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Introduction

Quantum Peculiarities

1.1 Introduction

Richard Feynman said: “Our imagination is stretched to the utmost, not, as in fiction, to imagine things which are not really there, but just to comprehend those things which are there.”[1] This book is an account of my attempt to meet this challenge, which comes to us in the form of the strange character of quantum theory. Specifically, it presents an overview and further development of the Transactional Interpretation (TI) of Quantum Mechanics, first proposed by John G. Cramer (1980, 1983, 1986, 1988). Quantum theory itself is an abstract mathematical construct that happens to yield very accurate predictions of the behavior of large collections of identically prepared microscopic systems (such as atoms). But it is just that: a piece of mathematics (together with rules for its application). The interpretational task is to understand what the mathematics signifies physically; in other words, to find “a way of thinking such that the law [i.e., the theory] is evident,” as expressed in the quotation from Richard Feynman that introduces Chapter 3. Yet quantum theory has been notoriously resistant to interpretation: most “commonsense” approaches to interpreting the theory result in paradoxes and riddles. This situation has resulted in a plethora of competing interpretations, some of which actually change the theory in either small or major ways.

One rather popular approach is to suggest that quantum theory is not “complete” – that is, it lacks some component(s) that, if known, would resolve the paradoxes – and that is why it presents apparently insurmountable interpretational difficulties. Some current proposed interpretations, such as Bohm’s theory, are essentially proposals for “completing” quantum theory by adding elements to it that (at least at first glance) seem to resolve some of the difficulties.

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[1] *The Character of Physical Law*, chapter 6, “Probability and Uncertainty: The Quantum Mechanical View of Nature” (Cambridge: MIT Press, 1967), pp. 127–28.

(That particular approach will be discussed below, along with other "mainstream" interpretations.) In contrast to that view, this book explores the possibility that quantum mechanics *is* complete and that the challenge is to develop a new way of interpreting its message, even if that approach leads to a strange and completely unfamiliar metaphysical picture. Of course, strange metaphysical pictures in connection with quantum theory are nothing new: Bryce DeWitt's full-blown "many worlds interpretation" (MWI) is a prominent example that has entered the popular culture. However, I believe that TI does a better job by accounting for more of the quantum formalism and that it resolves other issues facing MWI. It also has the advantage of providing a physical account of the measurement process without injecting any ad hoc changes into the basic dynamics.

1.1.1 Quantum Theory Is About Possibility

Besides presenting the relativistic elaboration of John Cramer's original Transactional Interpretation (Cramer, 1980, 1983, 1986, 1988), this work will explore the view that quantum theory is describing an unseen world of possibility that lies beneath, or beyond, our ordinary, experienced world of actuality. Such a step may, at first glance, seem far-fetched, perhaps even an act of extravagant metaphysical speculation. Yet there is a well-established body of philosophical literature supporting the view that it is meaningful and useful to talk about possible events, and even to regard them as real. For example, the pioneering work of David Lewis made a strong case for considering possible entities as real.[2] In Lewis' approach, those entities were "possible worlds": essentially different versions of our actual world of experience, varying over many (even infinite) alternative ways that "things might have been." My approach here is somewhat less extravagant:[3] I wish to view as physically real the possible quantum *events* that might be, or might have been, actualized. So, in this approach, *those possible events are real, but not actual; they exist, but not in spacetime*. The *actual* event is the one that can be said to exist as a component of spacetime. I thus dissent from the usual identification of "physical" with "actual": an entity can be physical without being actual. In more metaphorical language, we can think of the observable portion of reality (the actualized, spacetime-located portion) as the "tip of an iceberg," with the unobservable, unactualized, but still real, portion as the submerged part (see Figure 1.1).

Another way to understand the view presented here is in terms of Plato's original dichotomy between "appearance" and "reality." His famous allegory of

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[2] Lewis' view is known as "modal realism" or "possibilist realism."

[3] So, for example, I will not need to defend the alleged existence of "that possible fat man in the doorway" from the "slum of possibles," a criticism of the modal realist approach by Quine (1953, p. 15).

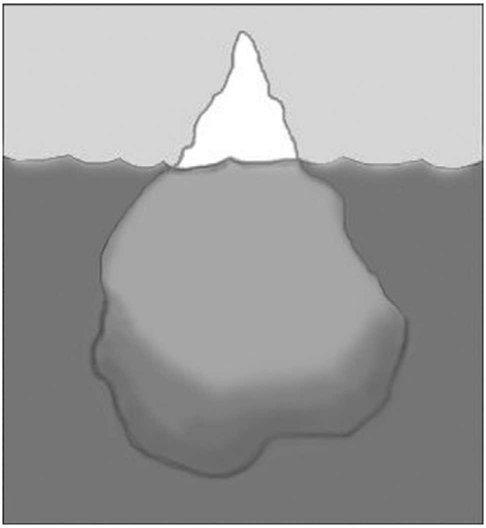

Figure 1.1 Possibilist TI: the observable world of spacetime events is the "tip of the iceberg" rooted in an unobservable manifold of possibilities transcending spacetime. These physical possibilities are what are described by quantum theory. Drawing by Wendy Hagelgans.

the Cave proposed that we humans are like prisoners chained in a dark cave, watching and studying shadows flickering on a wall and thinking that those shadows are real objects. However, in reality (according to the allegory) the real objects are behind us, illuminated by a fire that casts their shadows on the wall upon which we gaze. The objects themselves are quite different from the appearances of their shadows (they are richer and more complex). While Plato thought of the "unseen" level of reality in terms of perfect forms, I propose that the reality giving rise to the "shadow" objects that we see in our spacetime "cave" consists of the quantum objects described by the mathematical forms of quantum theory. Because they are "too big," in a mathematical sense, to fit into spacetime (just as the objects casting the shadows are too big to fit on a wall in the cave, or the submerged portion of the iceberg cannot be seen above the water) – and thus cannot be fully "actualized" in the spacetime theater – we call them "possibilities." But they are *physically real* possibilities, in contrast to the way in which the term "possible" is usually used. Quantum possibilities are physically efficacious in that they *can* be actualized and thus can be experienced in the world of appearance (the empirical world).

This basic view will be further developed throughout the book. As a starting point, however, we need to take a broad overview of where we stand in the endeavor of interpreting the physical meaning of quantum theory. I begin with some notorious peculiarities of the theory.

1.2 Quantum Peculiarities

1.2.1 Indeterminacy

The first peculiarity I will consider, *indeterminacy*, requires that I first discuss a key term used in quantum mechanics (QM), namely, “observable.” In ordinary classical physics, which describes macroscopic objects like baseballs and planets, it is easy to discuss the standard physical properties of objects (such as their position and momentum) as if those objects always possess determinate (i.e., well-defined, unambiguous) values. For example, in classical physics one can specify a baseball’s position x and momentum p at any given time t. However, for reasons that will become clearer later on, in QM we cannot assume that the objects described by the theory – such as subatomic particles – always have such properties independently of interactions with, for example, a measuring device.[4] So, rather than talk about “properties,” in QM we talk about “observables” – the things we can observe about a system based on measurements of it.

Now, applying the term “observable” to quantum objects under study seems to suggest that their nature is dependent on observation, where the latter is usually understood in an anthropocentric sense, as in observation by a conscious observer. The technical philosophical term for the idea that the nature of objects depends on how (or whether) they are perceived is “antirealism.” The term “realism” denotes the opposite view: that objects have whatever properties they have independent of how (or whether) they are perceived, that is, that the real status or nature of objects does not depend on their perception.

