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Quantum Mechanics and the Philosophy of Alfred North Whitehead

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EPPERSON

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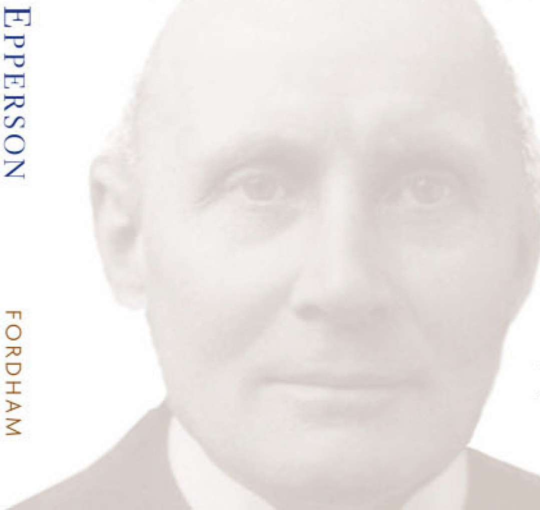

MICHAEL EPPERSON

QUANTUM MECHANICS
and the Philosophy of Alfred North Whitehead

by

MICHAEL EPPERSON

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Στην μνημη της αγαπημενης μου
Για γιας
Ελενη Ξυρουχακης Δοκιμακης
(1910–1999)

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PREFACE

WHATEVER ONE MAY SAY about the unsurpassed predictive power of quantum mechanics, few would argue that it is a more comfortable or intuitive theory than the classical mechanics of Newton and Galileo, which its innovators intended to replace as *die endgültige Physik*. For while we have for the past several hundred years enjoyed classical mechanics both in application of its predictive power and in contemplation of its descriptive power, quantum mechanics, though certainly providing vast improvements in the accurate prediction of phenomena, does so only in deficit of its ability to describe these phenomena intuitively.

A coherent and intuitive characterization of nature, such as that given us in classical mechanics and its underlying ontology of mechanistic materialism, has been sorely lacking in quantum mechanics. One reason is that many of its earliest innovators, Einstein, Planck, and Bohr among them, had presumed that quantum mechanics could be accommodated by the same classical ontology of fundamental materialism, with perhaps a few minor modifications, such that efforts toward a novel ontology were for many years thought unnecessary. But such an accommodation has, after several decades of work, proven to be an infamously uneasy one as evinced by the many notorious quantum-classical incompatibilities and "paradoxes" that have unfortunately become the defining characteristic of quantum mechanics for many.

One need look no further than the familiar problem of wave-particle duality to glimpse the difficulty. Quantum mechanics seems to entail two competing and incompatible fundamental descriptions of nature, and this leaves one with three alternatives: (i) to characterize nature as fundamentally particulate wherein wave-like properties are an abstraction; (ii) to characterize nature as fundamentally wave-like wherein particulate properties are an abstraction; (iii) to pass through these two horns and deny that nature is capable of fundamental characterization at all (apart from this sanction itself, of course) such that we merely characterize our complementary *experiences* of nature as wave-like or particle-like depending on the circumstances, rather than characterizing nature herself.

To each of these three viewpoints we can associate various theorists—Einstein, for example, to the first, Schrödinger to the second, Bohr to the third, and so forth—and we can trace the many various subsequent mediations of these three viewpoints back to a commitment to one against the others. The statistical interpretation of Born is such an example, wherein the wave-like aspects of nature operative in quantum mechanics are interpreted as statistical probability amplitudes pertaining to the largely unknowable positions, momenta, or other qualifications of particles. Such a mediation preserves the epistemic sanctioning of the third alternative—the admission of an epistemic veil that shrouds nature just enough that she cannot be known with complete deterministic certainty in every qualification; it preserves the viewpoint of the second alternative, such that the wave-like characterization of nature, interpreted as a probability amplitude, describes the precise transparency of this veil; and it preserves the viewpoint of the first alternative such that what lies beneath the veil—nature herself—is characterized as fundamentally particulate and deterministic. For Born, "events happen indeed in a strictly causal way, but . . . we do not know the initial state exactly. In this sense the law of causality is therefore empty; physics is in the nature of the case indeterminate, and therefore the affair of statistics."[1]

Of course, wave-particle duality as it pertains to quantum mechanics entails a host of other related difficulties, each of which has been similarly attended to by various theorists according to the three aforementioned viewpoints. For example: nature described as fundamentally (and classically) fluid and deterministic according to the first viewpoint; nature described as fundamentally discontinuous and probabilistic according to the second viewpoint; our experiences of nature described as either fluidly deterministic or discontinuously probabilistic, depending on the circumstances, according to the third viewpoint. The failure to accommodate quantum mechanics adequately according to a classical materialist ontology—that is, solely according to the first viewpoint described earlier—is especially evident in the phenomenon of nonlocal causal interrelations predicted by quantum mechanics.

[1] Max Born, *Atomic Physics, 8th ed.* (New York: Dover, 1989), 102.

As with the interpretation of Born, which entailed a mediation from among the three viewpoints, one finds a similar mediation in the nonlocal hidden variables interpretation of David Bohm. Certain quantum mechanical predictions, confirmed by experiment, entail nonclassical interactions between two spatially well separated systems such that a measurement performed upon one system instantly (and therefore nonclassically) affects measurement outcomes in the other system. A deterministic interpretation of quantum nonlocality would therefore seem to require a violation of special relativity, as if some sort of superluminal influence were transmitted from one system to the other. Bohm's mediation among the three alternative viewpoints mirrors that of Born when applied to an interpretation of this phenomenon, with the addition of a causally efficacious "pilot-wave" thought to propagate superluminally through an ether-like medium of point-particles. By the operation of this pilot-wave, the two spatially well separated systems are, despite appearances, fundamentally non-separate beneath the veil of epistemic uncertainty caused by this ether of point-particles—particles whose qualities are incapable of complete deterministic qualification and thus "hidden."

We have, in this and other interpretations, attempts to equip quantum mechanics with a descriptive power comparable in strength to its predictive power; but in the attempt to produce a characterization of nature as predictably and descriptively satisfying as that given by classical mechanics, these and other interpretations so contort the very classical fundamental materialism that they attempt to preserve that one tends to feel even less satisfied with these "classical" interpretations of quantum mechanics than one felt with no ontological interpretation at all. One cannot be surprised, then, by the widespread appeal of sheer instrumentalism when it comes to interpreting quantum mechanics in the classroom and laboratory, where the best interpretation is often held to be no interpretation at all.

There is, however, a fourth viewpoint which, for many physicists and philosophers, provides the key to a coherent and intuitive interpretation of quantum mechanics. This viewpoint begins with the understanding that formally, quantum mechanics describes nothing more than the evolution of a system of facts from an initial state to a final state, where the term "state" refers to a maximal specification of the facts belonging to the system measured. Further, the outcome state yielded by quantum mechanical prediction is not a singular state, but rather a matrix of probable states among which one will become actualized in accord with its probability valuation. This unique actualization is not accounted for by quantum mechanics, but it is anticipated by the mechanics and is confirmed retrodictively upon subsequent observation. In other words, actual initial facts give rise to sets of potential facts that evolve to become actual final fact in a quantum mechanical measurement interaction. Here, the terms "evolution" and "probability" both presuppose an actuality prior to the evolution and anticipate an actuality subsequent to the evolution: The expressions "X evolves to become Y" and "0.5 is the probability that X will become Y" reflect this presupposition and anticipation. Since these actualities are presupposed and anticipated by quantum mechanics, in the same way that matter is presupposed and anticipated by classical mechanics, quantum mechanics cannot be used to account for the existence of actualities any more than classical mechanics can be used to account for the existence of matter. The essence of quantum mechanics, then, lies not in the qualification of what exists before and after measurement as emphasized by the classical materialistic ontology—an ontology of being, where reality is identified with actuality; the essence of quantum mechanics, rather, is the evolution itself—an ontology of becoming, where reality is seen to comprise two fundamental species: actuality and potentiality—"first principles" in that each is incapable of abstraction from the other.

Heisenberg suggested a re-adoption of this Aristotelian concept of potentia as a means toward a coherent interpretation of quantum mechanics, and later theorists including Robert Griffiths, Murray Gell-Mann, James Hartle, and Roland Omnès, among others, have incorporated this notion of potentia into the concept of "histories" of quantum mechanical evolutions. A macroscopic material object thus becomes characterized most fundamentally as a history of evolutions of discrete facts or events—evolutions from actuality to potentiality to actuality. The problem of coherently interpreting quantum nonlocality, among other problems, is thus easily solved: As a particularly dramatic example, one can intuitively understand how the history describing the ongoing evolution of an atom or molecule or person or nation is instantaneously and "nonlocally" affected by an asteroid that has just been knocked by a comet into a collision course with Earth, with impact to occur in two years. Although Earth and the asteroid are spatially well separated, the newly evolved actuality pertaining to the asteroid's course change has instantaneously affected the potentia associated with the ongoing histories describing Earth and any fact associated with it. Since quantum mechanical histories are in a perpetual state of augmentation, quantum event by quantum event, at any such event the potentia associated with a history condition its future augmentation in a way similar to (but not identical to) the way antecedent facts condition a history's future augmentation.

In other words, as the potentia associated with a history change with even a single quantum event, the history itself changes, as does the system defined by the history. Although we on Earth cannot be causally *influenced* by the asteroid's course change sooner than the time it takes for a photon to travel from the asteroid to Earth, the potentia associated with any physical system on Earth have clearly been causally *affected*, and affected instantly and nonlocally (though not determined). In the same way, it has been demonstrated experimentally that the phenomenon of quantum nonlocality cannot be used for faster-than-light communication. This limitation is understandable and entirely intuitive according to this interpretation, since such communication would entail nonlocal causal influence of actualization rather than merely nonlocal causal affection of potentia as described in the example above.

This distinction between causal affection of potentia and causal influence of actualization is just one of many conceptual innovations inherent in the interpretation of quantum mechanics according to an event ontology—an ontology of historically evolving process—rather than an ontology of fundamental mechanistic materialism. Many theorists have gone on to show other advantages of such an interpretation, including how it is able to account for the one-way direction of time in thermodynamics as ontologically rather than merely epistemically significant—a concept whose compatibility with other interpretations of quantum mechanics is problematic at best. But the primary advantage is that it is an interpretation that defies any "quantum-classical" dualism, such that classical mechanics becomes an abstraction from the more fundamental quantum mechanical description of nature, rather than merely a complementary and incompatible description. And unlike the proposals of Born and Bohm, among others, this interpretation requires neither an arbitrary epistemic sanction in the form of "hidden variables" nor selective violations of the very classical mechanics these proposals were intended to preserve.

There are, however, a great many ontological innovations and implications inherent in the accommodation of quantum mechanics by a metaphysics grounded in this idea of historically evolving process, and these require a careful systematic exploration that is likely to exceed the purview and interests of most physicists. It is therefore both fortunate and remarkable that one finds in the philosophy of Alfred North Whitehead—developed in its most systematic form during the same years that brought the quantum theoretical innovations of Bohr, Born, Schrödinger, Heisenberg, Dirac, et al—a metaphysical scheme that so precisely mirrors the hypothetical deductions and inductions made by the physicists who have contributed to the development of the event-ontological, "historical process" interpretations of quantum mechanics. The purpose of this essay, then, is to point out and explicate these correlations and their significance to the interpretation of quantum mechanics, and more broadly, to the philosophy of science in general; for Whitehead's repudiation of fundamental materialism and Cartesian dualism echoes loudly in the work of recent theorists such as Robert Griffiths, Roland Omnès, Wojciech Żurek, and Murray Gell-Mann, among several others, whose own repudiation of fundamental materialism and "quantum-classical" dualism is the most recent attempt to solve a philosophical problem whose roots extend all the way back to the problem of χωρισμός introduced by Plato—the supposed chasm separating what is from what appears to be.

I am much indebted to the following people for their invaluable and generous advice, comments, criticisms, and instruction: John R. Albright of the Department of Physics at Purdue University; John B. Cobb, Jr. and David Ray Griffin of the Claremont Graduate University; Peter E. Hodgson, head of the Nuclear Physics Theoretical Group of the Nuclear Physics Laboratory of the University of Oxford; Timothy E. Eastman, Group Manager for Space Science, NASA Goddard Space Flight Center; Hank Keeton; and especially David Tracy and Franklin Gamwell of the University of Chicago.

M.G.E.

University of Chicago
July 2003

1

Introduction

This chapter is intended to provide a brief overview of the synthesis developed over the course of the book. As a result, it occasionally incorporates certain concepts and terminology that have yet to be introduced. Since this book was written for readers with varying familiarity with quantum mechanics and Whitehead's philosophy—including no familiarity with either—readers with some knowledge of both should begin with this chapter, whereas those who need familiarization with the subjects might skip ahead to chapter 2.

THE ATTEMPTED CORRELATION of quantum mechanics and Whitehead's cosmological scheme—or any philosophical scheme, for that matter—is an endeavor to be expected of both philosophers and physicists discomfited by the various "paradoxical" conceptual innovations inherent in quantum mechanics when interpreted according to the classical ontology of mechanistic materialism. That various proposed correlations of quantum mechanics and Whitehead's cosmology have come from both philosophers and physicists, then, should not surprise, nor should their respective emphases of approach: The philosophers tend to depict the physical side of the correlation in overly broad strokes in order to avoid the infamously complicated concepts and terminology inherent in quantum mechanics, and the physicists, who prefer to avoid the infamously complicated concepts and terminology inherent in Whiteheadian cosmology, tend to depict his metaphysical scheme in similarly broad strokes.

Some of the proposals made thus far—those suggested by Abner Shimony,[1] Henry Folse,[2] and George Lucas,[3] for example—have proven useful in establishing an initial dialogue; but they have tended to break down once a certain level of detail is approached, on either the physics side or the philosophy side. With respect to the latter, the reason lies not in any failure by philosophers to comprehend quantum mechanics adequately, but rather with the advocacy of certain popular interpretations of quantum mechanics founded upon and inspired by concepts wholly incompatible with the Whiteheadian cosmological scheme. These incompatibilities are most easily evinced by the extent to which a particular interpretation of quantum mechanics fails to meet the four desiderata Whitehead requires of his and any philosophical interpretation of experience—physical, microphysical, or otherwise. Such an interpretation, writes Whitehead, should be: (i) *coherent*, in the sense that its fundamental concepts are mutually implicative and thus incapable of abstraction from each other; (ii) *logical*, in the ordinary sense of the word, as regards consistency, lack of contradiction, and the like; (iii) *applicable*, meaning that the interpretation must apply to certain types of experience; (iv) *adequate*, in the sense that there are no types of experience conceivable that would be incapable of accommodation by the interpretation.[4]

Thus, for example, attempts to demonstrate the compatibility of Bohr's principle of complementarity and Whiteheadian metaphysics, though perhaps useful in terms of higher-order epistemological issues, fails for lack of coherence at the most fundamental level, the very level for which it was intended. Bohr's two complementary characterizations of our experiences of nature—classical and quantum—are not mutually implicative, and this is the very point of complementarity. Henry Folse suggests that a correlation of Bohr's interpretation of quantum mechanics and Whitehead's philosophy is in order, primarily because of the repudiation of fundamental mechanistic materialism common to both; "however," Folse admonishes, "the fate of any potential alliance is in jeopardy so long as current discussions of the subject insist on concentrating on the fine points of quantum interpretation rather than its broader more general ramifications." He continues:

> Quite naturally there are many aspects of the philosophy of organism which find no counterpart in the philosophical extrapolations of the Copenhagen Interpretation. . . . There is no reference to the equivalents of "feeling," "satisfaction," or "conceptual prehension." Yet Whitehead would have anticipated this, for the physicists' interpretation of theory is based on a very small segment of experience; Whitehead's system aims at far greater compass.[5]

The difficulty is that concepts like "feeling," "satisfaction," and "conceptual prehension" are fundamental to Whiteheadian metaphysics. They are not higher-order abstractions that should be, or even can be, ignored whenever applied to the specialized interpretation of physical experiences. But aside from specific correlatives in the physical sciences for the terms "feeling," "satisfaction," and "conceptual prehension," which Whitehead does, in fact, specify,[6] the incompatibility of Bohr's interpretation of quantum mechanics and Whitehead's metaphysical scheme lies most fundamentally in the simple failure of Bohr's principle of complementarity to meet the desideratum of ontological coherence.

