014) arxiv.org/abs/1409.2120 and P. Grangier, "Completing the quantum formalism: why and how?" 2020, arxiv.org/abs/2003.03121. These argue that quantum states must be attributed to the combination of the measured system and its context, defining these contexts operationally as classical systems.

   Both these approaches complement the present essay – in the first case by clarifying the physics of actual measurement processes, and in the second by clarifying the role of contexts in interpreting the quantum formalism.

7. We generally conceive measurement as a transfer of information from an observed system to an observer or recording device – so there seems to be a definite starting-point and end-point for the measurement. But I'm arguing that quantum systems don't contain in themselves the information that appears when they're measured, nor is there any particular point at which the superposition "collapses" to create a factual result. The "Wigner's friend" scenario shows that a measurement may have been completed from one observer's standpoint, but not from that of other observers. So at a fundamental level, measurements don't have definite starting or end-points. Measurement needs be defined recursively – that is, a measurement takes place only insofar as a specific result appears in the context set up by previous measurements, and then also contributes to the contexts in which further measurements occur. Measurements are possible only in an ongoing, self-sustaining process. Facts only exist in the communicative environment as long as they're relevant, contributing to the historical background in which new facts can be defined.

8. See references to Auffèves and Grangier in Note 6 above.

9. See "The Origins of Determinate Information" by the present author. The cyclical character of the wave-function and the phase-relationships that produce interference patterns are the most general of many kinds of "virtual" structure – structures that aren't directly observable, but appear in the equations that determine probabilities for measurement outcomes. This essay discusses the origin of the complex physical foundations of our universe, treating these "subliminal" aspects of quantum structure as evidence for earlier stages in the emergence of self-determining systems.

10. An extreme example of this is the "modal realism" of philosopher David Lewis, who argues that all possibilities are in fact actualized in other versions of the world. The notion that possibilities are physically real is central to the "possibilist transactional interpretation" of Ruth E. Kastner, The Transactional Interpretation of Quantum Mechanics, Cambridge University Press (2013). Kastner's website, transactionalinterpretation.org, offers a wealth of material on this approach. Here I also treat possibility as physical, but I emphasize the difference between the contextual structure of possibility and the structure of factual reality. Free and open possibility is basic; there get to be definite facts only insofar as the possibilities of a situation are constrained to the point that a specific fact becomes determinable.

11. I have in mind here Feynmann's path integral formulation of quantum mechanics, where at bottom all possible paths are equally likely. The difference in probability for different outcomes arises from the phase-relationships between possible paths: the probability of each outcome is determined by destructive and constructive interference among the many possible paths leading to that outcome.

    This contrasts with Heisenberg's suggestion reviving the Aristotelian notion of *potentia* – tendencies for things to happen in a certain way, built into the nature of things in themselves. This is another way of conceiving possibility in terms of reality, as an objective proclivity toward a particular actual outcome. It seems to me that Feynmann's approach makes such a notion unnecessary.

12. Philosophically, the source for this conception of possibility is Martin Heidegger's Being and Time, which develops a notion of fundamental ("authentic") temporality in which possibility plays the primary role. The notion that awareness is essentially anticipatory has been developed by many authors in psychology – see for example John McCrone (2000) Going Inside: A Tour Round a Single Moment of Consciousness, Faber and Faber. Heidegger's aim was a deeper understanding of time in fundamental ontology, but so far as I know this approach has not been pursued in physics.

13. This conception of information as selection from a space of possibilities was developed in C. E. Shannon's quantitative information theory, which originally brought the concept of information within the scope of physics.

14. Since quantum amplitudes are complex numbers, the probability is actually calculated as the square of the absolute value of the amplitude, or equivalently as the amplitude multiplied by its complex conjugate. This always gives a non-negative real number for the probability.

15. Because the amplitude is a complex number it can't be taken literally as a probability, but it is directly related to the relative probability of a particular outcome.

16. A somewhat similar understanding of the Born rule is presented in a "realist" form by Ruth E. Kastner in The Transactional Interpretation of Quantum Mechanics (2013), Cambridge University Press. See her website at transactionalinterpretation.org for extensive discussion of this approach to quantum theory, originally due to John Cramer. It envisions the collapse as taking place through a reciprocal relationship between two events, e.g. the emission and subsequent absorption of a particle. This is not a popular interpretation among physicists, since it envisions a time-reversed action from the absorber back to the emitter, happening in a level of reality underlying our empirical spacetime. Nonetheless, if we assume that quantum mechanics should be understood as describing some kind of objectively factual reality, this seems to me by far the most reasonable interpretation.

    Here I've argued the opposite: that in principle, no objectively factual reality can be the basis for an observable universe, and that the reality we experience must have foundations that are relational and contextual. Even so there are many points of similarity between this conception of quantum theory and the Transactional approach, especially in that they both treat measurement as a matter of agreement between two parties, explaining the Born rule on this basis. See Section 4 of my essay on "The Origins of Determinate Information" for discussion of the pre-metric, time-reversible structure of interactions that underlies our measurable spacetime.

17. The measurements are made in "spacelike separate" locations so that any connection between them would have to be faster than light. See my essay on "Your Present Moment in Spacetime" Section 1 for the meaning of "locality" and "non-locality" in physics, and Section 3 for discussion of the EPR scenario.

18. The situation is actually more complex than this, since quantum theory describes many kinds of "virtual" particles and interactions that obey some but not all the laws that apply to observable phenomena. Though these are not directly observable and not fully determinate, they play an important part in defining quantum statistics. I suggest in the essay on "The Origins of Determinate Information" that this virtual realm reflects deeper, more primitive layers of self-defining structure on which our observable world is built.