The antirealist flavor of the term “observable” in quantum theory has led researchers of a realist persuasion – a prominent example being John S. Bell – to be highly critical of the term. Indeed, Bell rejected the term “observable” and proposed instead a realist alternative, “beable.” Bell intended “beable” to denote real properties of quantum objects that are independent of whether or not they are measured (one example being Bohmian particle positions; see Section 1.3.3). The interpretation presented in this book does not make use of “beables,” although it shares Bell’s realist motivation: quantum theory – by virtue of its impeccable ability to make accurate predictions about the phenomena we can observe – is telling us something about reality, and it is our job to discover what that might be, no matter how strange it may seem.[5]

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[4] The apparent “cut” between macroscopic (e.g., a measuring device) and microscopic (e.g., a subatomic particle) realms has been one of the central puzzles of quantum theory; it is also known as the “shifty split.” We will see (in Chapter 3) that under the transactional interpretation this problem is solved; the demarcation between quantum and classical realms need not be arbitrary (or based on a subjectivist appeal to an observing “consciousness”).

[5] The realist accounts for the success of a theory in a simple way: it describes something about reality. Antirealist and pragmatic approaches such as “instrumentalism” – that theories are just instruments to predict phenomena – can provide no explanation for why the successful theory works better than a competing theory. A typical

I will address in more detail the issue of how to understand what an "observable" is in the context of the transactional interpretation in later chapters. For now, I simply deal with the perplexing issue of indeterminacy concerning the values of observables, as in the usual account of QM.

Heisenberg's famous "uncertainty principle" (also called the "indeterminacy principle") states that, for a given quantum system, one cannot simultaneously determine physical values for pairs of incompatible observables. "Incompatible" means that the observables cannot be simultaneously measured and that the results one obtains depend on the order in which they are measured. Elementary particle theorist Joseph Sucher has a colorful way of describing this property. He observes that there is a big difference between the following two processes: (1) opening a window and sticking your head out and (2) sticking your head out and then opening the window.[6]

Mathematically, the *operators* (i.e., the formal objects representing observables) corresponding to incompatible observables do not commute;[7] that is, the results of multiplying such operators together depend on their order. Concrete examples are position, whose mathematical operator is denoted X (technically, the operator is really multiplication by position x), and momentum, whose operator is denoted P.[8] The fact that X and P do not commute can be symbolized by the statement

$$\mathrm{XP} \neq \mathrm{PX}.$$

Thus, quantum mechanical observables are not ordinary numbers that can be multiplied in any order with the same result; instead, you must be careful about the order in which they are multiplied.

It is important to understand that the uncertainty principle is something much stronger (and *stranger*) than the statement that we just can't physically measure, say, both position and momentum because measuring one property disturbs the other one and changes it. Rather, in a fundamental sense, the quantum object *does not have* a determinate (well-defined) value of momentum when its position is being detected, and vice versa. This aspect of quantum theory is built into the very mathematical structure of the theory, which says in precise logical terms that there simply is no yes/no answer to a question about the value of a quantum object's position when you are measuring its momentum. That is, the question "Is the particle at position x?" generally has no yes or no answer in quantum theory in the context of a momentum measurement. This is the puzzle of quantum

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account in support of such approaches would say that the demand for an explanation for why the theory works simply need not be met. I view this as an evasion of a perfectly legitimate, indeed crucial, question.

[6] Comment by Professor Joseph Sucher in a 1993 UMCP quantum mechanics course.

[7] "Commute" literally means "go back and forth"; so that the standard commuting property is expressed by noting that for two ordinary numbers a and b, $ab = ba$.

[8] The mathematical form of P (in one spatial dimension) is given by $\mathrm{P} = (h/i)(d/dx)$.

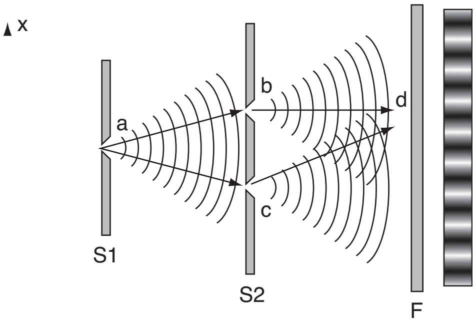

Figure 1.2 The double-slit experiment.
Source: http://en.wikipedia.org/wiki/File:Doubleslit.svg.

indeterminacy: quantum objects seem not to have precise properties independent of specific measurements designed to detect those specific properties.[9]

A particularly striking example of indeterminacy on the part of quantum objects is exhibited in the famous two-slit experiment (Figure 1.2). This experiment is often discussed in conjunction with the idea of "wave/particle duality," which is a manifestation of indeterminacy. (The experiment and its implications for quantum objects are discussed Feynman et al. (1964, chapter 1); I revisit this example in more detail in Chapter 3.)

If we shine a beam of light through two narrow slits, we will see an interference pattern (see Figure 1.2). This is because light behaves (under some circumstances) like a wave, and waves exhibit interference effects. A key revelation of quantum theory is that material objects (i.e., objects with nonzero rest mass, in contrast to light) also exhibit wave aspects. So one can do the two-slit experiment with quantum particles as well, such as electrons, and obtain interference. Such an experiment was first performed by Davisson and Germer in 1928 and was an important confirmation of Louis de Broglie's hypothesis that matter also possesses wavelike properties.[10]

The puzzling thing about the two-slit experiment performed with material particles is that it is hard to understand what is "interfering": our classical common sense tells us that electrons and other material particles are like tiny billiard balls that follow a clear trajectory through such an apparatus. In that picture, the electron must go through one slit or the other. But if one assumes that this is the case and calculates the expected pattern, the result will *not* be an interference pattern. Moreover, if one tries to "catch it in the act" by observing which slit the electron went through, this procedure will ruin the interference pattern. It turns out that

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[9] The exception is properties belonging to a compatible observable (whose operator commutes with the one being measured). Bohmians dissent from this characterization of the theory; this will be discussed below.

[10] Davisson (1928).

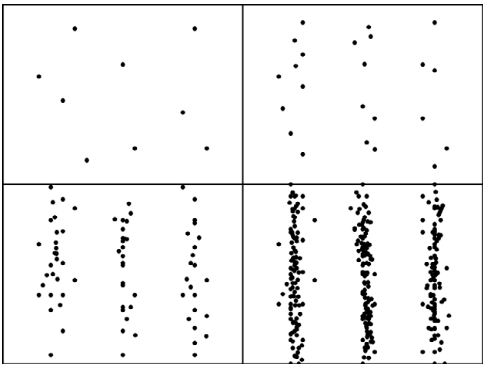

Figure 1.3 Typical results of a double-slit experiment showing the buildup of an interference pattern of single electrons.

interference is seen only when the electron is left undisturbed, so that in some sense it “goes through both slits.” Note that the interference pattern can be slowly built up dot by dot, with only one particle in the apparatus at a time (see Figure 1.3). Each of those dots represents an entity that is somehow “interfering with itself” and represents a particle whose position is indeterminate – it does not have a well-defined trajectory, in contrast to our classical expectations.[11]

1.2.2 Nonlocality

The puzzle of nonlocality arises in the context of composite quantum systems, that is, systems that are composed of two or more quantum objects. The prototypical example of nonlocality is the famous Einstein–Podolsky–Rosen (EPR) paradox, first presented in a 1935 paper (Einstein et al., 1935). The paper, entitled “Can quantum-mechanical description of reality be considered complete?,” attempted to demonstrate that QM could not be a complete description of reality because it failed to provide values for physical quantities that the authors assumed must exist.

Here is the EPR thought-experiment in a simplified form due to David Bohm, in terms of spin-1/2 particles such as electrons. Spin-1/2 particles have the property that, when subject to a non-uniform magnetic field along a certain spatial direction z, they can either align with the field (which is termed “up” for short) or against the field (termed “down”) (such a measurement can be carried out by a Stern-Gerlach device; see Figure 1.4).