Similar attempts to ally Whitehead's cosmology with David Bohm's nonlocal hidden variables interpretation of quantum mechanics fail for the same reason, despite the focus upon certain significant compatibilities, such as that of (i) Bohm's "implicate order" pertaining to the etherlike field of all actualities in the universe, correlate with (ii) the analogous concept of necessarily and mutually interrelated actualities in Whitehead's scheme, as well as the repudiation of fundamental classical "extended substance" common to both. In Bohm's scheme, however, the repudiation of fundamental substance (Bohm's particles, though concrete, are more akin to Einstein's "point-instants" and Whitehead's "actual occasions" than extended substance) is not a repudiation of deterministic, mechanistic materialism, as it is in Whitehead's ontology. Bohm's fundamentally deterministic "implicate order" inherent in the field of all actualities entails symmetrical and therefore purely deterministic relations among these actualities.

Insofar as these relations remain hidden within the deep realm of Bohm's "implicate order," our participation in this order is restricted to manifold epistemically limited observational contexts. Bohm suggests that because of this, his theory in no way vitiates conceptions of freedom, creativity, novelty, and so forth—principles central to Whiteheadian metaphysics. However, given that the fundamental implicate order of the universe is deterministic, hidden though this order may be, it is difficult to see how freedom grounded in epistemic ambiguity can be thought to be as significant as freedom grounded in an ontological principle—even if our finite observational contexts all but guarantee such ambiguity. Bohm writes:

> As long as we restrict ourselves to some finite structures of this kind, however extended and deep they may be, then there is no question of

complete determinism. Each context has a certain ambiguity, which may, in part, be removed by combination with and inclusion within other contexts. . . . If we were to remove all ambiguity and uncertainty, however, creativity would no longer be possible.[7]

An ontologically significant principle of freedom from determinacy requires an asymmetrical temporal modality and its associated logical order, where the past is settled and closed and the future is open—a temporality that is irreversible. This is a key feature of Whitehead's metaphysics. Though Bohm's implicate order is fundamentally temporally symmetrical and deterministic, he suggests that there is some similarity between Whitehead's process of concrescence and the quantum mechanical relationships among the actualities of his "implicate order" cosmology. "A key difference," he notes,

is that these relationships are grounded in the deeper, "timeless" implicate order that is common to all these moments. . . . It is this implicate "timeless" ground that is the basis of the oneness of the entire creative act. In this ground, the projection operator P_n, the earlier ones such as P_{n-1}, and the later ones such as P_{n+1} all interpenetrate, while yet remaining distinct (as represented by their invariant algebraic structures).[8]

Epistemic uncertainty as to the specifications of most of these relations manifests itself as the familiar, temporally asymmetrical "explicit order" characterizing our experiences, such that temporal priority appears reflective of logical priority. This reflection is evinced, for example, by the one-way direction of time associated with the laws of thermodynamics. But if one could peer through the epistemic veil of this temporal asymmetry—if one could perceive the implicate order of hidden variables and its associated "pre-space"—then the fundamentally symmetrical relationship among past, present, and future would be revealed. Bohm writes:

If it were possible for consciousness somehow to reach a very deep level, for example, that of pre-space or beyond, then all "nows" would not only be similar—they would all be one and essentially the same. One could say that in its inward depths now *is* eternity, while in its outward features each "now" is different from the others. (But *eternity* means the depths of the implicate order, not the whole of the successive moments of time.)[9]

But since temporal priority is merely epistemically significant by such an interpretation, it is unclear how it might have any significant correlation with an ontologically significant logical priority. As mentioned earlier, such a gulf between the contingent and the necessary has its roots in the problem of χωρισμός, or "separation" of necessary forms from contingent facts in Plato's metaphysics. It is a problem central to many interpretations of quantum mechanics, and also to interpretations of the special and general theories of relativity—the latter with respect to the relationship between the formal geometrical character of spacetime and the facts constitutive of spacetime. In the general theory of relativity, Einstein bridges Plato's χωρισμός by deriving the formal geometry of spacetime from the events themselves; this approach to χωρισμός, then, has a certain compatibility with the hidden variables interpretations of quantum mechanics discussed earlier. (The close relationship between quantum mechanics and theories of spatiotemporal extension is addressed at length in chapter 5.)

In the Whiteheadian cosmology, the integration of (i) the asymmetrical, logical modal relations among facts and (ii) the symmetrical, relativistic modal relations among spatiotemporal forms of facts, is a function of the fundamental dipolarity of actualities. But in Whitehead's scheme, the asymmetrical, logical ordering among actualities as genetically related, serially ordered becomings, is, in one sense, the fundamental order upon which their symmetrical, relativistic spatiotemporal ordering is predicated. The existence of facts is thus, by the requirement of logic, necessarily prior to their spatiotemporal ordering in Whitehead's metaphysical scheme. But Bohm's hidden variables interpretation entails the opposite—that it is the symmetrical, deterministic relations among actualities which are fundamental to the asymmetrical—and by his interpretation, ontologically insignificant—logical ordering of the actualities themselves. Thus, the irreversibility of thermodynamic processes, for example, is by Bohm's interpretation merely a statistical epistemic artifact of an underlying purely deterministic, symmetrical, "implicate" order.

Bohm and his colleague B. J. Hiley illustrate this fundamental deterministic symmetry of the implicate order by describing the workings of a particular experimental apparatus:

> This device consists of two concentric glass cylinders; the outer cylinder is fixed, while the inner one is made to rotate slowly about its axis. In between the cylinders there is a viscous fluid, such as glycerine, and

> into this fluid is inserted a droplet of insoluble ink. Let us now consider what happens to a small element of fluid as its inner radius moves faster than its outer radius. This element is slowly drawn out into a finer and finer thread. If there is ink in this element it will move with the fluid and will be drawn out together with it. What actually happens is that eventually the thread becomes so fine that the ink becomes invisible. However, if the inner cylinder is turned in the reverse direction, the parts of this thread will retrace their steps. (Because the viscosity is so high, diffusion can be neglected.) Eventually the whole thread comes together to reform the ink droplet and the latter suddenly emerges into view. If we continue to turn the cylinder in the same direction, it will be drawn out and become invisible once again.
>
> When the ink droplet is drawn out, one is able to see no visible order in the fluid. Yet evidently there must be some order there since an arbitrary distribution of ink particles would not come back to a droplet. One can say that in some sense the ink droplet has been enfolded into the glycerine, from which it unfolds when the movement of the cylinder is reversed.
>
> Of course if one were to analyse the movements of the ink particles in full detail, one would always see them following trajectories and therefore one could say that fundamentally the movement is described in an explicate order. Nevertheless within the context under discussion in which our perception does not follow the particles, we may say this device gives us an illustrative example of the implicate order. And from this we may be able to obtain some insight into how this order could be defined and developed.[10]

Bohm and Hiley go on to suggest that this implicate order "contains explicate suborders as aspects which are particular cases of the general notion of implicate order. In this way we clarify our earlier statement that the implicate order is general and necessary, while explicate orders are particular and contingent cases of this."[11]

The predication of actualities upon the relativistic spatiotemporal *relations* among actualities—the predication of facts upon their implicate ordering—similarly manifests itself in popular quantum cosmogonic models such as those proposed by Stephen Hawking and James Hartle, wherein a vacuous spacetime is purported to evolve quantum mechanically from a void of pure potentiality—potentiality somehow abstracted from actuality. Such a void, often termed a "quantum vacuum" or "quantum foam," is a fundamentally incoherent construction, given that the concept of actuality is necessarily presupposed by the concept of potentiality, such that the latter cannot be abstracted from the former. This is both a logical requirement and a requirement of quantum mechanics, which describes the evolution of actual facts and their associated potentia—not the evolution of vacuous potentia into actuality.

These conceptual impediments to the fundamental logic and coherence of the preceding interpretations of quantum mechanics all stem from a common source—the attempt to use quantum mechanics to account for the existence of actualities, when quantum mechanics both presupposes and anticipates their existence. This presupposition and anticipation is clearly reflected in the mathematical concept of probability, which—as it pertains to the termination of a quantum mechanical measurement in a matrix of probable actualities rather than a determined, unique actuality—is a quantifiable propensity that a *presupposed* fact will evolve to become a quantifiably *anticipated* novel fact. (In quantum mechanics, and in Whiteheadian metaphysics, the anticipated unique novel fact is both subsequent to *and* consequent of the evolution.) Any interpretation of quantum mechanics that meets the desideratum of logic, then, cannot include a quantum mechanical account of the existence of actualities, which are both presupposed and anticipated by the mechanics.

The two interpretations of quantum mechanics briefly described earlier—those of Bohr and Bohm—were both born of inductive philosophical generalizations, which is to be expected of scientific theories to some degree. But these generalizations, each in its own way, fail to meet one or more of the Whiteheadian desiderata for a sound philosophical scheme by which we can coherently and logically interpret our experiences of the physical world. "The only logical conclusion to be drawn, when a contradiction issues from a train of reasoning," writes Whitehead, "is that at least one of the premises involved in the inference is false."[12] As regards these two interpretations of quantum mechanics, the culprit premise is the concept of fundamental mechanistic materialism. Bohr attempts to salvage this concept by draining it, and its complementary quantum theoretical conception of nature, of all ontological significance; the facts of objective nature are thus permanently veiled to the extent that we must replace the notion of "objective facts of nature" with public coordinations of our experiences of nature.[13] And Bohm attempts to salvage the primacy of mechanistic materialism by resorting to a similar veil, such that the *apparent* openness of the future by its asymmetrical relations with the facts of the past—as related to the *apparent* indeterminacy of quantum mechanics, for example—is merely a statistical artifact of an epistemic handicap that prevents us from observing and specifying the ether of "hidden variables." This ether, for Bohm, constitutes the implicit, underlying universe of fundamentally symmetrically related facts—that is, a fundamentally deterministic universe.

In contrast, however, recent years have brought the development of a family of interpretations of quantum mechanics formulated in part as a response to these difficulties. This family of interpretations uses only the orthodox "Copenhagen" quantum theoretical formalism, but abstracted from the philosophical sanctions placed by Bohr upon its proper interpretation. Instead, it begins with a decidedly nonclassical concept, suggested by Heisenberg (and resurrected from Aristotle), that actuality and potentiality constitute two fundamental species of reality. This new characterization of potentia as ontologically significant by itself does much to eliminate the infamous paradoxes of quantum mechanics, as Heisenberg points out,[14] and it is an acute example of the importance, commended by Whitehead, of imaginative generalization in the construction of a sound philosophical scheme; for Heisenberg's characterization of potentia as ontologically significant picks up where the inductive generalizations from classical mechanics failed in their attempted logical and coherent application to the quantum theory. And coupled with the explicit acknowledgment that quantum mechanics cannot be used to account for the existence of actualities, which it necessarily presupposes and anticipates, these two concepts—actuality and potentiality as fundamental species of reality—form the cornerstone of this new family of interpretations. These interpretations characterize quantum mechanics not as a means of describing the actualization of potentia (for the terminal actuality, like the antecedent actuality, is presupposed by the mechanics), but rather as a means of describing the *valuation* of potentia. And as regards the central role of mathematics in these quantum mechanical valuations, Whitehead clearly believes that the success of specific mathematical concepts upon which the quantum theory is founded—probability, tensors, and matrices, to name a few—derives from their origination in the "imaginative impulse," controlled by the requirements of logic and coherence: "It is a remarkable characteristic of the history of thought that branches of mathematics, developed under the pure imaginative impulse, thus controlled, finally receive their important application. Time may be wanted. Conic sections had to wait for 1800 years. In more recent years, the theory of probability, the theory of tensors, the theory of matrices are cases in point."[15]

And as the imaginative impulse was central to the formulation of the mathematical concepts and formalism of quantum mechanics, so would it be to the formulation of a coherent and logical interpretation of quantum mechanics. Thus, from the imaginative conception of ontologically significant potentia, the speculative generalization is further expanded to include three more concepts—each of which is presupposed by the quantum formalism: (i) that actualities evolve to become novel actualities, forming historical routes of actualities, and it is their associated potentia which mediate this evolution from actuality to actuality; (ii) that the evolution of any actuality somehow entails relations with *all* actualities by virtue of the closed system, required by the Schrödinger equation, comprising all actualities; (iii) that these necessary relations, when relative to a single evolution, require a process of negative selection whereby the coherent multiplicity of relations is reduced into a set of decoherent, probability-valuated, mutually exclusive and exhaustive, potential novel integrations, such that superpositions of mutually interfering potentia incapable of integration are eliminated. This process of negative selection guarantees that histories of actualities are mutually consistent (that is, in compliance with the logical principles of non-contradiction and the excluded middle), such that the novelty of the future does not vitiate the actuality of the past.

This process of negative selection describes what is referred to as the "decoherence effect," and the family of interpretations referred to earlier consists of those that agree upon the ontological significance of this process, as well as those related concepts discussed earlier. Many notable theorists, including Robert Griffiths, Wojciech Żurek, Murray Gell-Mann, and Roland Omnès, among several others, have demonstrated that the interrelations among all facts—those belonging to a measured system, a measuring apparatus, and the environment englobing them—play a crucial conceptual and mechanical role in the elimination of superpositions of nonsensical, interfering potentia (and potential histories) via negative selection and the resulting decoherence effect. Though the proposals of each of these thinkers differ somewhat, they all emphasize the importance of this negative selection process. According to Żurek's Environmental Superselection interpretation, for example, "Decoherence results from a negative selection process that dynamically eliminates nonclassical [i.e., mutually interfering and thus incompatible] states."[16] Żurek, like many physicists who believe in the central importance of this process of negative selection, maintains that decoherence is a consequence of the universe's role as the only truly closed system, which, put another way, guarantees the ineluctable "openness" of every subsystem within it. "This consequence of openness is critical in the interpretation of quantum theory," Żurek continues, "but seems to have gone unnoticed for a long time."[17]

The quantum mechanical evolution of the state of a system is thus characterized as the valuation of potential novel facts, and potential novel histories of facts, as the evolution proceeds relative to the historical route of actualities constitutive of itself and its universe. The valuations of potentia terminal of this quantum mechanical evolution are describable as a matrix of probabilities, such that they are mutually exclusive and exhaustive—that is, additive in the usual sense. Also, as probabilities, the actualities of the past are presupposed, and a unique actuality terminal of the evolution is similarly presupposed and anticipated. It is understood, then, that this final phase of the evolution—the unitary reduction to a single actuality—lies beyond the descriptive scope of quantum mechanics.