I designate the corresponding quantum states as “$|z\,\mathrm{up}\rangle$” and “$|z\,\mathrm{down}\rangle$,” respectively. The notation used here is the bracket notation invented by Dirac, and

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[11] One of the interpretations I will discuss, the Bohmian theory, does offer an account in which particles follow determinate trajectories. The price for this is a kind of nonlocality that may be difficult to reconcile with relativity, in contrast to TI.

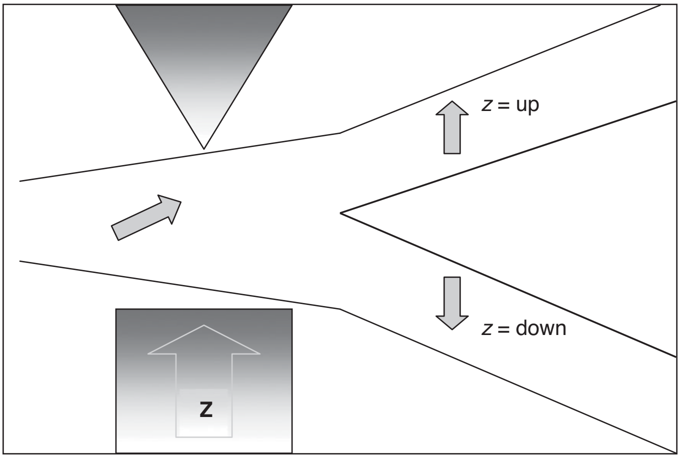

Figure 1.4 Spin "up" or "down" along the *z* direction in a Stern-Gerlach measurement.

the part pointing to the right is the "|ket⟩." We can also have a part pointing to the left, "⟨brac|." (Since one is often working with the inner product form ⟨brac|ket⟩, the name is an apt one.) We could measure the spin and find a corresponding result of either "up" or "down" along any direction we wish, by orienting the field along a different spatial direction, say, *x*. The states we could then measure would be called "|*x*up⟩" or "|*x*down⟩," and similarly for any other chosen direction.

We also need to start with a composite system of two electrons in a special type of state, called an "entangled state." This is a state of the composite system that cannot be expressed as a simple, factorizable combination (technically a "product state") of the two electrons in determinate spin states, such as "|*x*up⟩|*x*down⟩."

If we denote the special state by $|S\rangle$, it looks like

$$|\mathrm{S}\rangle = \frac{1}{\sqrt{2}}[|\mathrm{up}\rangle|\mathrm{down}\rangle - |\mathrm{down}\rangle|\mathrm{up}\rangle] \tag{1.1}$$

where no directions have been specified, since this state is not committed to any specific direction. That is, you could put in any direction you wish (provided you use the same "up/down – down/up" form); the state is mathematically equivalent for all directions.

Now, suppose you create this composite system at the 50-yard line of a football field and direct each of the component particles in opposite directions, say, to two observers "Alice" and "Bob" in the touchdown zones at opposite ends of the field. Alice and Bob are each equipped with a measuring apparatus that can generate a local non-uniform magnetic field along any direction of their choice (as illustrated in Figure 1.4). Suppose Alice chooses to measure her electron's spin in the *z* direction. Then quantum mechanics dictates that the spin of Bob's particle, if measured along z as well, must always be found in the opposite orientation from Alice's: if Alice's electron turns out to be $|z\,\text{up}\rangle$, then Bob's electron must be $|z\,\text{down}\rangle$, and vice versa. The same holds for any direction chosen by Alice. Thus it seems as though Bob's particle must somehow "know" about the measurement performed by Alice and her result, even though it may be too far away for a light signal to reach in time to communicate the required outcome seen by Bob. This apparent transfer of information at a speed greater than the speed of light ($c = 3 \times 10^8$ m/s) is termed a "nonlocal influence," and this apparent conflict of quantum theory with the prohibition of signals faster than light is termed "nonlocality."[12]

Einstein termed this phenomenon "spooky action at a distance" and used it to argue that there had to be something "incomplete" about quantum theory, since, in his words, "no reasonable theory of reality should be expected to permit this."[13]

However, it turns out that we are indeed stuck with quantum mechanics as our best theory of (micro)-reality despite the fact that it does, and must, permit this, as Bell's Theorem (1964) demonstrated. Bell famously showed that no theory that incorporates local "elements of reality" of the kind presumed by Einstein can reproduce the well-corroborated predictions of quantum theory; specifically, the strong correlations inherent in the EPR experiment. *Quantum mechanics is decisively nonlocal*: the components of composite systems described by certain kinds of quantum states (such as the state (1.1)) seem to be in direct, instantaneous communication with one another, regardless of how far they may be spatially separated.[14] The interpretational challenge presented by the EPR thought-experiment combined with Bell's Theorem is that a well-corroborated theory seems to show that reality *is* indeed "unreasonable," in that it allows influences at

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[12] I say "apparent conflict" here because it is a very subtle question as to what constitutes a genuine violation of, or conflict with, relativity. In later chapters we'll see that PTI (which is also called "relativistic TI" or RTI) can provide "peaceful coexistence" of QM with relativity, as envisioned by Shimony (2009).

[13] I am glossing over some subtleties here concerning Einstein's objection. A more detailed account of the EPR paper would note that Einstein's objection was in terms of "elements of reality" concerning the presumably determinate physical spin attributes of either electron and the fact that their quantum states seemed not to be able to specify these. As noted in the subsequent discussion, Bell's Theorem of 1964 showed that there can be no such "elements of reality."

[14] I should note that some researchers dissent from this characterization. One way out of the conclusion that quantum theory is necessarily nonlocal is to dispute the way "elements of reality" are defined. See, for example, Willem M. de Muynck's discussion at www.phys.tue.nl/ktn/Wim/qm4.htm!thermo_analogy. I am skeptical of this approach because it must introduce what appears to be an ad hoc further level of statistical randomness, beyond that of the standard theory, whose sole purpose is to enforce locality. Adherents of Everettian approaches argue that these can retain locality, but that has been disputed, for example, in Kastner (2011c), which points out that nonlocal correlations persist. This is a matter of ongoing debate in the literature. But in a nutshell, in Everettian approaches, "splitting" becomes the means to eliminate nonlocality, so the viability of "splitting" becomes crucial here, which brings us back to the fact that standard decoherence arguments do not establish measurement outcomes and therefore cannot support "splitting." Adherents of Qbism attempt to "save locality," but Henson (2015) has pointed out that their argument fails in that it also must designate explicitly nonlocal theories as "local."

apparently infinite (or at least much faster than light) speeds, despite the fact that relativity seems to say that such things are forbidden.

1.2.3 The Measurement Problem

The measurement problem is probably the most perplexing feature of quantum theory. There is a vast literature on this topic, testifying to the numerous and sustained attempts to solve this problem. Erwin Schrödinger's famous "cat" example, which I will describe below, was intended by him to be a dramatic illustration of the measurement problem (Schrödinger, 1935).

The measurement problem is related to quantum indeterminacy in the following way. Our everyday experiences of always-determinate (clearly defined, nonfuzzy) properties of objects seems inconsistent with the mathematical structure of the theory, which dictates that sometimes such properties are *not* determinate. The latter cases are expressed as superpositions of two or more clearly defined states. For example, a state of indeterminate position, let's call it "$|?\rangle$," could be represented in terms of two possible positions x and y by

$$|?\rangle = a|x\rangle + b|y\rangle \tag{1.2}$$

where a and b are two complex numbers called "amplitudes." A quantum system could undergo some preparation leaving it in this state. If we wanted to find out where the system was, we could measure its position, and, according to the orthodox way of thinking about quantum theory, its state would "collapse" into either position x or position y.[15] The idea that a system's state must "collapse" in this way upon measurement is called the "collapse postulate" (see Section 1.3.4) and is a matter of some controversy. Schrödinger's cat makes the controversy evident. I now turn to this famous thought-experiment.

Here is a brief description of the idea (with apologies to cat lovers). A cat is placed in a box containing an unstable radioactive atom which has a 50% chance of decaying (emitting a subatomic particle) within an hour. A Geiger counter, which detects such particles, is placed next to the atom. If a click is registered indicating that the atom has decayed, a hammer is released which smashes a vial of poison gas, killing the cat. Otherwise, nothing happens to the cat. With this setup, we place all ingredients in the box, close it, and wait one hour.

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[15] The probability of ending up in x would be a^*a and in y would be b^*b. This prescription for taking the absolute square of the amplitude of the term to get the probability of the corresponding result is called the "Born Rule" after Max Born, who first proposed it. Amplitudes are therefore also referred to as "probability amplitudes." There is no way to predict which outcome will result in any individual case. TI provides a concrete, physical (as opposed to statistical or decision-theoretic) basis for the Born Rule.

The atom’s state is usually written as a superposition of “undecayed” and “decayed,” analogous to state (1.2):

$$|\mathrm{atom}\rangle = \frac{1}{\sqrt{2}}[|\mathrm{undecayed}\rangle + |\mathrm{decayed}\rangle] \tag{1.3}$$

Prior to our opening the box, since no measurement has been performed to “collapse” this superposition, we are (so the usual story goes[16]) obligated to include the cat’s state in the superposition as follows:

$$|\mathrm{atom} + \mathrm{cat}\rangle = \frac{1}{\sqrt{2}}[|\mathrm{undecayed}\rangle|\mathrm{alive}\rangle + |\mathrm{decayed}\rangle|\mathrm{dead}\rangle] \tag{1.4}$$

This superposition is assumed to persist because no “measurement” has occurred which would “collapse” the state into either alternative. So we appear to end up with a cat in a superposition of “alive” and “dead” until we open the box and see which it is, upon which the state of the entire system (atom + Geiger counter + hammer + gas vial + cat) “collapses” into a determinate result. Schrödinger’s example famously illustrated his exasperation with the idea that something macroscopic like a cat seems to be forced into a bizarre superposition of alive and dead by the dictates of quantum theory, and that it is only when somebody “looks” at it that the superposed system is found to have collapsed, even though this mysterious “collapse” is never observed nor (apparently) is there any physical mechanism for it. This is the core of the measurement problem.

In less colorful language, the measurement problem consists in the fact that, given an initial quantum state for a system, quantum theory does not tell us *why* or *how* we only get one specific outcome when we perform a measurement on that system. On the contrary, the quantum formalism seems to tell us about several possible outcomes, each with a particular weight. So, for example, I could prepare a quantum system in some arbitrary state X, perform a measurement on it, and the theory would tell me that it might be A, or B, or C, but it will not tell me *which* result actually occurs, nor does it provide any reason for *why* only one of these is actually observed.

So there seems to be a very big and mysterious gap between what the theory appears to be saying (at least according to the usual understanding of it) and what our experience tells us in everyday life. We are technically sophisticated enough to create and manipulate microscopic quantum systems in the laboratory, to the extent

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[16] TI does not have to tell the story this way; in TI one does not need to characterize the system by Equation (1.4). This fact, a major reason to choose TI over its competitors, is discussed in Chapters 3 and 4. A key component of the puzzle raised by Schrödinger’s cat is that it is not at all obvious that a macroscopic object like a cat should be describable as a component of a unitarily evolving quantum state as in Equation (1.4) (indeed, I argue that it is *not*). While many current approaches recognize this issue and try to address it, I believe that TI’s approach is the only noncircular and unambiguous one.

that we can identify them with a particular quantum state (such as X above). We can then put these prepared systems through various experimental situations intended to measure their properties. But, in general, for any of those measurements, the theory just gives us a weighted list of possible outcomes. And obviously, in the laboratory, we see only *one* particular outcome.

Now, the theory is still firmly corroborated in the sense that the weights give extremely accurate predictions for the *probabilities* of those outcomes when we perform the same kind of measurement on a large number of identically prepared systems (technically known as an *ensemble*). But the measurement problem consists in the fact that any individual system is still described by the theory, yet the theory fails to specify (1) what sort of interaction counts as a "measurement," (2) what that individual system's outcome will actually be, or (3) even why it has only one.

It should be emphasized that this situation is completely different from what classical physics tells us. For example, consider a coin flip. A coin is a macroscopic object that is well described by classical physics. If we knew everything about all the (classical) forces acting on the coin, and all the relevant details of the coin itself, we could in principle calculate the result of any particular coin flip. That is, we could predict with 100% certainty (or at least within experimental error) whether it would land heads or tails. But when it comes to the microscopic objects described by quantum theory, even if we start with precise knowledge of their initial states, in general the theory does not allow us to predict *any* given outcome with 100% certainty.[17] The situation is made even more perplexing by the fact that classical physics and quantum physics must be describing the same world, so they must be compatible in the limit of macroscopic objects (i.e., when the sizes of our systems become much larger than subatomic particles like electrons and neutrons). This means that macroscopic objects must also be describable (in that same limit) by quantum theory. This consideration raises the important question of: Exactly *what* is a "macroscopic object" anyway, and how is it different from the objects (like electrons) that can *only* be described by quantum theory? The quick answer, under TI, is that macroscopic objects are phenomena resulting from actualized transactions, whereas quantum objects are not. I explore this point in detail in Chapters 6–8.

Typical prevailing interpretations even encounter difficulty in specifying exactly what counts as a measurement, and (as noted above) that question is a component of the measurement problem. For example, discussions of the Schrödinger cat

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[17] The exception, of course, is that measurements of observables commuting with the preparation observable result in determinate outcomes.

paradox have dealt not only with the bizarre notion of a cat seemingly in a quantum superposition but also with the conundrum of *when or how* measurement of the system can be considered truly finished. That is, does the observer who opens the box and looks at the cat also enter into a superposition? At what point does this superposition really “collapse” into a determinate (unambiguous) result? An example of this statement of the problem in the literature is provided by Clifton and Monton (1999):

> Unfortunately, the standard dynamics [and the standard way of interpreting] quantum states together give rise to the measurement problem; they force the conclusion that a cat can be neither alive nor dead, and, worse, that a competent observer who looks upon such a cat will neither believe that the cat is alive nor believe it to be dead. The standard way out of the measurement problem is to . . . temporarily suspend the standard dynamics by invoking the collapse postulate. According to the postulate, the state vector $|\psi(t)\rangle$, representing a composite interacting “measured” and “measuring” system, stochastically [randomly] collapses, at some time t' during their interaction.. . . The trouble is that this is not a way out unless one can specify the physical conditions necessary and sufficient for a measurement interaction to occur; for surely “measurement” is too ambiguous a concept to be taken as primitive in a fundamental physical theory. *(p. 698)*

Thus, the measurement problem arises from the apparent unitary-only (deterministic, linear) evolution of standard quantum theory, together with ambiguity about when to invoke a non-unitary “collapse postulate” which seems not to have any physical content. The problem has recently been sharpened to an even more devastating form in the latest version of the “cat paradox” by Frauchiger and Renner (2018). These authors devised a scenario that results not just in an absurd macroscopic superposition (like Schrödinger’s cat) but in an overt inconsistency: different observers will disagree on the result of a measurement that could, in principle, be performed. We will see in subsequent chapters that TI provides a very effective way out of this conundrum, including the puzzle of defining what constitutes a “measurement.”