The evolutionary valuation of potentia in quantum mechanics can be correlated phase by phase, and concept by concept, with Whitehead's metaphysical scheme, such that the former can be characterized as the fundamental physical exemplification of the latter. Both entail that a world of mutually interrelated facts (Whitehead's "actual occasions") is presupposed and anticipated in the evolution of each novel fact, and that the inclusion of these facts of relatedness (Whitehead's "prehensions" of facts as "data") in the act of measurement, by these necessary mutual interrelations, somehow entails the following: (i) all other facts and their associated potentia—either in their inclusion in the specification, or their necessary exclusion from the specification. This requirement is reflected in Whitehead's "Principle of Relativity" and his "Ontological Principle," and in quantum mechanics by the Schrödinger equation's exclusive applicability to closed systems, with the universe being the only such system. The exclusions relate to the process of negative selection productive of the decoherence effect, to be discussed presently, and Whitehead refers to these eliminations as "negative prehensions." Their form and function with respect to environmental degrees of freedom are identical to those related to the process of decoherence; (ii) the evolution of the system of all facts into a novel fact—namely, a maximal specification (the "state" specification) of the relevant facts (those not excluded by decoherence or "negatively prehended" in Whitehead's terminology). State specification—the maximal specification of many facts via the necessary exclusion of some facts—thus entails the evolution of a novel fact—namely, a unification of the facts specified; and (iii) the requirement that this evolution proceed relative to a given fact, typically belonging to a particular subsystem of facts. In quantum mechanics, these are, respectively, the "indexical eventuality" and the "measuring apparatus"; Whitehead's equivalent conceptions are, respectively, the "prehending subject" and its "nexus"—that is, the system of actualities to which the subject belongs. This requirement that state evolution (Whiteheadian "concrescence") always proceed relative to a particular fact or system of facts is given in Whitehead's "Ontological Principle" and "Category of Subjective Unity"; their correlates in quantum mechanics—the necessary relation of a state evolution to some preferred basis characteristic of the measuring apparatus—has often been misapprehended as a principle of sheer subjectivity, the source of the familiar lamentations that quantum mechanics destroys the objective reality of the world.

Measurement or state specification thus entails, at its heart, the anticipated actualization (concrescence) of one novel potential fact/entity from a matrix of many valuated potential facts/entities that themselves arise from antecedent facts (data); and it is understood that the quantum mechanical description of this evolution terminates in this matrix of probability valuations, anticipative of a final unitary reduction to a single actuality. Ultimately, then, concrescence/state evolution is a unitary evolution, from actualities to unique actuality. But when analyzed into subphases, both concrescence and quantum mechanical state evolution are more fundamentally nonunitary evolutions, analogous to von Neumann's conception of quantum mechanics as most fundamentally a nonunitary state evolution productive of an anticipated unitary reduction.[18] It is an evolution from (i) a multiplicity—the actual many—to (ii) a matrix of potential "formal" (in the sense of applying a "form" to the facts) integrations or unifications of the many (Whitehead's term is propositional "transmutations" of the many—a specialized kind of "subjective form"—and he also groups these into "matrices"[19]). Each of these potential integrations is described in quantum mechanics as a projection of a vector representing the actual, evolving multiplicity of facts onto a vector representing a potential "formally integrated" outcome state *(eigenstate)*. The Whiteheadian analog of the actual multiplicity's "projection" onto a potential integration is "ingression"—where a potential formal integration arises from the ingression of a specific "potentiality of definiteness"[20] via a "conceptual prehension" of that specific potentiality (Whitehead also refers to these potential facts as "eternal objects" and explicitly equates the two terms[21]). But whereas in quantum mechanics, the state vector representing the actual multiplicity of facts is *projected onto* the potential integration (the *eigenvector* representing the eigenstate), in Whitehead's scheme it is the latter which *ingresses into* the prehensions of the actual multiplicity. This difference reflects Whitehead's concern with the origin of these potentia, for if they ingress into the evolution, then by his Ontological Principle they must be thought of as coming from somewhere. The eigenstate, or object of projection in quantum mechanics, is, in contrast, simply extant, and indeed, this is one of the infamous philosophical difficulties of quantum mechanics.

There are, furthermore, two important characteristics shared by both the quantum mechanical and Whiteheadian notions of potentia that should be noted here. First, there is a sense in which both are "pure" potentia, referent to no specific actualities. For Whitehead, "eternal objects are the pure potentials of the universe; and the actual entities differ from each other in their realization of potentials."[22] "An eternal object is always a potentiality for actual entities; but in itself, as conceptually felt, it is neutral as to the fact of its physical ingression in any particular actual entity of the temporal world."[23] In quantum mechanics, this pure potentiality is reflected in the fact that the state vector $|\Psi\rangle$ can be expressed as the sum of an infinite number of vectors belonging to an infinite number of subspaces in an infinite number of dimensions, representing an infinite number of potential states or "potentialities of definiteness" referent to no specific actualities and potentially referent to all. Many of these are incapable of integration, forming nonsensical, interfering superpositions, and are eliminated as negative prehensions in a subsequent phase of concrescence.

Second, quantum mechanical potentia are also "inherited" from the facts constituting the initial state of the system (as well as the historical route of all antecedent states subsumed by the initial state) such that preferred bases in quantum mechanics are typically reproduced in the evolution from state to state. Similarly, in Whitehead's scheme, antecedent facts, when prehended, are often "objectified" according to one of their own historical "potential forms of definiteness"—typically, the given potential forms that were antecedently actualized at some point in the historical route of occasions constituting the system measured.

> An actual entity arises from decisions *for* it and by its very existence provides decisions *for* other actual entities which supersede it.[24]

> Some conformation is necessary as a basis of vector transition, whereby the past is synthesized with the present. The one eternal object in its two-way function, as a determinant of the datum and as a determinant of the subjective form, is thus relational. . . . An eternal object when it has ingression through its function of objectifying the actual world, so as to present the datum for prehension, is functioning "datively."[25]

Whitehead's characterization of potentia as "relational," then, is clearly exemplified by the manner in which potentia mediate the actuality of a measured system and the actuality of the outcome of the measurement—that is, the mediation between the initial and final system states.

The quantum mechanical state evolution/concrescence thus continues into its next phase: (iii) a reintegration of these integrations into a matrix of "qualified propositional" transmutations,[26] involving a process of negative selection where "negative prehensions" of potentia incapable of further integration are eliminated. The potential unifications or propositional transmutations in this reduced matrix are each qualified by various valuations. Each potential transmutation relative to the indexical eventuality of the measuring apparatus (i.e., each potential outcome state relative to the apparatus and some prehending subject belonging to it) is thus a potential "form" into which the potential facts of the universe will ultimately evolve. Whitehead terms these "subjective forms." As applied to quantum mechanics, the term *subjective* refers to the fact that the "form" of each potential outcome state is reflected in the preferred basis relative to the indexical eventuality of the measuring apparatus (i.e., the prehending subject). Again, it is only the form that is thus subjective—for any number of different devices with different preferred bases could be used to measure a given system, and any number of different people with their own "mental preferred bases" could interpret (measure) the different readings of the different devices, and so on down the von Neumann chain of actualizations. The potential facts to which each subjective form pertains, however, are initially "given" by the objective facts constitutive of the world antecedent to the concrescence at hand. Thus, again, the "subjective form" of a preferred basis is in no way demonstrative of sheer subjectivity—that is, the evolution of novel facts *as determined* by a particular subject. It is, rather, demonstrative of the evolution of novel facts jointly determined by both the world of facts antecedent to the evolution *and* the character of the subject prehending this evolution by virtue of its inclusion in it. According to Whitehead's "Ontological Principle,"

> Every condition to which the process of becoming conforms in any particular instance, has its reason either in the character of some actual entity in the actual world of that concrescence, or in the character of the subject which is in process of concrescence. . . .[27]
>
> The actual world is the "objective content" of each new creation.[28]

The evolution thus proceeds to and terminates with what Whitehead terms the "satisfaction," which in quantum mechanical terms is described as (iv) the anticipated actualization of the final outcome state—that is, one subjective form from the reduced matrix of many subjective forms—in "satisfaction" of the probability valuations of the potential outcome states in the reduced matrix. In quantum mechanics, as in Whitehead's model, this actualization is irrelevant and transparent apart from its function as a datum (fact) in a subsequent measurement, such that the "prehending subject" becomes "prehended superject." Again, this is simply because both Whitehead's process of concrescence and quantum mechanics presuppose the existence of facts, and thus cannot account for them. For Whitehead, "satisfaction" entails "the notion of the 'entity as concrete' abstracted from the 'process of concrescence'; it is the outcome separated from the process, thereby losing the actuality of the atomic entity, which is both process and outcome."[29] Thus, the probability valuations of quantum mechanics describe probabilities that a given potential outcome state *will be actual* upon observation—implying a subsequent evolution and an interminable evolution of such evolutions. Every fact or system of facts in quantum mechanics, then, subsumes and implies both an initial state and a final state; there can be no state specification S without reference, implicit or explicit, to $S_{initial}$ and $S_{final.}$ This is reflected in Whitehead's scheme by referring to the "subject" as the "subject-superject":

> The "satisfaction" is the "superject" rather than the "substance" or the "subject." It closes up the entity; and yet is the superject adding its character to the creativity whereby there is a becoming of entities superseding the one in question.[30]

> An actual entity is to be conceived as both a subject presiding over its own immediacy of becoming, and a superject which is the atomic creature exercising its function of objective immortality. . . .[31]

> It is a subject-superject, and neither half of this description can for a moment be lost sight of. . . .[32]

> [The superject is that which] adds a determinate condition to the settlement for the future beyond itself.[33]

Thus, the process of concrescence is never terminated by actualization/satisfaction; it is, rather, both begun and concluded with it. The many facts and their associated potentia become one novel state (a novel fact), and are thus increased historically by one, so that, as Whitehead puts it, "the oneness of the universe, and the oneness of each element in the universe, repeat themselves to the crack of doom in the creative advance from creature to creature."[34] "The atomic actualities individually express the genetic unity of the universe. The world expands through recurrent unifications of itself, each, by the addition of itself, automatically recreating the multiplicity anew."[35]

The specific phase-by-phase, concept-by-concept correlation of Whitehead's cosmological scheme and the decoherence-based interpretations of quantum mechanics—such that the latter are seen as a fundamental physical exemplification of the former—satisfies Whitehead's intention that his cosmological model be compatible with modern theoretical physics. Indeed, much of the development of the "Copenhagen" quantum formalism occurred contemporaneously with Whitehead's development of his cosmological scheme. Whitehead writes: "The general principles of physics are exactly what we should expect as a specific exemplification of the metaphysics required by the philosophy of organism."[36] But it also satisfies the intention of the quantum theory's originators that it provide the fundamental physical characterization of nature—"*die endgültige Physik*"—an intention that can be fulfilled only within the context of a coherent, logical, applicable, and adequate ontological interpretation.[37]

Ultimately, the test of the synthesis proposed herein, as is the case for any adventure in speculative philosophy, is to be found in renewed observation mediated by the metaphysical scheme both in areas of physics and in other areas as well—areas that, apart from the scheme, might have seemed entirely unrelated.

> The success of the imaginative experiment is always to be tested by the applicability of its results beyond the restricted locus from which it originated. . . . The partially successful philosophic generalization will, if derived from physics, find applications in fields of experience beyond physics. It will enlighten observation in those remote fields, so that general principles can be discerned as in process of illustration, which in the absence of the imaginative generalization are obscured by their persistent exemplification.[38]

The study of complex adaptive systems in nature, as one such application, has been the topic of a great deal of research and debate over the past several years, and has significant roots in attempts by several physicists to demonstrate that quantum mechanics describes such complexity at the most fundamental physical level. The "balanced complexity"[39] described by Whitehead as the "subjective aim" governing the evolution of novel actuality in his cosmological scheme has a direct analog in the concept of "effective complexity"—also a balance of regularity (Whitehead's genetic "reproduction" of potentia) and diversity ("reversions" of potentia from the genetic regularity). Efforts have been made in the sciences to disclose the fundamental function and exemplification of effective complexity by referring to quantum mechanics, and the decoherence-based interpretations are particularly well suited to this task. The reasons are especially clear in the context of the Whiteheadian cosmology; for the decoherence effect is predicated upon the very notions of contrast of (i) *diverse* multiplicities of facts with (ii) *regulated* potential integrations of these facts (the regulation being a product, in part, of negative selection) into alternative, probability-valuated, mutually exclusive forms of definiteness.

The application of the decoherence-based interpretations of quantum mechanics to the study of complexity in nature, where the former is seen as a fundamental exemplification of the latter, is an area of inquiry significant not only to the philosophy of science but also, potentially, to the philosophy of religion. The contextualization of quantum mechanics in terms of the Whiteheadian cosmological scheme is commended here, for Whitehead's repudiation of fundamental mechanistic materialism is also a repudiation of its correlate characterization of the universe as a cold realm of mechanical accidents from which our purportedly illusory and sheerly subjective perceptions of purpose and meaning are, by certain views, thought to derive. In the words of Jacques Monod, the Nobel-laureate biochemist: "Man knows at last that he is alone in the universe's unfeeling immensity, out of which he emerged only by chance."[40] In sharp contrast, by Whitehead's cosmology as exemplified by the decoherence interpretations of quantum mechanics, the universe is instead characterized as a fundamentally complex domain with an inherent aim toward an ideal balance of reproduction and reversion—a balance formative of a nurturing home for a seemingly infinitely large family of complex adaptive systems such as ourselves.

The usefulness of the synthesis of quantum mechanics and Whitehead's cosmology to conversations among philosophy, science, and religion is further demonstrated as it might apply to the role of God as primordial actuality in quantum mechanical cosmogonic models of *creatio ex nihilo*, such as the one proposed by Stephen Hawking and James Hartle[41] mentioned earlier. Quantum mechanics describes the evolution of the state of a system of actualities always in terms of an initial state antecedent to the evolution, and a matrix of probable outcome states subsequent to and consequent of the evolution. Therefore, the application of quantum mechanics to the description of any cosmogonic model—an inflationary universe model, for example—still requires a set of "initial conditions" or initial actualities at $t = 0$, when the evolution begins. In such an evolution, there must logically be, in other words, some actuality which evolves. Renaming these initial conditions "quantum vacuum" or "quantum foam" (equating them mathematically to the empty set), despite the intended connotations of these linguistic and mathematical terms, does nothing to relieve the theory of its logical obligation to presuppose the existence of facts antecedent to and subsequent to (and consequent of) a quantum mechanical evolution—whether this evolution describes the emission of an X ray from a black hole, or the emission of the universe from a black foam. For without these initial actualities, there can be no spacetime structure in which a quantum mechanical state evolution might operate. Hawking's suggestion that it is a vacuous spacetime that first evolves quantum mechanically into actuality from sheer potentiality (i.e., from no initial actuality) defies the logically necessary predication of spacetime upon existence—the logically necessary predication of the ordering among actualities upon the actualities themselves.