1.3 Prevailing Interpretations of QM

1.3.1 Decoherence Approaches

“Decoherence” refers to the way in which interference effects (like what we see in a two-slit experiment, Figures 1.2 and 1.3) are lost as a given quantum system interacts with its environment. Roughly speaking, decoherence amounts to the loss of the ability of the system to “interfere with itself” as the electron does in the two-slit experiment. This basic idea – that a quantum system suffers decoherence when it interacts with its environment – has been developed to a high technical degree in recent decades. In effect this research has shown that in most cases, quantum systems cannot maintain coherence, and its attendant interference effects, in processes which amplify such systems to the observable level of ordinary experience. In general, this approach to the classical level is described by a greatly increasing number of "degrees of freedom" of the system(s) under study.[18] So, decoherence shows that systems with many degrees of freedom – macroscopic systems – do not exhibit observable interference. In addition, the decoherence approach seems to provide a way to specify a determinate "pointer observable" for the apparatus used to measure a given system once the interactions of the system, apparatus, and environment are all taken into account. This apparent emergence via the decoherence process of a clearly defined, macroscopic "pointer observable" for a given measurement interaction is sometimes referred to as "quantum Darwinism," since the process seems analogous to an evolutionary process.

Many researchers have taken this as at least a partial solution to the measurement problem in that it is taken to explain why we don't see interference effects happening all around us even though matter is known to have wavelike properties. It appears to explain, for example, why Schrödinger's cat need not be thought of as exhibiting an interference pattern (which is something of a relief). But decoherence alone does not explain why the cat is clearly *either* alive *or* dead (and not in some superposition) at the end of the experiment. The reason for this is somewhat technical, and amounts to the fact that we can still have quantum superpositions without interference. Such superpositions cannot be thought of as representing only an epistemic uncertainty (uncertainty based only on lack of knowledge about something that really is determinate). In order to regain the classical world of ordinary experience, we need to be able to say that our uncertainty about the status of an object is entirely epistemic – it is just our ignorance about the object's properties – and not based on an indeterminacy inherent in the object itself. Decoherence fails to provide this. G. Bacciagaluppi emphasizes this point his entry on decoherence in the *Stanford Encyclopedia of Philosophy*:

> Unfortunately, naive claims of the kind that decoherence gives a complete answer to the measurement problem are still somewhat part of the "folklore" of decoherence, and deservedly attract the wrath of physicists (e.g. Pearle 1997) and philosophers (e.g. Bub 1997, Chap. 8) alike.[19]

Here is a crude way to understand the distinction between merely epistemic uncertainty and quantum (objective) indeterminacy. Suppose I put 10 marbles in

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[18] "Degrees of freedom" basically means "ways in which an object can move." A system of one particle (neglecting spin) can move in a spatial sense (in three possible directions), so it has three degrees of freedom. A system of three particles has nine degrees of freedom, and so on. If one assumes that the particles have spin, then additional, rotational degrees of freedom are in play.

[19] Bacciagaluppi (2016).

an opaque box; 3 red and 7 green, and then close the box. I could represent my uncertainty about the color of any particular marble I might reach in and grab by a statistical “mixture” of 30% red and 70% green. My uncertainty about those marbles is entirely contained in my ignorance about which one I will happen to touch first. There is nothing “uncertain” about the marbles themselves. Not so with a quantum system prepared in a state, say,

$$|\Psi\rangle = a \mid \text{red}\rangle + b \mid \text{green}\rangle. \tag{1.5}$$

We may be able to eliminate all interference effects from phenomena based on this object’s interactions with macroscopic objects, but we have not eliminated the quantum superposition based on its state. In some sense, the state describes an *objective* uncertainty that cannot be eliminated by eliminating interference. The technical way to describe this is that the statistical state of the decohered system is a mixture, but an *improper* one. The state of the marbles was a *proper* mixture. We need a proper mixture in order to say that we have solved the measurement problem, but decoherence does not provide that.

Yet perhaps a more serious challenge for the overarching goal of the decoherence program to explain the emergence of a classical (determinate, non-interfering) realm from the quantum realm is found in the recent work of Chris Fields (2011). Fields shows that in order to determine from the quantum formalism which pointer observable “emerges” via decoherence, one must first specify the boundary between the measured system and the environment; that is, one must say which degrees of freedom belong to the system being measured and which belong to the environment. But in order to do this, one must use information available only from the macroscopic level, since it is only at that level that the distinction exists; only the experimenters know what they consider to be the system under study. So it cannot be claimed that the macroscopic level naturally “emerges” from purely quantum mechanical origins. The program is circular because it requires macroscopic phenomena as crucial inputs to obtain macroscopic phenomena as outputs.[20]

Therefore, the decoherence program does not actually solve the measurement problem, due to the persistence of improper mixtures which cannot be interpreted as mere subjective ignorance of existing (“determinate”) facts or states of affairs. Nor does it succeed in the goal of demonstrating that the classical world of

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[20] Technically, Fields’ argument is independent of the scale of the phenomena; it shows that classical information must be put in to get out classical information (such as the relevant pointer observables). But in practice, this information comes from the macroscopic level – that is, the experimenters’ choices concerning what they want to study. See also Butterfield (2011, p. 17) for why the decoherence program does not solve the measurement problem.

experience arises naturally from the quantum level.[21] In later chapters it will be shown that TI can readily account for the emergence of a macroscopic realm from the quantum realm. This emergence dovetails with the quantitative predictions of decoherence theory (as we will see in Section 6.5). However, in the TI account, measured systems are described by proper instead of improper mixtures; thus it achieves a resolution of the measurement problem that has eluded the standard approach regarding decoherence.

1.3.2 Many Worlds Interpretations

Many worlds interpretations are variants of an imaginative proposal by Hugh Everett (1957), which he called the "relative state interpretation." The basic core of Everett's proposal was simply to deny that any kind of "collapse" ever occurs and assert that the linear, unitary[22] evolution of quantum state vectors is the whole story. He suggested that any given observer's perceptions will be represented in one branch or other of the state vector, and that this is all that is necessary to account for our experiences. That is, the observer will become correlated with the system they are observing, and a particular outcome for the system can only be specified *relative to the corresponding state* for the observer (hence the title).

However, most researchers were not satisfied with this as a complete solution to the measurement problem. For one thing, it did not seem clear what was meant by an observer being somehow associated with many branches of the state vector. A variant proposed by Bryce DeWitt "took the bull by the horns" and asserted that these branches described actual separate worlds – that is, that the apparent mathematical evolution of the state vector into branches corresponded to an actual physical splitting of the world. This version of Everett's approach became known as the full-blown

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[21] It should be noted that Deutsch (1999) and Zurek (2003) have presented "derivations" of the Born Rule. However, these derivations are observer-dependent, based on the specification of a non-intrinsic, classical division of objects into "system" and "observer" (or measuring device). Thus these approaches provide a subjective or purely epistemic probabilistic interpretation, based on defining ignorance on the part of some conscious observer. In contrast, TI derives the Born Rule in a physical way, with probability being a natural interpretation of what are pre-probabilistic physical weights. Thus objective probability arises out of a specific physical entity in TI – the incipient transaction. TI's physical, as opposed to epistemic, approach to probability is appropriate to the interpretation of quantum theory as being about objective, rather than subjective, probabilities. Another way to put it: Zurek's and Deutsch's approaches are *epistemic* motivations in the same way that Gleason's is a "mathematical motivation" (as characterized by Schlosshauer and Fine, 2003). Insofar as they presuppose the presence of a classical "observer," they show consistency of quantum probabilities with what such an observer would observe, rather than deriving the probabilities in terms of a physical referent. The handicap hindering such accounts is that they must work with state vectors as the only physical referent. They do not have a physical referent for the projection operators (incipient transactions) which carry the real physical content of objective probabilities in quantum theory.

[22] "Linear" means that the quantum state only appears in the first power, and "unitary" means that no physically or mathematically ambiguous "collapse" has occurred. I refer to a "state vector" rather than a "wave function" because the former is the most general mathematical form of the quantum state: an element of Hilbert space. The wave function is just an amplitude obtained from projecting the state vector into a basis.

"many worlds interpretation."[23] (Perhaps not surprisingly, the MWI has become the basis for many science fiction stories – a good example being the episode "Parallels" of *Star Trek: The Next Generation* (seventh season) in which the character Worf finds himself "transitioning" between different possible Everettian worlds with differing versions of events.) Proponents of MWI rely on decoherence in order to specify a basis for the splitting of worlds – that is, to explain why splitting seems to happen with respect to possible positions of objects rather than, say, their momenta or any other mathematically possible observable.

Other Everettians, who adhere to a version called the "bare theory," prefer not to subscribe to an actual physical splitting of worlds, but instead attribute a quantum state to an observer and describe that observer's mental state as branching. Adherents of the bare theory argue that consistency with experience is achieved by noting that a second, nonsplitting observer (call him Bob) can always ask the first observer (Alice, who is observing a quantum system) whether she sees a determinate result, and Alice can answer yes without specifying what that result is.[24] Thus, an observer's state will either split along with a previous observer (if they inquire what the particular result was) and each of their branches will be correlated in a consistent way with the first observer's branches; or it will not split, and the second observer will still receive a consistent answer, if they only ask whether the first observer perceived a determinate result (but does not ask what the specific result is).

However, Bub (1997) and Bub et al. (1997) have argued that this approach ultimately fails to solve the measurement problem. Their critique is rather technical, but it boils down to two essential observations. (1) It turns out that there is an arbitrariness about whether the first observer will report "yes" or "no" concerning the determinateness of their perceptions and that the choice of "yes" can be seen as analogous to choosing a "preferred observable" – that is, a particular observable that is assumed to always have a value. But that assumption contradicts the original intent of the interpretation – it is supposed to be a "bare" theory, after all, with no additional assumptions necessary besides the linear, unitary development of the quantum state. (2) It is not enough for Alice to simply report that she perceived a determinate result: we commonly take ourselves not only to perceive something definite, but also to perceive *what* that thing is. Bub et al. argue that inasmuch as the "bare theory" exhibits feature (1), it is not really so "bare" after all and actually resembles what they term a "nonstandard" approach to interpreting quantum theory, that is, an approach in which something is added to the "bare theory" such as the stipulation that one observable is to be "preferred" over others, either in having an always-determinate value or at least in being a

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[23] DeWitt (1970).

[24] Technically, this is described as Alice being in an eigenstate of "determinate measurement result," even if she is not in an eigenstate of one particular result or another.

"default" for determinacy. (Bohm's interpretation, to be discussed below, is an example of a nonstandard approach of this type, in that position is the privileged observable.) And regarding (2): as Bub et al. point out, other nonstandard approaches can give an account of how Alice could report not only that she had some definite belief about the result she observed, but what that result was. So, in their analysis, the bare theory falls short, both of actually being "bare" and of actually solving the measurement problem.

As for the DeWitt full-blown MWI version of the Everett approach, a major challenge is to explain what the quantum mechanical weights, or probabilities, mean if each outcome is actually *certain* to occur in some branch (world) or another. Doesn't the fact that something comes with a probability attached to it mean that there is some uncertainty about the actual outcome? The basic position of MWI – that all outcomes will certainly occur – has led to rather tortuous and esoteric arguments about the meaning of probability and uncertainty.[25]

But the situation may yet be worse for Everettian interpretations. Recently, Kent (2010) has argued that the whole program of deriving the Born Rule[26] from a decision-theoretic approach based on the presumed strategies of rational inhabitants of a "multiverse" (a MWI term for the entire collection of universes) is suspect. Any presumed strategy of a "rational" agent is no more than that – a probably sensible strategy among other possibly sensible strategies, and is therefore not unique. As Kent (2010) puts it:

> The problem is that abandoning any claim of uniqueness also removes the purported connection between theoretical reasoning and empirical data, and this is disastrous for the program of attempting to interpret Everettian quantum theory via decision theory. If Wallace's arguments are read as suggesting no more than that one can consistently adopt the Born rule if one pleases, it remains a mystery as to how and why we arrived at the Born rule empirically. *(p. 10)*[27]

Besides the dependence on assumptions about what a rational agent would do, many approaches to deriving the Born Rule in the Everettian scheme depend on assumptions about mind–brain correspondences which are highly speculative as well as explicitly dualistic. As Kent (2010) observes:

> the fact that we don't have a good theory of mind, even in classical physics, doesn't give us a free pass to conclude anything we please. That way lies scientific ruin: any physical

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[25] Greaves (2004, pp. 426–27) proposes giving up the idea that the Born probabilities associated with the set of possible outcomes implies uncertainty about which outcome will happen. Meanwhile, Wallace (2006, pp. 672–73) proposes giving up the idea that being probabilistically uncertain of something pertains to the occurrence of some objective fact (outcome).

[26] The Born Rule is the prescription for calculating probabilities; see note 13.

[27] Kent refers to Wallace (2006).

> theory is consistent with any observations if we can bridge any discrepancy by tacking on arbitrary assumptions about the link between mind states and physics. *(p. 21)*

Nevertheless, it would seem that Everettian arguments for the emergence of the Born Rule are crucially based on just such assumptions.

1.3.3 Bohm's Interpretation

In a nutshell, David Bohm (1917–92) proposed that the measurement problem can be solved by adding actual particles, possessing always-precise positions, to the wave function. To distinguish these postulated objects from the general term "particle" which is often used to refer to a generic quantum system, I will follow Brown and Wallace (2005) in terming these postulated Bohmian objects "corpuscles." The "equilibrium" distribution of these corpuscles is postulated to be given by the square of the wave function, in accordance with the Born Rule. The uncertainty and indeterminacy discussed earlier is still present in the Bohmian account. However, it is epistemic (rather than ontological) since they do possess definite positions but we cannot know what their positions were prior to detecting a particular measurement result. That is, the knowledge we can have of corpuscle positions at any time before a given measurement is limited to the distribution given by the square of the wave function of the system of interest (e.g., an electron in a hydrogen atom) (see Figure 1.5). The wave function then acts as a guiding or "pilot wave" for the corpuscle, as first suggested by Louis de Broglie (1923).[28] At the end of a measurement, the wave function will still have various "branches" (corresponding to different possible outcomes), but the corpuscle will occupy only one of them, and according to Bohm's formulation, this determines which result will be experienced. Thus the idea is that the Bohmian corpuscle acts as a kind of "agent of precipitation" which allows for the experience of one outcome out of the many possible ones. In terms of measurement, Bohm argues that the "corpuscular" aspect of the measuring apparatus, on interacting with the measured quantum system, ultimately enters one of the distinct guiding wave "channels" of the wave function of the entire system (apparatus plus quantum system) created through the process of measurement, and this process singles out that particular channel as the one which yields the actual result. (Brown and Wallace call this the "result assumption."[29])

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[28] As far as I know, there is no physical account of how the "guiding wave," which lives in a $3N$-dimensional configuration space (where N is the number of corpuscles), guides the corpuscle – which is postulated to live in physical space. In the interest of a "level playing field" for competing interpretations, this lacuna should be kept in mind when considering criticisms of TI asserting that no specific "mechanism" is given for how a particular transaction is actualized.