But the Whiteheadian philosophy is likely to be useful in such conversations for another reason that has less to do with the facts of his philosophy than its form. For the spirit of speculative philosophy which animated both the development of Whitehead's cosmological scheme and that of the decoherence-based interpretations of quantum mechanics will be equally useful to the rapidly widening conversation among philosophy, science, and religion. An appeal to the Whiteheadian spirit of speculative philosophy would do much to mediate and advance such conversations; for theories would, in this spirit, have the character of philosophic generalization hypothetically deduced relative to careful scientific observations, but coupled with the play of a free imagination and conditioned by the requirements of coherence and logic. The product of this creative amalgam, applied to subsequent observations, propels the process forward with the explicit understanding that the theories thereby created shall never achieve their perfect, final form—that the conversation shall never terminate.

The discussion that follows, because of the complexity inherent in each side of the synthesis, has been divided into two parts. Part I consists of an examination of the ontological innovations and consequences of quantum mechanics; therein, the decoherence family of interpretations will be introduced and contrasted with a representative selection of other interpretations. Part II consists of the correlation of the ontological interpretation of quantum mechanics explored in Part I with Whitehead's cosmological scheme—both "mechanically" in terms of the phases of concrescence exemplified by quantum mechanical state evolution, and conceptually, in terms of Whitehead's nine Categoreal Obligations as fundamental principles presupposed and exemplified by the mechanics.

When considering this distinction between "mechanical" and "conceptual," however, one must take care to avoid conflating the concept of "mechanism" with the concept of "materialism"—a conflation that lies at the heart of the conventional connotation of "mechanism." Both quantum mechanics and Whiteheadian metaphysics describe a nondeterministic, nonmaterialistic process. But it is a mechanical process nonetheless, evinced in two aspects. First, it entails a realistic physics and metaphysics, grounded upon the objective actuality of the past; second, potentia are ontologically significant components of this process. They are integrated and reintegrated with other data into matrices of probability-valuated subjective forms according to a set of governing principles (Whitehead's Categoreal Obligations, the various postulates of quantum mechanics, etc.)—principles capable of representation as rule-governed, mathematically describable constructions. Thus it is a nondeterministic, nonmaterialistic process that both Whiteheadian concrescence and quantum mechanical state evolution describe, both conceptually and mechanically; it is mechanism devoid of misplaced concreteness.

The intent of this book, then, is to suggest a narrow, phase-by-phase, concept-by-concept correlation of quantum mechanics and Whitehead's metaphysical scheme—that is, a correlation that avoids any omissions of the conceptual and comparative phases of Whitehead's "supplementary stage" of concrescence. Such omissions are often thought warranted when applying Whiteheadian philosophy to the physical sciences because of the presumed pertinence of these phases exclusively to conscious, high-order mental processes. This misplaced presumption might be due in part to Whitehead's choice of the term "mental pole" as an alternative to the "supplementary stage" of concrescence, which for some readers unfortunately implied a Cartesian connotation even though the repudiation of Cartesian mind-matter dualism is a fundamental principle of Whitehead's metaphysical scheme.

By contrast, other attempts to correlate Whiteheadian metaphysics with quantum mechanics (particularly the information theoretic interpretations) have tended to elevate the operations of the mental pole to primacy. In these syntheses, the spatiotemporal coordinative operations of the physical pole (the "primary stage" of concrescence) are often either merged into the supplementary stage/mental pole, or they are done away with altogether. The intent of such approaches seems to be to render the spatiotemporal extensiveness of actualities and systems of actualities, as well as any theory describing such extensiveness (such as Einstein's special and general theories of relativity), as mere abstractions derivable entirely from fundamental quantum events, in the same way that the concept of "material body" is so derivable in Whiteheadian metaphysics. By such interpretations, Whitehead's "fallacy of misplaced concreteness" finds its exemplification not only in the conventional notion of "fundamental materiality" but also in the conventional notion of "fundamental extensiveness in spacetime."

But for Whitehead, the spatiotemporally *extensive* morphological structure of actualities and nexūs of actualities given via "coordinate division" of actuality, primarily pertinent to the physical pole, is as crucial to concrescence as the *intensive* features of their relations given via "genetic division" of actualization, primarily pertinent to the mental pole. This close relationship, attended to in detail in chapter 5, is a key aspect of the dipolarity of concrescence in Whiteheadian metaphysics and the avoidance of a Cartesian bifurcated Nature.

It is hoped, then, that the close, concept-by-concept correlation proposed in this book will serve to demonstrate how quantum mechanics, as a fundamental physical exemplification of Whitehead's metaphysical scheme, might be heuristically useful toward a sound understanding of this scheme, and vice versa. Quantum mechanical concepts presented in Part I will thus be easily recognized when encountered in their analogous Whiteheadian forms in Part II; and likewise, readers already familiar with Whitehead will recognize these forms in their analogous quantum mechanical incarnations in Part I.

NOTES

1. Abner Shimony, "Quantum Physics and the Philosophy of Whitehead," *Boston Studies in the Philosophy of Science*, ed. R. Cohen and M. Wartofsky (New York: Humanities Press, 1965), 2:307.

2. Henry Folse, "The Copenhagen Interpretation of Quantum Theory and Whitehead's Philosophy of Organism," *Tulane Studies in Philosophy* 23 (1974): 32.

3. George Lucas, *The Rehabilitation of Whitehead: An Analytic and Historical Assessment of Process Philosophy* (Albany: State University of New York Press, 1989), 189–199.

4. Alfred North Whitehead, *Process and Reality: An Essay in Cosmology, Corrected Edition*, ed. D. Griffin and D. Sherburne (New York: Free Press, 1978), 3.

5. Folse, "The Copenhagen Interpretation," 46–47.

6. See, for example, Whitehead, *Process and Reality*, 116.

7. David Bohm, "Time, the Implicate Order, and Pre-space," in *Physics and the Ultimate Significance of Time*, ed. David R. Griffin (Albany: State University of New York Press, 1986), 198.

8. Ibid., 196.

9. Ibid., 199.

10. David Bohm and B. J. Hiley, *The Undivided Universe: An Ontological Interpretation of Quantum Theory* (London: Routledge, 1993), 358.

11. Ibid., 361.

12. Whitehead, *Process and Reality*, 8.

13. Niels Bohr, *Atomic Theory and the Description of Nature* (Cambridge: Cambridge University Press, 1934).

14. Werner Heisenberg, *Physics and Philosophy* (New York: Harper and Row, 1958), 185.

15. Whitehead, *Process and Reality*, 6.

16. Wojciech Żurek, "Letters," *Physics Today* 46, no. 4 (1993): 84.

17. Ibid.

18. John von Neumann, *Mathematical Foundations of Quantum Mechanics* (Princeton, N.J.: Princeton University Press, 1955).

19. Whitehead, *Process and Reality*, 285.

20. Ibid., 40.

21. Ibid., 149.

22. Ibid., 149.

23. Ibid., 44.

24. Ibid., 43.

25. Ibid., 164.

26. Ibid., 285–286.

27. Ibid., 24.
28. Ibid., 65.
29. Ibid., 84.
30. Ibid., 84.
31. Ibid., 45.
32. Ibid., 29.
33. Ibid., 150.
34. Ibid., 228.
35. Ibid., 286.
36. Ibid., 116.
37. The most thorough and systematic example of an interpretation of quantum mechanics that explicitly recognizes these desiderata is to be found in Roland Omnès's *The Interpretation of Quantum Mechanics* (Princeton, N.J.: Princeton University Press, 1994); although some readers might find them too technical, his "21 Theses," which pertain to these philosophical desiderata, are extremely useful.
38. Whitehead, *Process and Reality*, 5.
39. Ibid., 278.
40. J. Monod, *Chance and Necessity: An Essay on the Natural Philosophy of Modern Biology* (New York: Vintage, 1972), 180.
41. James Hartle and Stephen Hawking, "The Wave Function of the Universe," *Physical Review D* 28 (1983): 2960–2975.

I

The Philosophical Implications of Quantum Mechanics

2

The Ontological Interpretation of Quantum Mechanics

IN ANY MODERN EXPLORATION of the philosophy of science, one is at some point doomed to encounter that old, strangely constructed bridge that is quantum mechanics, the path across which seems to provide anything but sure footing. On one side of the chasm lie the conventional materialist ontologies, exemplified via the inductions of classical physics—inductions from our usual experiences of the macroscopic world. In general, these materialist ontologies characterize nature as fundamentally atomic and fluid—a collection of bits of matter whose motions, among other qualities and interactions, are deterministic and continuous through space and time. On the other side of the chasm lie modern experiences of the microscopic world, which, when initially accounted for by Planck and Einstein via the conventional materialist ontologies, characterized nature as a collection of material particles as before, but whose motions and interactions, when measured, appeared discontinuous and probabilistic rather than fluid and deterministic.

Bohr's 1913 model of the atom embodies this initial envisagement of the quantum mechanical microscopic world through the lens of mechanistic materialism. In this model, electrons are posited to be fundamentally material particles occupying a number of possible spatial "stationary states" around a fundamentally material nucleus. But rather than moving continuously through space from state to state according to previous conceptions, the electrons in Bohr's model must be thought of as making quantum leaps from one fixed state to another, each state associated with a discrete volume of space a certain distance from the nucleus and associated with a specific energy level. An electron making such a leap, in other words, must be thought of as making an instantaneous transition from one volume of space to another *without* moving through the space in between. Consideration of when or where an electron is during its transition from one state to another is rendered nonsensical in this model, despite the sensibility of such considerations given the materialist ontological framework Bohr's model otherwise requires. The demand for this troublesome caveat derives from the inescapable fact that any calculative prediction of an electron's state will yield only a probability as to which state it will occupy at the conclusion of a measurement, and never a unique factual outcome of the sort rendered by classical mechanics. And since the accuracy of these predicted probabilities is always confirmed retrodictively by experiment, the induction toward a "quantum" characterization of nature's most fundamental elements is, as concerns the science of physics, as justified as the materialist ontologies that preceded it.

The desire for a bridging of these two equally justifiable yet seemingly incompatible conceptions of nature—that of the conventional materialism of classical physics on one hand, and that inspired by the "old" quantum theory of Planck, Einstein, and Bohr on the other—fueled the subsequent work of Heisenberg, Bohr, Schrödinger, von Neumann, deBroglie, Dirac, Born, Jordan, and others during the years 1924–1928. But their efforts, while productive of a far more systematized and elegant quantum formalism, only served to emphasize and augment, rather than mitigate and reduce, the incompatibility of an ontological framework induced from classical mechanics and one induced from quantum mechanics. Granting for the moment that quantum mechanics is indeed ontologically significant at all, Abner Shimony distills these incompatibilities into five conceptual innovations implied by the quantum theory: (i) objective indefiniteness, (ii) objective chance, (iii) objective nonepistemic probability, (iv) objective entanglement, and (v) quantum nonlocality.[1]

Though the ontological implications of these innovations will be explored later in this chapter, it will be helpful to suggest now that there is a common source from which all five spring—a source that can be traced back even to the "old" quantum theory embodied by Bohr's atomic model: Though quantum mechanics makes use of facts—the facts constitutive of that which is being measured, for example, and the facts constitutive of the result of measurement—quantum mechanics cannot *account* for these facts, nor are the "mechanics" of quantum theory productive of facts. The mechanics are productive of probabilities only. When used to predict and therefore describe a measurement interaction, quantum mechanics makes use of facts stipulated to exist antecedent to the measurement interaction—facts that account for that which is to be measured, as well as the apparatus that will perform the measurement. These facts are, according to the quantum formalism describing the measurement interaction, causally productive of a matrix of mutually exclusive and exhaustive probabilities—probabilities referent to a unique, factual outcome. Although this unique outcome is anticipated by the mechanics, it is not accounted for by the mechanics, and therein lies the key to the conflict among various competing interpretations of the quantum theory. For many theorists, typically those most heavily invested in the classical mechanical worldview, the failure of quantum mechanics to account deterministically for a unique outcome is indicative of the incompleteness of the theory. Thus the five conceptual innovations suggested by Shimony are, for such theorists, properly viewed as epistemological artifacts to be cleared up either by augmenting the theoretical formalism or by improving experimental technology.

For other theorists, the failure of quantum mechanics to account for the unique outcome states it presupposes and anticipates is really no failure at all; it is instead properly recognized as a logical, and indeed, ontological limitation operative in any scientific theory. With respect to a conceptually analogous case suggested by Murray Gell-Mann,[2] when one wishes to predict the probability of a horse's winning a race, one necessarily presupposes (i) the fact of the horse (and everything else the race entails) antecedent to the race; and (ii) the fact of the horse's winning, or losing, at the conclusion of the race. By this view, even classical mechanics makes such presuppositions, which it cannot account for via its equations and formulas—namely, the very existence of the material particles whose motions and interactions are described by the mechanics.

That quantum mechanics is unable to account for its presupposed and anticipated facts has proven especially troublesome for some, given that quantum mechanics purports to characterize their relationship, via the Schrödinger equation, such that the matrix of probable measurement outcomes is not only subsequent to the measurement interaction and all the antecedent facts such an interaction presupposes, but also causally *consequent* of this interaction, which includes not only the facts constitutive of that which is measured, *but also the facts of the apparatus performing the measurement.* John Bell states the difficulty thus:

> When it is said that something is "measured" it is difficult not to think of the result as referring to some preexisting property of the object in question. This is to disregard Bohr's insistence that in quantum phenomena the apparatus as well as the system is essentially involved. If it were not so, how could we understand, for example, that "measurement" of a component of "angular momentum" . . . in an arbitrarily chosen direction . . . yields one of a discrete set of values?[3]

The outcome of a quantum mechanical measurement, in other words, is consequentially affected, at least to some degree, by that which measures—a conclusion described by Heisenberg's famous uncertainty relations. In their original 1927 incarnation, these relations were primarily intended to describe wave-particle duality with respect to position and momentum measurements and the Compton Effect manifest in such measurements: Measurement of the position or velocity of a particle, according to Heisenberg, necessarily entails the collision of the particle to be measured with particles associated with the measuring apparatus. These collisions will always affect position or velocity measurements such that, among other consequences, a simultaneous position and velocity measurement upon the same particle is impossible.

Given this particular application of the uncertainty relations, it might appear that they are more epistemically significant than ontologically significant—that they have more to do with a deficiency in the measuring procedure or apparatus than with the actualities being measured. However, a more generalized incarnation of Heisenberg's uncertainty relations in terms of the unavoidable change in a system's energy caused by a measurement interaction provides a more fundamental and ontologically significant description: For example, a measurement with duration Δt is made of the energy of a system, and the measurement interaction causes an uncertainty or change ΔE in the energy measured, the magnitude of which is given by:

$$\Delta E \Delta t \geq \frac{h}{4\pi}$$

where h is Planck's constant.

Thus, the *outcome* of a quantum mechanical measurement is shown to be consequentially affected by that which measures. Unfortunately, however, this conclusion is often taken to imply that *that which is measured* via quantum mechanics is somehow causally influenced by that which measures—the source of the familiar lamentation that quantum mechanics has permitted the intrusion of sheer subjectivity into physics.

Such an alarming implication, however, should not be inferred from the Heisenberg uncertainty relations and the quantum formalism itself; it can only be inferred from the quantum formalism as interpreted via a classical materialist ontology, according to which a material object with factual material qualities antecedent to measurement continuously endures throughout measurement, thus remaining the same object at the conclusion of the measurement interaction—though by the Heisenberg uncertainty relations, with potentially different factual qualities somehow caused by the measurement. In other words, the object endures measurement by such an interpretation, yet its factual qualities change *because of* measurement and the particular apparatus used to perform the measurement. It is only when one attempts to interpret quantum mechanics via this classical materialist ontological notion of the qualification of an enduring substance by quality that quantum mechanics appears to thus threaten, via its supposed implication of sheer subjectivity, the objective reality of the world.

Alternatively, an ontological interpretation of quantum mechanics derived from the formalism itself, rather than from the formalism classically mediated, leads one toward a much different picture of the fundamental constituents of nature—again, granting for the moment that quantum mechanics is ontologically significant at all; one must keep in mind that all one can say for certain about quantum mechanics is that it is a theory by which physicists are able to successfully predict probabilities that specific types of measurements, under specific types of circumstances, will yield specific types of results. Whether or not this theoretical instrument is truly incapable of accommodation by the conventional materialist ontologies which otherwise reign supreme in physics is, to this day, a matter of heated debate, and arguments affirming a classical ontological interpretation of quantum theory have yet to be presented in this discussion.[4] That stated, one can consider, even at this very early stage of the discussion, the following chain of reasoning productive of innovative ontological generalizations from the quantum formalism:

1. Quantum mechanics describes the evolution of initial facts antecedent to a measurement interaction to final novel facts subsequent to a measurement interaction. It describes this evolution via the linear, deterministic Schrödinger equation, which yields a matrix of probable novel facts, from which a unique final fact will obtain indeterministically. The term "measurement interaction," therefore, is a relational term that presupposes the objective existence of the facts thus related by the quantum mechanical evolution. Without these facts, there is nothing to relate, and the concept of measurement becomes meaningless.

2. Quantum mechanics reveals, per the Heisenberg uncertainty relations, that the facts subsequent to a measurement interaction are also *consequent of* the measurement interaction, and in this sense, facts presuppose measurement as much as measurement presupposes facts. Bohr thus rightly induces from quantum mechanics "the impossibility of any sharp separation between the behaviour of atomic objects and the interaction with the measuring instruments which serve to define the conditions under which the phenomena appear."[5] According to quantum mechanics, then, the concepts of "fact" and "measurement" are mutually implicative; each is incapable of abstraction from the other, and both are therefore equally fundamental concepts. Put another way, facts are necessarily interrelated in quantum mechanics such that the notion of a single fact in isolation is meaningless.

3. Quantum mechanics therefore further reveals, per the Heisenberg uncertainty relations, that interrelations among facts are productive of novel facts, given that a measurement outcome is a novel fact (or an ensemble of novel facts) *consequent of,* and not merely subsequent to, the interrelations among facts comprising the measuring apparatus and the system measured. This is correctly interpreted not as a principle of sheer subjectivity, but as the fundamental physical exemplification of an ontological principle of relativity, such that any fact or system of facts cannot be considered apart from its interrelations with other facts. Measurement is an example of such interrelations.

Necessarily interrelated facts are therefore, according to the quantum formalism, the most fundamental constituents of nature capable of description via the physical sciences—and hence, by ontological induction, the most fundamental constituents of nature herself. Apart from such an induction, quantum mechanical "facts" are merely epistemically significant in their role as purely subjective qualifications of a material substance by quality. According to any ontology strictly induced from the quantum formalism, then, all the materialistic conceptions of nature—conceptions, for example, of material bodies whose motions, among other qualifications, are continuous through space and time—become abstractions from the most fundamental constituents of nature, which are discontinuous, yet necessarily interrelated, quantum facts. The notion, then, of a classically "isolated" object of measurement in quantum mechanics cannot be taken as ontologically significant, but merely as a conceptual abstraction; a fact, by its ontologically necessary interrelations with other facts as induced from the quantum formalism, can never be isolated from other facts in the classical sense.

The obvious implication is that every measurement interaction somehow involves the entire universe of all facts—an idea clearly alluded to by Heisenberg, for example, when he writes, "the transition from the 'possible' to the 'actual' takes place as soon as the interaction of the object with the measuring device, and thereby with the rest of the world, has come into play."[6] And indeed, a great many contemporary quantum theorists whose work will be explored in chapter 3 have demonstrated that the necessary interrelation among all facts in the universe is not only an interesting ontological induction one might draw from quantum mechanics; rather, theorists such as Robert Griffiths, Wojciech Żurek, Murray Gell-Mann, and Roland Omnès, among many others, have demonstrated that the interrelations between "measured" facts and facts belonging to the "environment" englobing the measurement interaction actually play a crucial mechanical role in the production of the measurement outcome.

Bohr's Strategy: "Complementarity" as Evidence of an Unknowable Objective Reality

The conception of necessarily interrelated facts as nature's most fundamental elements constitutes the first major departure from conventional materialist ontologies that hold that measurement necessarily presupposes fact—"measurement" in this sense being a qualification of a material substance by quality—but fact need not presuppose measurement, such that a fact, as well as the material body it qualifies, can be considered in isolation. Bohr's insistence that even quantum mechanical measurements must be made with a classically described apparatus exemplifies the initial attempt to at least partially mediate quantum mechanics with a classical materialist ontology in order to avoid this troublesome, mutually implicative relationship between fact and measurement. That this classical mediation prescribed by Bohr utterly contradicts his insistence on "the impossibility of any sharp separation" between the system measured and the apparatus measuring, as exemplified by the Heisenberg uncertainty relations, has of course been the source of a great deal of confusion; the difficulty manifests itself in the formalism, for example, when one attempts to account for the correlations between alternative potential microscopic measured-system outcomes and their respective alternative potential macroscopic measuring apparatus outcomes—a difficulty frequently referred to as "the problem of measurement" in quantum mechanics.

Indeed, most, if not all, of the conceptual difficulties and "paradoxes" associated with quantum mechanics can be traced to attempts to mediate or even wholly accommodate the latter within a classical mechanical ontology. There have been, over the years, a great number of proposed interpretations of quantum mechanics intended to solve these difficulties—some of which attempt to more coherently account for quantum mechanics as an abstraction from classical mechanics, and some of which attempt to account for classical mechanics as an abstraction from quantum mechanics. Many of these ontological proposals will be explored later in this chapter, but it will be useful here to introduce, and then quickly dispense with, an interpretation that stands apart from all others: the instrumentalist interpretation—more a mindset than an interpretation, given that it denies that any interpretation of quantum mechanics is necessary. It is a tradition advocated, in the words of Popper, by physicists who have turned away from interpretations of quantum mechanics "because they regard them, rightly, as philosophical, and because they believe, wrongly, that philosophical discussions are unimportant for physics. . . . [It is] a tradition which may easily lead to the end of science and its replacement by technology."[7]

This tradition is sometimes confused with Bohr's "pragmatic interpretation" of quantum mechanics, which is unfortunate given Bohr's obvious interest in the philosophical implications of the quantum theory. Though to confuse the two would be unfair, it would certainly be fair to say that Bohr's pragmatic interpretation significantly inspired the instrumentalist mindset popular among many physicists today; for Bohr prescribes, as we have seen thus far, two utterly incompatible conceptions of a quantum mechanical measurement interaction, for no other reason than it is practical to do so. On the one hand, he explicitly proscribes the possibility of any "sharp separation between the behaviour of atomic objects and the interaction with the measuring instruments which serve to define the conditions under which the phenomena appear."[8] Yet, on the other hand, Bohr prescribes treating the measuring apparatus classically, so that one is able to consider the facts pertaining to that which is measured as "external" to the apparatus, and therefore merely externally related, rather than mutually interrelated, thus preserving the conventional materialist notions of "subject" measuring "object." Likewise, the facts pertaining to the environment englobing that which is to be measured are similarly treated, such that the facts to be measured quantum mechanically can be considered as a "closed system," external to the surrounding environment.

An important justification for maintaining this classical conception of a closed, noninteracting system as the "object" of measurement is that the linear, deterministic Schrödinger equation at the very heart of quantum mechanics is applicable only to such closed systems. Bohr's prescription, however, also renders quantum mechanics nonuniversal and therefore ontologically insignificant, since the applicability of the mechanics becomes predicated upon an arbitrary dividing line separating the quantum and the classical.

That in itself may or may not be seen as a drawback, given that for practical purposes quantum mechanics is simply a tool used to predict the outcomes of measurements under specific conditions—not universal conditions. However, given Bohr's insistence that the interrelations between the apparatus and the atomic objects measured render them inseparable, as expressed via the Heisenberg uncertainty relations, this utterly contradictory classical, subject-object ontological mediation of quantum mechanics necessarily implies the following: The object of measurement, though classically isolated from the subject which measures, is nevertheless influenced somehow by this subject. Again, it is this conclusion that has led many to lament that quantum mechanics severely vitiates, via its implied sheer subjectivity, the objective reality of the world—a grievous and paradoxical violation of the same materialist characterization of quantum mechanical measurement which predicates such a conclusion. The ontologically classical characterization of quantum mechanical measurement, prescribed by Bohr, implies a relationship between subject and object that violates this very characterization.

One may attempt to escape such a conclusion, however, by appealing to the previous conclusion that quantum mechanics is non-universal, and therefore ontologically insignificant—at least to the extent that it requires no ontological innovation; its significance is epistemological only. The Heisenberg uncertainty relations can therefore be interpreted as holding that only one's *knowledge* of that which is measured—knowledge yielded via the outcome of a measurement—depends on the apparatus performing the measurement. The apparatus does not influence that which it measures, but merely affects one's knowledge of that which is measured. That which is to be known about an object, then, depends on the questions asked. This pragmatic characterization of quantum mechanical measurement as prescribed by Bohr is a component of what has come to be commonly referred to as the Copenhagen Interpretation of the quantum formalism, and although it perhaps serves to mitigate the perceived intrusion of subjectivity into physics, it does not remove this intrusion altogether. For according to the ontological requirements of classical physics—which the Copenhagen Interpretation attempts to subsume at least conceptually in its intended role as "*die endgültige Physik*" (the "absolutely final" physics)—the knowledge of an object, gleaned via measurement, presupposes (i) the objective existence of the object measured; and (ii) that the knowledge of such an object constitutes a factual qualification of the object—that "a fact of knowledge" is "knowledge of a fact." Therefore, if the factual qualification of an object is affected by the subject making this qualification, as implied by quantum mechanics, and a factual qualification of an object derives from real "qualities" of the object as required by the conventional materialism of classical physics, then one must conclude, based on these premises, that qualifications of an object not only derive from the qualities of an object, but also *affect* the qualities of an object.

Therefore, even the characterization of quantum mechanics as merely epistemically significant does not prevent a violation of the classical, materialist ontology from which the premises of measurement—as prescribed by Bohr—derive. Even if one were to retreat to the notion that knowledge of an object gleaned via measurement does not necessarily reveal factual qualities pertaining to the object—that "a fact of knowledge" yielded by a quantum mechanical measurement does not necessarily entail "knowledge of a fact"—the objectively real material world thus immunized from sheer subjectivity is immunized only by the belief that the actual facts of such a world are essentially unknowable at all. Yet it is precisely this retreat which Bohr advocates as the best way to bridge quantum and classical mechanics: "In physics," he writes, "our problem consists in the co-ordination of our experience of the external world,"[9] such that "in our description of nature the purpose is not to disclose the real essence of phenomena but only to track down as far as possible relations between the multifold aspects of our experience."[10]

Thus, where the physical sciences were conventionally held to reveal factual qualities of nature, the objective reality of which was thought to be demonstrable by the apparently universal laws inducible from these qualities, Bohr suggests that quantum mechanics necessarily leads one to a much different conception of physics: The laws of physics, once thought to reveal the essence of nature's most fundamental constituents, now merely reveal subjective coordinations of our experiences of nature. "In quantum mechanics," Bohr writes, "we are not dealing with an arbitrary renunciation of a more detailed analysis of atomic phenomena, but with a recognition that such an analysis is *in principle* excluded" (emphasis in original).[11] Physical laws, for Bohr, must be seen as qualifications of experience only, and the apparent regularity of those experiences capable of description by a physical law cannot be taken as evidence for or against a qualitative characterization of nature herself. For if one were to do so, one would be confronted with the fact that such inductions from the laws of quantum mechanics on one hand, and from the laws of classical mechanics on the other, each lead to entirely incompatible characterizations of nature. Better to say that the laws of quantum mechanics and classical mechanics reveal incompatible yet "complementary"—and for some unknown reason, exceedingly regular—coordinations of our experiences of nature. It is by means of such complementary coordinations of experience that one may bridge quantum and classical mechanics as mutually applicable to the task of characterizing our experiences of nature without characterizing nature herself.

Bohr's proscription against the induction of a fundamental characterization of nature from the laws of quantum mechanics—or classical mechanics—is the cornerstone of his proposed bridge linking quantum and classical mechanics; and in laying this cornerstone, he of course violates that very proscription. For it is clear that it was indeed quantum mechanics that led Bohr to impose the epistemic sanctions embodied by his "principle of complementarity"—and those sanctions clearly constitute an *ontological characterization of nature* whose essence, by this very ontology, consists of a fundamentally *unknowable* reality,[12] subjectively experienced at two levels: (i) publicly, when these subjective experiences are regular enough to be described via physical laws which appear to hold universally; (ii) privately, when these subjective experiences are not regular enough to be described via a physical laws. These ontological generalizations, which Bohr clearly induced from quantum mechanics, and which clearly violate their own desiderata by the qualification of an "unknowable reality" as "unknowable," closely resemble, according to Henry Stapp, the ontology proposed by William James,[13] which characterizes the world as consisting of (i) "hypersensible realities"; (ii) public "sense objects" (those subjective experiences whose coordination is regular enough to be expressible by physical laws); (iii) "private concepts" (those experiences that are truly "subjective" by the conventional meaning of the term, and incapable of coordination expressible by physical laws).[14]

The central claim of the Copenhagen Interpretation is that quantum mechanics is complete—that it cannot be abstracted from a more fundamental characterization of reality. Bohr's justification for this claim via the Jamesian-style ontology he prescribes, however, hinges on the even broader claim that reality is incapable of objective characterization at all. Since it is only one's experiences of reality that can be characterized and coordinated, the seeming incompatibility between the ontological implications and presuppositions of classical mechanics and those of quantum mechanics is resolved by stripping both of any ontological significance at all. Quantum and classical mechanics are thus relegated to the level of merely epistemically significant complementary coordinations of experience, and as such their incompatibility becomes unimportant. The practical advantages of this Jamesian ontological accommodation of the Copenhagen Interpretation are, then, as follows:

First, it allows for the classical conceptions of "subject" and "object" as *externally related,* such that a measurement outcome reveals the state of the object subsequent to the measurement interaction. One may, then, arbitrarily divide the components of a quantum mechanical measurement interaction into an object of measurement, classically isolated from the subject apparatus performing the measurement, as well as from the external environment englobing both. The evolution of the classically closed object/system through the measurement interaction is then capable of description via the linear, deterministic Schrödinger equation, which can be applied only to such a classically closed system.