[29] Brown and Wallace, in their careful analysis of Bohm's seminal 1952 papers, comment in passing that Bohm apparently did not intend to "surpass" quantum theory – to propose, in their words, a theory with "truly novel predictions" (Brown and Wallace, 2005, p. 521). This may be a reference to the fact that the Bohmian approach

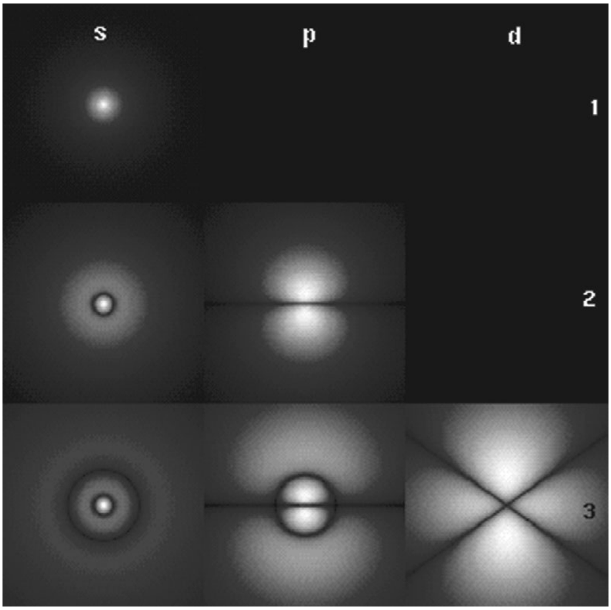

Figure 1.5 The squared wave function of an electron in various excited states of the hydrogen atom.
Source: https://commons.wikimedia.org/wiki/File:HAtom Orbitals.png.

1.3.4 Von Neumann's Projection Postulate

The formulation of John von Neumann, one of the pioneers of measurement theory in quantum mechanics, is not so much an interpretation as an analysis of the logical and statistical characteristics of the theory. It was von Neumann who first realized

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amounts to a slightly different theory from standard quantum theory (cf. Valentini, 1992). The aspect of concern to me is the characterization of such a development as a "surpassing" of quantum theory and the implication that a good interpretation should make "novel predictions" (i.e., predictions that deviate from those of standard quantum theory). This language seems to imply that quantum theory is in need of improvement or remediation and that a proper interpretational approach should generate a "better" (different) theory. In contrast, I think nothing is wrong with the theory itself and that prevailing interpretational approaches have not gotten to the root of the measurement problem: namely, the need to include absorption as a real physical process generating advanced states (confirmations). Technically, this might be considered a different theory or at least a different formulation, but it is empirically equivalent at the level of probabilities to the standard theory. I do not believe that a successful *interpretation* (or formulation) needs to generate any novel predictions, but should provide a coherent and illuminating account of the theory itself, which effectively addresses the measurement problem. As a side note, an anonymous referee once commented in response to a statement like the preceding: "Since when has physics *not* dealt with difficult interpretational problems by changing the theory?" However, such changes were made not in response to *interpretational* problems, but rather to deal with the failure of a particular theory's *predictions*. For example, classical electrodynamics prior to relativity predicted that the speed of light should be dependent on the observer's motion. This prediction was refuted by the Michelson–Morley experiment. In contrast, the predictions of quantum theory are impeccable; it is probably the most strongly corroborated modern physical theory we have. What is at issue is arriving at a proper understanding of why the theory has the structure that it does, and to define measurement from within the theory. To modify the theory in an ad hoc way in order to get around these problems is, I believe, to fail to address the real scientific challenge it presents: What unexpected message does it convey about reality?

that the mathematical structure of the theory is a special kind of vector space (called a *Hilbert space*, in honor of the brilliant mathematician David Hilbert, who first defined it). While systems in classical mechanics can be represented mathematically as simple points labeled by their spatial position and momentum (technically, their coordinates in "phase space"), quantum systems have to be represented by rays in Hilbert space, which are objects that do not have simple coordinate-type labels and which reflect an infinitely expansive ambiguity as to the "actual" characteristics of the systems they represent. Roughly speaking, one can think of the classical phase space coordinatization as only one of an infinite number of ways to provide a coordinatization in Hilbert space.[30]

Von Neumann's view of measurement is often referred to as the "standard collapse approach," since it simply assumes that, on measurement, the state of the quantum system "collapses" (technically, it is "projected" onto a particular state corresponding to the type of measurement performed). He identified two different types of processes undergone by quantum systems: the "collapse" or "projection" that occurs on measurement he termed "Process 1," and the simple deterministic evolution of a system's state between measurements he termed "Process 2." Of course, he left unclear exactly what is supposed to precipitate the collapse of "Process 1," and this remains part of the measurement problem. (An additional problem traditionally associated with collapse is that it appears to be in conflict with relativity, since it seems to call for a preferred frame of simultaneity denied by relativity. On the other hand, TI's approach to collapse is harmonious with relativity, as will be demonstrated in Chapters 5 and 8.)

As I will discuss later in the book, the question of what triggers collapse cannot be properly answered unless absorption accompanied by non-unitarity is included in the dynamics. Without it, there is no clear "stopping point" at which a measurement can be regarded as completed (this was alluded to in Section 1.2.3), and all we have are vague "irreversibility" arguments that attribute *apparent* collapse to environmental dissipation or to "consciousness," but never really allow for a genuine physical collapse. At some point, an arbitrary "cut" is made at which the measurement is declared finished, "for all practical purposes" (a phrase which is often abbreviated "FAPP" in honor of John Bell, who introduced the term as an expression of derision[31]). This arbitrary demarcation between the microscopic systems clearly described by quantum theory and the macroscopic objects which

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[30] This observation reinforces the point made in note 28: the mathematical structure of the theory is qualitatively different from that of classical mechanics, in a very striking way. To understand the physical reason for this mathematical structure, I suggest, is the real interpretational challenge. The Everettian approach is one way of embracing the challenge, but I think it fails because it disregards half the dynamics (the advanced solutions to the complex conjugate Schrödinger equation) and cannot provide a physical (as opposed to epistemic/statistical) explanation for the Born Rule.

[31] Bell introduced this term in his essay, "Against measurement" (Bell, 1990).

"measure" them is often referred to as the "Heisenberg cut" in view of Heisenberg's discussion of the issue (cf. Bacciagaluppi and Crull, 2009).

Under TI, with absorption taken into account, collapse occurs much earlier in the measurement process than is usually assumed, so that we don't need to include macroscopic objects such as Geiger counters, cats, or observers in quantum superpositions. This issue is discussed in Chapters 3 and 4.

1.3.5 Bohr's Complementarity

Neils Bohr, one of the pioneers of quantum theory along with Werner Heisenberg, developed a philosophical view of the theory that he termed "complementarity." Complementarity has been the subject of enormous quantities of research and elaboration. Readers interested in a detailed critique of Bohr's formulation are invited to consult Kastner (2016b). Bohr's views will be described in more detail in Chapter 2. In brief, Bohr considered the properties of quantum systems to be fully dependent on what observers choose to measure, in that the experimental setup determines what sorts of properties a system can exhibit.[32] The Kantian flavor of his approach (after German philosopher Immanuel Kant) consists in denying that it is even meaningful to talk about the nature of the systems "in themselves," apart from their being observed in a macroscopic context. Based on Bohr's designation of such questions as "meaningless" or as beyond the domain of legitimate inquiry, his approach has been sardonically referred to as "shut up and calculate" (SUAC), a phrase coined by David Mermin (1989).