Second, it allows for the nonclassical conceptions of subject and object as *internally related*—per the Heisenberg uncertainty relations—such that a measurement outcome reveals the state of both subject and object as consequent of, not merely subsequent to, the measurement. In this way, subject and object are nonclassically inseparable, since quantum mechanics describes the effect of the subject apparatus upon the measurement outcome, even when the apparatus and the object measured are spatially well separated.

These allowances were, for Bohr, thought to be possible only by virtue of his proviso requiring an ultimately unknowable reality, such that these wholly incompatible conceptions of subject and object in measurement do *not* constitute incompatible characterizations of the "real things" measuring and measured, which would render quantum mechanics incoherent and incomplete; they are instead to be considered only as complementary coordinations of our experiences of these things. Apart from this Jamesian ontological accommodation of the Copenhagen Interpretation, then, Bohr's "principle of complementarity" would amount to little more than an argument for the inescapable ontological incoherence of quantum mechanics, and therefore the completeness of quantum mechanics—the central claim of the Copenhagen Interpretation—would be anything but demonstrable.

Von Neumann's Alternative to Bohr's Epistemic Schism: Objective Reality via a Coherent Ontological Interpretation

The two advantages of the Jamesian ontology prescribed by Bohr are, however, readily achievable without adopting this conflicted ontology and its notion that reality is most fundamentally hypersensible and incapable of revelation via our experiences. And indeed, the completeness of the Copenhagen Interpretation—the notion that it entails the most fundamental characterization of our experiences of nature—is quite sensible apart from such an ontology. For as discussed at the beginning of this chapter, the most fundamental constituents of nature one might induce from quantum mechanics are necessarily interrelated facts from which all other conceptions—including classical notions of material objects with continuous motions and other attributes—can be shown to be abstractions. The ontological significance of the classical notion of an "objective reality" is preserved in the sense that interrelated facts are *facts*; measurement, as an example of such interrelation, presupposes the facts to be related—the fact of that which is measured, the fact of that which performs the measurement, and the anticipated fact of the outcome of the measurement. And the ontological significance of the Heisenberg uncertainty relations—wherein facts and measurement are mutually implicative—is guaranteed via the conceptually innovative notion of *necessarily interrelated* facts, such that the existence of a fact cannot be considered in isolation from other facts. In other words, since the fundamental constituents of nature are not just facts, but necessarily interrelated facts, fact presupposes measurement (interrelations with other facts) as much as measurement presupposes fact. The creation of a novel fact in quantum mechanics, in the form of a measurement outcome, requires and is conditioned by its interrelations with the facts antecedent to it—facts pertaining to that which is measured (system), but also to that which measures (apparatus) and, by implication, even to that which is not measured (environment).

According to such an ontological framework, an "experience of reality," as Bohr used the term, is ultimately the ontologically fundamental interrelation among facts—facts pertaining to we who experience, interrelated with the facts of the world we experience. The concept of "experience," then, is by this ontology identical to the concept of "measurement"; both are exemplifications of the ontologically fundamental notion of necessarily interrelated facts. An "experience of physical reality," given Bohr's use of the term, thus becomes a chain of interrelations: The interrelations of facts constituting that which is measured with the facts constituting the measuring apparatus; and the interrelation of facts constituting the apparatus with facts constituting the experimenter who observes the apparatus, et cetera. Bohr's concept of a hypersensible reality is no longer necessary, since *experience* itself—necessarily interrelated facts—is ontologically fundamental, rather than an underlying, essentially unknowable material "object" subjectively qualified by experience. The notion of quantum mechanical measurement as a chain of interrelated facts constituting that which is measured and that which measures, however, implies that the measuring apparatus—envisioned as a classical object by Bohr and thus in some sense isolated from the quantum mechanical system that it measures—should instead be envisioned fundamentally as an ensemble of facts interrelated quantum mechanically with the facts being measured.

This was the approach proposed by von Neumann[15] as a way of mathematically accounting for the correlations between the facts constituting the measuring apparatus and the facts constituting that which is measured. Moreover, if quantum mechanics is to be a truly coherent, universal theory, von Neumann suggests that these correlations should further extend to the facts constituting that which "measures" the measuring apparatus—in other words, the body and mind of the human observer. In this way, the classical conceptions of "subject of measurement" and "object of measurement" become properly understood as arbitrary abstractions from a more fundamental quantum mechanical characterization of measurement as the correlation of serially ordered quantum actualizations. Every particular subject-object correlation, then, becomes a datum for a subsequent subject-object correlation. It is only by such a scheme of "psycho-physical parallelism," suggests von Neumann, that the innovative and classically problematic "subjective" features of quantum mechanics might be mediated with the necessary "objective" realism in which modern science is grounded.

> It is a fundamental requirement of the scientific viewpoint—the so-called principle of the psycho-physical parallelism—that it must be possible so to describe the extra-physical process of the subjective perception as if it were in reality in the physical world—i.e., to assign to its parts equivalent physical processes in the objective environment, in ordinary space. (Of course, in this correlating procedure there arises the frequent necessity of localizing some of these processes at points which lie within the portion of space occupied by our own bodies. But this does not alter the fact of their belonging to the "world about us," the objective environment referred to above.) In a simple example, these concepts might be applied about as follows: We wish to measure a temperature. If we want, we can pursue this process numerically until we have the temperature of the environment of the mercury container of the thermometer, and then say: this temperature is measured by the thermometer. But we can carry the calculation further, and from the properties of the mercury, which can be explained in kinetic and molecular terms, we can calculate its heating, expansion, and the resultant length of the mercury column, and then say: this length is seen by the observer. Going still further, and taking the light source into consideration, we could find out the reflection of the light quanta on the opaque mercury column, and the path of the remaining light quanta into the eye of the observer, their refraction in the eye lens, and the formation of an image on the retina, and then we would say: this image is registered by the retina of the observer. And were our physiological knowledge more precise than it is today, we could go still further, tracing the chemical reactions which produce the impression of this image on the retina, in the optic nerve tract and in the brain, and then in the end say: these chemical changes of his brain cells are perceived by the observer. But in any case, no matter how far we calculate—to the mercury vessel, to the scale of the thermometer, to the retina, or into the brain, at some time we must say: and this is perceived by the observer. That is, we must always divide the world into two parts, the one being the observed system, the other the observer. In the former, we can follow up all physical processes (in principle at least) arbitrarily precisely. In the latter, this is meaningless. The boundary between the two is arbitrary to a very large extent. In particular we saw in the four different possibilities in the example above, that the observer in this sense needs not to become identified with the body of the actual observer: In one instance in the above example,

> we included even the thermometer in it, while in another instance, even the eyes and optic nerve tract were not included. That this boundary can be pushed arbitrarily deeply into the interior of the body of the actual observer is the content of the principle of the psycho-physical parallelism—but this does not change the fact that in each method of description the boundary must be put somewhere, if the method is not to proceed vacuously, i.e., if a comparison with experiment is to be possible. Indeed experience only makes statements of this type: an observer has made a certain (subjective) observation; and never any like this: a physical quantity has a certain value.[16]

One of the implications of this interpretation of quantum mechanical measurement is that the unique qualities of a particular actual "subject" in some way govern the correlations between that subject and its particular object. In this way, the set of probability outcomes yielded by quantum mechanics for any given measurement in a chain of measurements, such as the chain described above, "fits" the particular qualities of *that* subject within the chain. Von Neumann noted that the quantum mechanical mechanism governing these subject-object correlations is very different from the quantum mechanical mechanism by which a *unique* measurement outcome is actualized for any given measurement interaction. For one thing, the mechanism governing subject-object correlations does not yield a unique measurement outcome, but rather a mixture of probable measurement outcomes. This and other distinguishing features led von Neumann to further suggest that a coherent, universal interpretation of quantum mechanics requires that the process of subject-object correlation in a quantum mechanical measurement interaction must be distinct from the process descriptive of a unitary wavefunction evolution in such an interaction. He thus proposes a "Process 1" productive of subject-object correlation and the influence of such correlation on the evolution of the *mixture* of probable measurement outcomes yielded by quantum mechanics; and "Process 2" describes the causal, unitary wavefunction evolution to a *particular* probable outcome state. Process 1, in other words, is a non-unitary and thus "non-causal" evolution explicative of the subject-object correlation characteristic of the particular mixture of probable measurement outcomes yielded by this process; this particular mixture of probable outcome states, in other words, would have been otherwise *if* the subject had been otherwise. Process 2, by contrast, is descriptive of a more generic, unitary, and thus "causal" evolution of the wavefunction to a particular probable outcome state—an evolution von Neumann characterizes as an "automatic" change, as opposed to the "arbitrary" change effected by a specific subject-object measurement interaction described by Process 1. Since quantum mechanics cannot account for the existence of actualities (though it can describe their evolution), Process 2 is merely descriptive of the unitary evolution from initial factual system state to final probable system state. But Process 1 is explicative, in that it accounts for the particular probability outcomes yielded; they are functions of the necessary quantum mechanical correlations between a particular subject (i.e., a particular measuring apparatus) and a particular measured system. Von Neumann writes:

> Why then do we need the special Process 1 for the measurement? The reason is this: In the measurement we cannot observe the system S by itself, but must rather investigate the system $S + M$, in order to obtain (numerically) its interaction with the measuring apparatus M. The theory of the measurement is a statement concerning $S + M$, and should describe how the state of S is related to certain properties of the state of M (namely, the positions of a certain pointer, since the observer reads these). Moreover, it is rather arbitrary whether or not one includes the observer in M, and replaces the relation between the S state and the pointer positions in M by the relations of this state and the chemical changes in the observer's eye or even in his brain (i.e., to that which he has "seen" or "perceived"). . . . In any case, therefore, the application of [Process] 2 is of importance only for $S + M$. Of course, we must show that this gives the same result for S as the direct application of [Process] 1 on S. If this is successful, then we have achieved a unified way of looking at the physical world on a quantum mechanical basis.[17]

Von Neumann's "Process 1" and its relevance to the modern decoherence-based interpretations of quantum mechanics will be explored further in chapter 3. For now, let us return to his more general thesis that an ontologically coherent interpretation of quantum mechanics requires that both measuring apparatus and measured system be treated quantum mechanically. Though von Neumann's proposal would seem warranted by an ontology of fundamentally interrelated facts, the overwhelming complexity of a quantum mechanically described macroscopic measuring apparatus would entail calculations far too unwieldy, if not impossible, to be employed in practice. This criticism, however, cannot be taken as a sensible argument against his proposal; for the notion of necessarily interrelated facts as ontologically fundamental was induced *from* quantum mechanics by virtue of the fact that the formalism presupposes this notion. As mentioned earlier, quantum mechanics does not account for the existence of facts, nor can it, since a quantum mechanical description of a measurement interaction presupposes the existence of facts. By the same token, quantum mechanics does not *explain* the interrelation of facts; it presupposes this interrelation, and though it *describes* this interrelation, it cannot *account* for it. To fault quantum mechanics for its inability to explain the existence of necessarily interrelated facts presupposed by the mechanics is as unreasonable as to fault classical mechanics for its inability to explain the existence of matter, similarly presupposed. The notion of matter as ontologically fundamental was an induction made from classical mechanics and its description of matter; and the notion of necessarily interrelated facts as ontologically fundamental is an induction made from quantum mechanics and its description of these facts.

The conceptual advantage of von Neumann's approach is that it exemplifies the fundamental ontological concept that the process by which facts are interrelated should pertain to *all* facts—not just those facts which are arbitrarily "isolated," constituting that which is measured. The Schrödinger equation, which describes this interrelation, should apply to the facts comprised by the measuring apparatus as well as to the facts comprised by that which is measured. And, by implication, the facts comprised by the person observing (or "measuring" or "experiencing") the measuring apparatus should, by their interrelations with the facts of the apparatus and the system measured, also evolve according to the Schrödinger equation during the measurement interaction. Again, if the Schrödinger equation were used to describe the evolution of such a so-called von Neumann chain of interrelated facts, the calculations required would be entirely unmanageable; but conceptually, such a chain of interrelated facts is quite reasonable given the ontological inductions made thus far—and quite necessary if these inductions are to be coherent and consistent.

Von Neumann's program exemplifies the requirement, for the sake of ontological coherence, that the quantum mechanical interrelation of facts be universal, such that when we treat the measuring apparatus as a classical object as physicists do in practice, it is explicitly understood that the classicality of the apparatus is not an ontological characterization, but merely a conceptual abstraction from its more fundamental description as an ensemble of interrelated facts, which are themselves interrelated with the facts pertaining to that which is measured. So that when it seems as though the apparatus as a classical object, separated from that which it measures, somehow affects that which it measures, one is able to dispense with the abstraction and reclaim the underlying, ontologically fundamental notion of mutually and necessarily interrelated facts as the ultimate constituents of nature.

Closed Systems

We should recall, however, that treating the measuring apparatus as a classical object—whether as an abstraction from a more fundamental ontological conception, or as a "complementary" way of subjectively coordinating our experiences of a more fundamental "hypersensible reality"—is not merely to make the Schrödinger equation manageable; it is to make the Schrödinger equation applicable at all. For as mentioned earlier, the Schrödinger equation can be applied only to a classically "closed" system, and it is the treatment of the measuring apparatus as a classical object, isolated from that which it measures, which effectively renders the system measured "closed." It is, in this sense, difficult to suppose how an ontology based on mutually, necessarily interrelated facts can accommodate the requirement that *some* facts—those constituting the arbitrarily defined closed system—are incapable of interrelations with other facts. And since the Schrödinger equation lies at the heart of quantum mechanics, from which we have drawn our ontological inductions thus far, the coherence of these inductions depends upon their accommodation of this equation. For it is this equation that describes the mechanics of the interrelations among facts in a measurement interaction, and most significantly, it qualifies these relations as causally efficacious; without this qualification, then, quantum mechanics would be rendered utterly incapable of describing our experiences of physical causality.

The means by which a closed system can be abstracted from ontologically fundamental interrelated facts is quite simple, however, and is no threat at all to the coherence of this ontology; in fact, it is the requirement that the ontology *be* coherent and universal which provides the solution, already alluded to by von Neumann: If reality fundamentally consists of necessarily and mutually interrelated facts, then the only closed system capable of accommodation by such an ontology is, of course, the system of *all* facts. This would mean that the interrelations of *some* facts in a measurement interaction somehow entail the interrelations of all facts—that is, the entire universe. It would require, in other words, that even facts which are neither measured nor measuring—facts belonging to the "environment" englobing the measurement at hand—play some role in the quantum mechanical measurement of selected facts. Every quantum mechanical measurement, then, somehow must be thought to involve the entire universe—an implication, as indicated before, stressed by advocates of the decoherence-based interpretations of quantum mechanics that will be explored in chapter 3.

But even von Neumann's proposal to treat the measuring apparatus quantum mechanically as an ensemble of interrelated facts was sufficient to render the calculations unmanageable. It therefore seems inconceivable that the experimental environment—let alone the entire universe—must be accounted for quantum mechanically as facts interrelated with the facts of the system measured and the measuring apparatus—particularly since the environment, unlike the measuring apparatus, seems to play no appreciable role in the orthodox quantum formalism. Although the universal interrelation of all facts is entirely justified as an implication of the ontological inductions made from quantum mechanics thus far, it is natural that those physicists who would embrace such inductions would want to see this implication exemplified functionally somehow by quantum mechanics itself. And indeed, as physicists, Griffiths, Omnès, Gell-Mann, Żurek, and their like-minded colleagues stress the *physical* necessity of this implication—the quantum mechanical *function* of the interrelation between "environmental" facts and facts comprised by the system measured and the measuring apparatus—more than they do the philosophical necessity. And for them, environmental facts not only play a role in quantum mechanics, but a crucial role.

At this stage of the discussion, however, it will be helpful to emphasize that this notion of the universe as the only "closed system" involves an equally crucial conceptual innovation—one that is the hallmark of those interpretations of quantum mechanics which embrace this concept of "closed system": The "environment," via its necessary interrelations with all other facts, is thus able to "make measurements" as well as any apparatus or human observer, and indeed does so continuously given the necessary interrelations of all facts within the closed system of the universe. Whereas "measurement" was typically characterized either tacitly or explicitly anthropically as the interrelations among facts comprised by a human-observed "measuring apparatus" and facts comprised by a "measured system," the necessary interrelations of all facts within a closed system not only bring the facts comprised by the environment into play; the "measurement" of one "object" (subsystem of facts) by an "apparatus" (another subsystem of facts) in any given experimental procedure is now seen as a specific exemplification of the mutual interrelations among all facts, including those belonging to the environment, in the wider closed system.

This, of course, provides welcome relief to those who would lament that quantum mechanics entails the intrusion of necessary human subjectivity into physics; "facts as *consequent of* measurement" in quantum mechanics implied, for some, that facts would not exist at all unless measured by an observer—that the moon would exist with precise factual qualities such as position, size, shape, only when observed, or that a cat in a closed box containing a vial of poison that may or may not have spilled is somehow neither "factually alive" nor "factually dead" until the box is opened and the cat is observed. When the universe is properly considered as a closed system, however, one is able to acknowledge the interrelations between the cat and moon subsystems with facts environmental to these subsystems: Photons from the universal microwave background radiation are scattered off the moon, thus continuously "measuring" it; the molecules of the box interact with the cat as well as with the outside world, so the cat is similarly in a constant state of "measurement." Whereas a classical ontological conception of the cat, or any other item in the universe, characterizes it as an object which endures measurement (or the lack thereof), the ontological conception suggested by quantum mechanics characterizes the cat as a subsystem of facts in a state of perpetual creation by their interrelations with all other facts in the universe—a universe which, by the same process, is therefore itself in a perpetual state of creation. The classical conception of material existence thus becomes an abstraction from a more fundamental conception of creative factual interrelations.

In the closed system of the universe, all facts are interrelated, and therefore the interrelations of some facts—the measurement of one subsystem by another—necessarily entails interrelations with facts environmental to these subsystems. This "environmental monitoring" of measured systems in quantum mechanics is, as mentioned before, more than conceptually significant as regards the ontological coherence it affords to quantum mechanics; it is also directly and pragmatically reflected in the mathematical formalism of the mechanics, from which further interesting ontological inductions and hypothetical deductions such as those suggested in the paragraph above can be made, and that will be explored later in chapter 3.

Leaving aside, for the moment, the formal quantum mechanical function of the interrelations between environmental facts and facts belonging to the system measured and the measuring apparatus, it is clear that consideration of the universe as the only truly closed system affords quantum mechanics a genuine ontological coherence and consistency only approximated or vaguely suggested by other interpretations. It is a coherence and a consistency far more substantial, for example, than that supposedly provided by Bohr's principle of complementarity, with its arbitrary dividing line demarking nature's quantum and classical essences as we experience and coordinate them via quantum and classical mechanics, respectively. And yet it must be emphasized that quantum mechanics does not merely entail the mutual interrelations among all facts comprised by the universe as the singular "closed system"; rather, quantum mechanics entails the interrelation of all facts antecedent to a *given measurement interaction* with facts subsequent to and, by the Heisenberg uncertainty relations, consequent of, this *particular* measurement interaction. Quantum mechanics, then, describes the interrelations among facts comprised by a closed system—the universe—such that these interrelations are always (i) productive of a consequential novel fact (the measurement outcome); and therefore (ii) always *relative to that consequential novel fact*, such that the novel fact in production is consequentially related with all facts antecedent to it.

The Ontological Significance of Potentia

Since, however, it is the *production* of a consequent novel fact—that is, a measurement outcome—that is conditioned by its interrelations with antecedent facts, and not the factual outcome itself (for as a "fact," a measurement outcome is already settled, "objectively real," and cannot be conditioned, influenced, altered, or undone), an ontology based on mutually related facts requires an additional innovation—the concept of a *potential* fact. Potential facts as mathematical components of the quantum formalism provide the means by which the creation of a novel fact, such as a measurement outcome, can be causally related with antecedent facts in quantum mechanics.

Heisenberg, in his analysis of the ontological significance of quantum mechanics, insists upon the fundamental reality and function of potentia in this regard. For him, potentia are not merely epistemic, statistical approximations of an underlying veiled reality of predetermined facts; potentia are, rather, ontologically fundamental constituents of nature. They are *things* "standing in the middle between the idea of an event and the actual event, a strange kind of physical reality just in the middle between possibility and reality."[18] Elsewhere, Heisenberg writes that the correct interpretation of quantum mechanics requires that one consider the concept of "probability as a new kind of 'objective' physical reality. This probability concept is closely related to the concept of natural philosophy of the ancients such as Aristotle; it is, to a certain extent, a transformation of the old 'potentia' concept from a qualitative to a quantitative idea."[19]

Quantum mechanics thus becomes characterized as the mechanics of interrelations among facts—among "actualities"—toward the production of novel actualities (i.e., measurement outcomes), and these interrelations are mediated by potentia—the real "things" upon which the mechanics operate. Therefore, a coherent ontology induced from quantum mechanics as suggested by Heisenberg in the preceding quotations presupposes not one but two fundamental constituents of nature—two species of reality: (i) necessarily interrelated facts, or "actualities"; (ii) potential facts, or "potentia," which provide the means by which a novel fact is causally interrelated with the facts antecedent to it. One would expect that if potentia are, indeed, one of the two fundamental species of reality implied by quantum mechanics, that potentia and their ontological function would find some exemplification in the quantum formalism. And they do, in the form of the matrix of probabilities yielded in a quantum mechanical measurement interaction. These probabilities, terminal of every quantum mechanical measurement interaction, are understood to be potential outcomes—potential facts which will be constitutive of the measured system after measurement.

When one speaks of the "state" of a system, one is referring to a maximal specification of these facts, so that in quantum mechanics one is concerned with (i) the initial, actual state of the system prior to the measurement interaction; (ii) the matrix of mutually exclusive and exhaustive potential outcome states predicted by quantum mechanics, each of whose propensity for actualization is valuated as a probability; and (iii) the actual, unique outcome state observed at the end of the measurement. It is always the case that only a single outcome state is ever observed—that only one potential outcome state ever becomes actual in any given measurement interaction. But it is also the case that the "actualization" of this unique potential outcome lies beyond the scope of quantum mechanics, which yields only a matrix of probable outcomes and never a singular, determined outcome. This difficulty is typically referred to as the "problem of state reduction" or the "problem of the actualization of potentialities."

One might connote in these two terms the idea of a physical, dynamical reduction mechanism which should be thought to operate upon the matrices of potentia yielded by a quantum mechanical measurement interaction. For if potentia are indeed ontologically significant—that is, "real"—there should be, it has been suggested, some equally "real" physical mechanism describing their dynamical evolution to a unique, actual state, in the same way that the Schrödinger equation describes the dynamical evolution from the initial, unique, actual state to the matrix of potential outcome states. Quantum mechanics, by such an argument, is therefore incomplete and in need of augmentation. Some physicists have developed a variety of proposals to this end—stochastic and nonlinear modifications of the Schrödinger equation intended to account mechanically for the actualization of potentia. The ontological implications of some of these programs will be explored presently, but for now it is enough to note that these proposed remedies for the incompleteness of quantum mechanics were inspired by the belief in the ontological significance of potentia as suggested by Heisenberg. The difficulty is that these proposals treat potentia as though they were actualities, conflating the two concepts such that the Schrödinger equation is interpreted as producing "coexistent" *actual* alternative measurement outcomes that must, then, be physically and dynamically reduced to a single outcome.

The conceptual difficulties produced by such conflation of actuality and potentiality in quantum mechanics were most notably forewarned by Schrödinger himself in his infamous "cat" hypothetical, conveyed in a brief paragraph of his 1935 essay *"Die gegenwartige Situation in der Quantenmechanik."*[20] A cat, placed in a box, is subjected to a procedure wherein it will either live or die as a result. A quantum mechanical measurement of the cat, then, yields a matrix of two probability outcomes. The problem of state reduction manifests here in two questions: (i) If quantum mechanics is ontologically significant, then the matrix of two probability outcomes yielded (cat-alive and cat-dead) must be ontologically significant; if this is so, then why do we never experience the monstrosity of a live-dead cat superposition terminal of a quantum mechanical measurement? (ii) Since a quantum mechanical measurement of the cat yields such a matrix or superposition of coexisting states, yet observation always yields a unique state wherein the cat is always either dead *or* alive and never both, what is the *physical mechanism* by which the superposition or matrix of coexistent, "real" states is reduced to a unique "real" state, and when is this mechanism effected? Many physicists have concluded that, as mentioned earlier, the Schrödinger equation requires modification to account for this elusive mechanism; for unless one were inclined to assign the same ontological significance to "potentia" as is assigned to "actualities" in classical mechanics, one must interpret the matrix of probable outcome states yielded by quantum mechanics as a matrix of coexisting actual states.

The conception of potentia as a separate species of reality—ontologically, rather than merely epistemologically significant—has not been widely embraced by physicists biased toward a classical ontological accommodation of quantum mechanics. And indeed, most of the proposed solutions to the problem of state reduction entail attempts to fit quantum mechanics into a classical ontological framework. Many of these attempts have proven to be extremely unappealing because they either entail presuppositions even more radical than the concept of "real" potentia suggested by Heisenberg and championed by Popper, or because they have been experimentally disconfirmed. They are, nevertheless, important to any exploration of the ontological significance of quantum mechanics, for they have helped to disclose the standards of coherence, logical consistency, empirical applicability, and empirical adequacy sought after in its interpretation.

The particular classical, materialist ontological interpretations of quantum mechanics referred to above characterize the matrix of probable measurement outcomes as a set of coexistent, actualized (classically real) alternatives, the superposition of which is dynamically reduced by some physical process to yield a unique actuality. The proposal of Eugene Wigner is representative of this approach to state reduction. For Wigner, the continuous evolution of the state of the measured system as described by the Schrödinger equation is inconsistent with the seemingly discontinuous actualization of a unique outcome state. He suggested that this inconsistency might be remedied by a nonlinear modification of the Schrödinger equation, which would account for a dynamical mechanism by which the matrix of alternative real states is discontinuously reduced to a single state. Wigner further suggested that the mechanism described by this nonlinear modification might even be attributed to the influence of the mind of the observer upon that which is measured, which would account for why we never observe superpositions or matrices of alternative states in nature; for the act of observation itself *is* the nonlinear mechanism causative of state reduction.[21] One finds a similar conclusion given by Walter Heitler, who wrote: "One may ask if it is sufficient to carry out a measurement by a self-registering apparatus or whether the presence of an observer is required." Heitler concluded that "the observer appears, as a necessary part of the whole structure, and in his full capacity as a conscious being."[22]

It should be stressed that despite occasional assertions to the contrary, Heisenberg did not ultimately hold this view as an appropriate induction from quantum mechanics. For Heisenberg, again, potentia are ontologically significant constituents of nature that provide the means by which the facts comprising the measuring apparatus and the facts comprising the system measured (as well as those comprising the environment) are interrelated in quantum mechanics: "The transition from the 'possible' to the 'actual' takes place," he writes, "as soon as the interaction of the object with the measuring device, and thereby with the rest of the world, has come into play; it is not connected with the act of registration of the result by the mind of the observer."[23] The conflation of Heisenberg's ontological inductions and those of Wigner, Heitler, and others is, however, understandable; for Heisenberg's ontologically innovative contribution to the Copenhagen Interpretation was amalgamated with the severe epistemic sanctioning of Bohr's worldview. Heisenberg thus interprets the matrix of probable outcome states not as an objective integration of potentia—despite his belief that potentia are "real" in the Aristotelian sense—but rather as a mathematical representation of *our incomplete knowledge* of the evolution of the measured system. Though he clearly holds that, ontologically, the integration of potentia is productive of, and will "reduce to," a unique actuality, the density matrix itself is, for Heisenberg, merely an epistemic reflection of these potentia. And the discontinuous reduction of the density matrix is, likewise, an epistemic reflection of an increase in one's knowledge of the facts that have actualized. Heisenberg explains that although the ontological actualization of potentia is not driven by any physical mechanism associated with the conscious registration of the actualized by the mind of the observer, "the discontinuous change in the probability function, however, takes place with the act of registration, because it is the discontinuous change of our knowledge in the instant of registration that has its image in the discontinuous change of the probability function."[24] Heisenberg's concept of potentia thus seems to imply both an unavoidable subjectivity veiling nature and, at the same time, her reliable objective reality. Patrick Heelan explains this dual function thus:

> The objective tendency or *potentia* . . . is on the one hand *not* simply the thing-in-itself in the external world, *nor* on the other hand is it simply the transcendental ego; it bridges both the external world and the transcendental subjectivity of the knower. As Heisenberg wrote in the *Martin Heidegger Festschrift* (1959), "the search for the natural laws of the [ultimate structure of matter,] entails the use of general principles of which it is not clear whether they apply to the empirical behaviour of the world or to *a priori* forms of our thought, or to the way in which we speak."[25]

Most of the confusion with respect to Heisenberg's concept of potentia and its dual implication of subjectivity and objectivity in nature has to do with the habitual classical tendency to apply the fundamental mediative function of potentia solely to facts belonging to (i) "measured system" and (ii) "measuring apparatus"—that is, the classical "object" and "subject"; the result is that the broader, more accurate role of potentia is overlooked. For a coherent ontological interpretation of quantum mechanics reveals that most fundamentally, potentia are mediative of *facts*, whether they belong to the measured system, the measuring apparatus, the human observer, or the universal environment—for all are subsumed by the singular closed system of the universe. It is not the subjective interaction of "human" facts with object "measured system" facts that somehow alters or actualizes the latter; it is, rather, the interrelations among all facts relative to a given fact or subsystem of facts, which are productive of potentia which will evolve to become novel facts. With their most fundamental role in mind, then, it is clear that Heisenberg's potentia are not indicative of a fundamental subjectivity pervading nature, but rather a fundamental relativity.