1.3.6 Ad hoc Nonlinear "Collapse" Approaches

So-called "spontaneous collapse" approaches such as that first proposed by Ghirardi, Rimini, and Weber (GRW) (Ghirardi et al., 1986) impose an explicit theoretical modification on the mathematics of the standard theory – an additional nonlinear term in the usual dynamics – in order to force a collapse into a determinate state. The added nonlinear component takes a poorly localized wave function and compresses it. This approach is explicitly and unapologetically ad hoc and faces several problems, among them the following. (1) A wave function that is compressed in terms of position must, by the uncertainty principle, gain a large uncertainty in momentum and therefore energy, which opens the door for observable effects, such as a system suddenly heating up – such effects are never observed. (2) Such collapses could occur only rarely; otherwise, the well-

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[32] Bub has shown (1997) that complementarity can be viewed as a kind of "preferred observable," "no-collapse" approach, akin to the Bohmian interpretation which views position as the preferred observable. Bohr's preferred observable is whatever is measurable using the experimental setup.

corroborated normal evolution of the wave function would be noticeably disturbed. So it is not clear that their occurrence would be sufficient to account for the determinate results we see. Such "compression of the wave function" approaches are generally acknowledged as not viable, even by proponents of nonlinear collapse, and Tumulka (2006) has proposed a variant which purports to avoid some of the pitfalls known to afflict the original GRW approach.

Tumulka's proposal, a "relativistic flash ontology" version (rGRWf), avoids the compression problem (1) cited above. However, rGRWf still involves a physically unexplained and ad hoc "collapse" mechanism, and evades what I believe is the central interpretational issue of explaining why the theory has the mathematical Hilbert space structure that it does (see notes 28 and 29). In addition, in order to be reconcilable with relativity, rGRWf ultimately appeals to time symmetry. TI already makes use of time symmetry without needing to make any ad hoc change to the basic theory. I deal with this issue in more detail in Chapter 6.

1.3.7 Relational Block World Approaches

The term "block world" refers to a particular kind of ontology[33] in which it is assumed that spacetime itself exists as a "block" consisting of past, present, and future events. The block is unchanging and it is only our perception of it that seems to involve change as we "move" along our worldline. Such a view seems implied by relativity, and some researchers have proposed that quantum theory should be interpreted against such a backdrop. The challenge in doing so lies in explaining why the unitary evolution of a particular quantum state "collapses" to a particular result. Adherents of this view propose that such events simply correspond to a discontinuity of the relevant worldlines: that it is just a "brute fact" about nature that such discontinuities must exist.

This principle of a spacetime block with uncaused (primal) discontinuities was pioneered by Bohr, Mottelson, and Ulfbeck (BMU), who say (Bohr et al., 2003):

> The principle, referred to as genuine fortuitousness, implies that the basic event, a click in a counter, comes without any cause and thus as a discontinuity in spacetime. From this principle, the formalism of quantum mechanics emerges with a radically new content, no longer dealing with things (atoms, particles, or fields) to be measured. Instead, quantum mechanics is recognized as the theory of distributions of uncaused clicks that form patterns laid down by spacetime symmetry. (abstract)

BMU take macroscopic "detector clicks" as primary uncaused events and refer to atoms as "phantasms." Thus they are explicitly antirealist about quantum objects.

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[33] "Ontology" refers to what is assumed to exist, what is real.

BMU's approach has been developed more recently into a "relational block world" (RBW) interpretation by Silberstein, Stuckey, and Cifone (Silberstein et al., 2008). RBW advocates take spacetime relations and their governing symmetries as fundamental and attempt to derive a version of quantum mechanics based on this ontology.[34] One basis for criticism of RBW is that it makes fundamental use of dynamical concepts such as momentum while denying that those concepts refer to anything dynamical.[35]

1.3.8 Statistical/Epistemic Approaches

Some researchers (e.g., Spekkens, 2007) have been investigating an approach in which the quantum state reflects a particular preparation procedure but does not necessarily describe the physical nature of the quantum system under study. This implies that the quantum state characterizes only our knowledge; "epistemic," from the Greek word for "knowledge," is the technical term used. The statistical aspect consists in connecting a particular preparation procedure to a particular distribution of outcomes. The key feature distinguishing this "statistical" approach from the "hidden variables" approaches – such as Bohm's theory – is that in the former the quantum state is not uniquely determined by whatever "hidden" properties the quantum system possesses. In contrast, a quantum system under the Bohm theory is physically described by its wave function as well as an unknown position x of the postulated particle associated with the wave function; there is only one wave function that can be associated with these properties, even though the same wave function can be associated with another system with a different particle position x'.

However, a theorem by Pusey et al. (2011) casts serious doubt on epistemic/statistical approaches. It shows that, given some fairly weak assumptions, the statistics of a system whose state is not uniquely determined by its physical properties can violate the quantum mechanical statistical predictions.[36] The implication is that the quantum state really does describe a physical system, not just our knowledge of our preparation procedure.

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[34] I do, however, share RBW's rejection of a "building block" ontology: the empirical world is a network of transactions, not collections of primitive individuals.

[35] For example, in RBW, experimental configurations are described by symmetry operators such as the translation operator $T(a) = \begin{pmatrix} e^{-ika} & 0 \\ 0 & e^{ika} \end{pmatrix}$, because momentum k is the generator of spatial translations. But, in RBW, there are no entities that possess momentum. It thus remains unclear what dynamical terms such as "momentum" refer to, in an adynamical account such as RBW.

[36] Granted, one of those assumptions is that there is no retrocausality. However, it is unclear to what extent adding retrocausality about an underlying ontology would help to support the basic statistical/epistemic program, which is to restore a more commonsense (i.e., classical) interpretation of quantum states than appears to be available from being realist about quantum states. If one is going to admit retrocausal influences anyway, then why not embrace a straightforward realist time-symmetric interpretation such as TI?

1.4 Quantum Theory Presents a Genuinely New Interpretational Challenge

Some researchers take the point of view that the appropriate response to quantum theory's apparently intractable puzzles is to adopt a strictly empiricist, pragmatic point of view, for example, to simply say that there is no physical explanation for the puzzling behavior of quantum objects as reflected in the theory, that nature simply "refuses to answer" the questions we try to pose about that behavior. One such approach, "Qbism" (proposed by Christopher Fuchs and David Mermin), holds that quantum theory is no more and no less than an instruction manual for predicting our experiences (a form of instrumentalism). Such approaches are variants of the Bohrian/Kantian view that people can gain knowledge *only* of the phenomenal level of appearance; that quantum theory might permit us to "knock at the door" of the subempirical, subphenomenal world but that the door must remain forever closed. This approach, I believe, is to evade a genuine, nontrivial interpretational challenge posed by the theory; that is, it admonishes us to renounce the idea that physical theories can describe nature itself.

While I certainly agree with the idea that quantum theory has an unexpected message, I think that message *is* one about reality – like all profoundly corroborated and powerfully predictive theories – and that the challenge is to figure out what the theory is telling us about reality. As this book will reveal, I think it is an exciting, strange, and indeed revolutionary message; certainly more interesting and revolutionary than the notion that theories of small things can only be about subjective knowledge or only about appearances. It was the behavior of hydrogen atoms that inspired Heisenberg to arrive at his first successful version of quantum theory. Clearly, the theory he arrived at was about those atoms and not just about his knowledge, since without reference to, and guidance from, those atoms he would never have constructed the theory. That is, the theory's structure was *driven by the behavior of atoms*. (Yes, the "observable behavior" of atoms, but the conclusion that the theory is only about our knowledge of them does not follow; this point will be explored further in the following chapter.) Jeeva Anandan underscored this point when he said:

> [Quantum] theory is so rich and counterintuitive that it would not have been possible for us, mere mortals, to have dreamt it without the constant guidance provided by experiments. This is a constant reminder to us that nature is much richer than our imagination. (Anandan, 1997, p. 31)

The true puzzle of quantum theory is that there are physical entities beyond our power to perceive directly in the ordinary way and that they behave in strange and amazing ways. This is not just anthropocentrically about "our knowledge"; it is also about the physical entities. What are they saying to us? Heisenberg listened, and in the next chapter I will further explore his initial insights.