For many, Heisenberg's epistemological interpretation of the density matrix has overshadowed and obfuscated the ontological implications he proposed—the reality of potentia and the idea that novel actualities are somehow produced by a process involving the integration and valuation of these potentia. The conflation of his interpretation of state reduction and those of Wigner, Heitler, and others, is an unfortunate consequence of this obfuscation, but understandable in light of it. Much theoretical work has been done in recent years, however—proposals by several physicists mentioned earlier, such as Roland Omnès, Robert Griffiths, Murray Gell-Mann, and Wojciech Żurek, to name a few—which begins with Heisenberg's ontological interpretation of potentia. These theories then depict, explicitly, the evolution of the state of a measured system—the integration and valuation of the potentia associated with this system—as an ontological process, rather than merely an epistemological representation of an underlying ontology, as given by Heisenberg. These interpretations will be explored more fully in the following chapter, but they are mentioned here to suggest that the ontological characterization of state reduction implied by Wigner and Heitler, wherein the density matrix is depicted as an integration of coexisting actualities reduced by some physical mechanism to a unique actuality, is not the only ontological characterization that physicists have considered. For the depiction of the density matrix as an integration of coexisting actualities, though it would certainly render quantum mechanics ontologically significant, exacts a price many physicists are unwilling to pay—the implication that until the box containing Schrödinger's cat is opened, the cat exists as a superposition of two alternative, yet equally actual states.

Yet for many physicists, this price is entirely reasonable given the undeniable value of an ontological interpretation of quantum mechanics. The "Continuous Spontaneous Localization" theory of GianCarlo Ghirardi, Alberto Rimini, and Tulio Weber (GRW), based on early work by Phillip Pearle in the 1970s, also treats the superposition of states yielded by the Schrödinger equation as a superposition of actual physical states, upon which there should operate some physical mechanism causative of reduction to a unique state such that macroscopic superpositions like Schrödinger's cat are extremely short-lived. Like Wigner, GRW propose a modification of the Schrödinger equation to this end; but whereas Wigner proposed a characterization of state reduction as ultimately discontinuous via a nonlinear modification, the spontaneous localization theory characterizes state reduction as ultimately continuous, via a linear modification. The proposed mechanism for unitary reduction represented by this modification is a stochastically fluctuating field, which continuously and spontaneously "collapses" the superposition of states into a unique state.[26] Where particle density is high, as in the case of a macroscopic object such as a cat, these stochastic field fluctuations cause extremely rapid collapses such that, according to John Bell, "any embarrassing macroscopic ambiguity in the usual theory is only momentary in the GRW theory. The cat is not both dead and alive for more than a split second."[27] However, the disconcerting ontological implications of the cat's being simultaneously alive and dead at all, even if for only a split second, cannot be overlooked. Among other difficulties is the implied double-violation of the logical principles of non-contradiction and the excluded middle—violations which undermine one of the first principles of modern science: the presupposed correlation of causal relation and logical implication.

And indeed, the spontaneous localization theory of GRW is intended to be ontologically significant given that it purports to specify "the physical reality of *what exists out there*"[28] according to Ghirardi. The spontaneous localization theory is to provide, he writes, "a mathematically precise formalism allowing a unified description of all phenomena, containing a single fundamental dynamical principle that governs all processes."[29] Thus, the theory not only implies the coexistence of alternative versions of entities like Schrödinger's cat, even if only for a split second; even more troubling, it entails an ontology whose "fundamental dynamical principle" is the continuous destruction of most of these entities. Indeed, it would seem that any interpretation of quantum mechanics that treats the density matrix as comprising, against Heisenberg's admonition, coexisting, alternative actualities rather than coexisting potentia, would require an ontological principle whereby the vast majority of these entities are destroyed—whether continuously, per GRW's proposal, or discontinuously, per Wigner's proposal.

The "Relative State" interpretation of Hugh Everett—often referred to as the "many worlds interpretation"[30]—purports to avoid this troubling ontological implication. It is similar in its treatment of the density matrix as an amalgam of coexisting, actual alternative states; but whereas the interpretations discussed earlier proposed the need for a physical mechanism to reduce this matrix to a unique state, Everett suggests that no such mechanism or modification of the Schrödinger equation is necessary, given that the concept of a single unique outcome state is itself unnecessary. We never experience a superposition of equally real alternative states because each alternative state can be thought of as a unique outcome state occurring in its own relative universe. An alternative state is, in this way, always relative to its particular universe in the same way that a temporal duration, by the theory of special relativity, is always relative to its particular inertial frame.

A key advantage of Everett's proposal is that it provides a conceptual account of the correlations between the facts comprised by the measuring apparatus and those comprised by the system measured; like von Neumann, Everett suggests that both the apparatus and the system measured evolve quantum mechanically. But whereas von Neumann was unable to account for the correlations between the separate evolutions of the system and apparatus, Everett is able to do so by virtue of the fact that each probable system outcome, and its correlated apparatus outcome, occurs in the same "relative universe." One universe contains a live cat, correlated with an observer who sees a live cat, and another universe contains a dead cat, correlated with an observer who sees a dead cat.

Though Everett's proposal avoids the implicit ontological principle by which most coexistent, alternative entities must be destroyed, there remains the difficulty of accepting an ontology that entails that there be multiple "copies" of oneself—an ontology where there is no distinction between potentiality and actuality. Such an implication is arguably far more radical and philosophically problematic than that suggested by Heisenberg, wherein potentia are fundamentally "real," though not "actual," constituents of nature. Indeed, an ontology where everything that can happen does happen renders meaningless the idea of things that *should* happen. "If such a theory were taken seriously," writes John Bell, "it would hardly be possible to take anything else seriously. So much for the social implications."[31]

Common to all these proposals and a great many others is the conflation of actuality and potentiality symptomatic of any attempt at a classical accommodation of quantum mechanics. The "reality" of the alternative probability outcomes yielded by quantum mechanics is indeed acknowledged in these theories, but it is reality as classically defined—reality monopolized by actuality—such that Schrödinger's cat in its bizarre live-dead superposition is necessarily as real as any other cat. Heisenberg's conception of potentia as ontologically significant, fundamental constituents of nature answers this mischaracterization, such that the matrix of alternative states yielded by quantum mechanics is a matrix of coexisting *potential*—but nevertheless *real*—states, not a matrix of coexisting actual states. For Heisenberg, the concept of potentia, then, constitutes, in his words,

> a first definition concerning the ontology of quantum theory. . . . One sees at once that this use of the word "state," especially the term "coexistent state," is so different from the usual materialistic ontology that one may doubt whether one is using a convenient terminology. . . . One may even simply replace the term "state" by the term "potentiality"—then the concept of "coexistent potentialities" is quite plausible, since one potentiality may involve or overlap other potentialities.[32]

The problem of state reduction thus becomes redefined: The question is no longer, "What is the mechanism by which a unique actuality physically evolves from a matrix of coexistent actualities?" but rather, "What is the mechanism by which a unique actuality evolves from a matrix of coexistent potentia?"

The answer to that question can be found in the quantum formalism itself: The matrix of states yielded by quantum mechanics is not merely a matrix of potential states; they are, rather, mutually exclusive and exhaustive *probable* states. That is to say, they are a *selection* of potential states that have evolved, via the Schrödinger equation, to become probabilities—that is, potentia qualified by a valuation between 0 and 1, such that together, these probable states represent mutually exclusive and exhaustive potential outcomes, satisfying the logical principles of non-contradiction and the excluded middle, respectively. Thus one (and only one) outcome *must* occur. Unlike purely potential outcomes, then, probability outcomes clearly presuppose and anticipate the necessary actualization of a unique outcome; for without such an outcome, the concept of a probability itself is utterly meaningless. In this sense, the actualization of potentia is less a physical, dynamical function of quantum mechanics than it is a conceptual function logically presupposed by the mechanics.

As stated earlier, to attempt to account for the existence of facts via a mechanism that presupposes their existence is logically untenable. Nevertheless, the inability of quantum mechanics to account for a *unitary* evolution from a pure-state superposition to a unique measurement outcome—rather than to a matrix of alternative probable outcomes—is considered by many physicists to be a defect of the formalism, or as we have seen in the examples above, at least a problem that should be solved. Against such objections, we may simply recall the previously cited analogy suggested by Murray Gell-Mann: When one wishes to predict the probability of a horse winning a race, one necessarily presupposes (i) the fact of the horse (and everything else the race entails) antecedent to the race; and (ii) the fact of the horse's winning, or losing, at the conclusion of the race. In the same way, quantum mechanics cannot account for the existence of facts, given that (i) quantum mechanics presupposes their existence antecedent to the measurement interaction—facts which account for that which is to be measured, as well as the apparatus which will perform the measurement; and (ii) quantum mechanics *anticipates* their existence, via the yielded mutually exclusive and exhaustive probability outcomes, subsequent to and consequent of the measurement interaction.

Put simply, quantum mechanics does not describe the actualization of potentia; it only describes the *valuation* of potentia. The answer to the problem of state reduction is thus at once as simple and as elusive as the "problem" of the three interior angles of a triangle adding up to 180 degrees, or the "problem" of the existence of the universe in classical mechanics. In the case of the latter, most cosmologists have found it much more interesting to simply logically stipulate the existence of the primordial $t = 0$ initial conditions of the universe, in whatever form it may have had, and focus instead on the mechanics describing how those initial conditions have evolved to become what the universe is today, and thus glean what it might become tomorrow. Similarly, in quantum mechanics, the "problem of the actualization of potentia," or more generally, the problem of the existence of facts, is far less interesting than the mechanics that describe how facts are causally productive of potentia, and how these potentia evolve to become valuated probabilities subsequently and consequently anticipative—and somehow creative—of novel facts.

Notes

1. A. Shimony, "Search for a Worldview Which Can Accommodate Our Knowledge of Microphysics," in *Philosophical Consequences of Quantum Theory: Reflections on Bell's Theorem*, ed. J. Cushing and E. McMullin (Notre Dame, Ind.: Notre Dame University Press, 1989), 27.

2. Murray Gell-Mann, *The Quark and the Jaguar: Adventures in the Simple and the Complex* (New York: W. H. Freeman, 1994), 141.

3. John Bell, "Against Measurement," in *Sixty-Two Years of Uncertainty: Historical, Philosophical, and Physical Inquiries into the Foundations of Quantum Mechanics*, ed. Arthur I. Miller (New York: Plenum, 1990).

4. Quantum mechanics is often interpreted as an incomplete classical theory, for example, where probability, nonlocality, and entanglement are ontologically insignificant epistemic artifacts. These artifacts are consequential of our inability to account for a continuum of classically deterministic "hidden variables," which would otherwise complete the theory. Max Born, in this spirit, demonstrated how quantum mechanical probability outcomes can be equated with classical statistical probability outcomes. This purely classical, statistical interpretation of quantum mechanics has, with respect to nonlocality, since been theoretically disconfirmed by John Bell (J. S. Bell, "On the Einstein Podolsky Rosen Paradox," *Physics* 1, no. 3 [1964]: 195–200), and later experimentally disconfirmed (A. Aspect, J. Dalibard, and G. Roger, *Phys. Rev. Lett* 44 [1982]: 1804–1807). Various "mostly classical" nonlocal hidden-variables interpretations, such as the one of David Bohm, became newly championed in response to these disconfirmations. Thus the relegation of quantum mechanics to mere epistemic significance by Bohm's interpretation, in defense of classicality, now

depends upon the concept of an etherlike field of point-particles causally influencing each other nonlocally, in flagrant violation of the otherwise classical ontology the interpretation was designed to preserve.

5. Niels Bohr, "Discussion with Einstein on Epistemological Problems in Atomic Physics," in *Albert Einstein: Philosopher-Scientist*, ed. Paul Arthur Schilpp (New York: Harper, 1959), 210.

6. Werner Heisenberg, *Physics and Philosophy* (New York: Harper Torchbooks, 1958), 54–55.

7. K. Popper, *Quantum Theory and the Schism in Physics* (New Jersey: Rowman and Littlefield, 1956), 100.

8. Bohr, "Discussion with Einstein," 210.

9. Niels Bohr, *Atomic Theory and the Description of Nature* (Cambridge: Cambridge University Press, 1934), 1.

10. Niels Bohr, *Atomic Physics and Human Knowledge* (New York: Wiley, 1958), 18.

11. Bohr, *Atomic Theory and the Description of Nature,* 1.

12. To posit an ontological characterization of the world as fundamentally unknowable is, of course, to doom the ontology to incoherence by its own reasoning, reducing it to the paradox of Epimenides. An admonition from Whitehead comes to mind: "The requirement of coherence is the great preservative of rationalistic sanity. But the validity of its criticism is not always admitted. If we consider philosophical controversies, we shall find that disputants tend to require coherence from their adversaries, and to grant dispensations to themselves" (*Process and Reality,* 6).

13. Henry P. Stapp, *Mind, Matter, and Quantum Mechanics* (Berlin: Springer-Verlag, 1993), 60.

14. William James, *Pragmatism and the Meaning of Truth* (Cambridge, Mass.: Harvard University Press, 1978), 239.

15. John von Neumann, *Mathematical Foundations of Quantum Mechanics* (Princeton, N.J.: Princeton University Press, 1955).

16. Ibid., 418–420.

17. Ibid., 352.

18. Heisenberg, *Physics and Philosophy,* 41.

19. Werner Heisenberg, "The Development of the Interpretation of the Quantum Theory," in *Niels Bohr and the Development of Physics,* ed. Wolfgang Pauli (New York: McGraw-Hill, 1955), 12.

20. Erwin Schrödinger, "Die gegenwartige Situation in der Quantenmechanik," *Naturwissenschaftern* 23 (1935): 807–812, 823–828, 844–849. English translation, John D. Trimmer, *Proceedings of the American Philosophical Society* 124 (1980): 323–338.

21. E. P. Wigner, in *The Scientist Speculates: An Anthology of Partly-Baked Ideas,* ed. Irving John Good (New York: Basic Books, 1962), 284.

22. Walter Heitler, "The Departure from Classical Thought in Modern Physics," in *Albert Einstein: Philosopher-Scientist*, ed. Paul Arthur Schilpp (New York: Harper, 1959), 194.
23. Heisenberg, *Physics and Philosophy*, 55.
24. Ibid.
25. Patrick Heelan, S.J., *Quantum Mechanics and Objectivity* (The Hague: Martinus Nijhoff, 1965), 151.
26. G. Ghirardi, A. Rimini, and P. Pearle, in *Sixty-Two Years of Uncertainty*, ed. A. Miller (New York: Plenum, 1990), 167, 193.
27. John Bell, *Speakable and Unspeakable in Quantum Mechanics* (Cambridge: Cambridge University Press, 1987).
28. G. Ghirardi, in *Structures and Norms in Science*, ed. M. L. Dalla Chiara et al. (Dordrecht: Kluwer Academic, 1997).
29. G. Ghirardi, *Physics Today* (Letters) April 1993: 15.
30. Hugh Everett III, *Rev. Mod. Phys*. 29 (1957): 44. See also B. S. DeWitt and N. Graham, eds., *The Many Worlds Interpretation of Quantum Mechanics* (Princeton, N.J.: Princeton University Press, 1973).
31. Bell, *Speakable and Unspeakable in Quantum Mechanics*, 159–168.
32. Heisenberg, *Physics and Philosophy*, 185.

3

The Evolution of Actuality to Probability

IF, AS HEISENBERG SUGGESTED, potentia indeed constitute an ontologically fundamental species of reality, then the mathematical representation of the quantum mechanical evolution of the matrix of potentia to the matrix of probabilities—that is, the valuation of potentia as probabilities between zero and one—ought to be heuristically useful in understanding the ontological implications of this evolution. The mathematical representation should prove helpful in visualizing not only the process described by quantum mechanics but also, as we shall see in the following chapters, the process described by Whitehead. The basic formalism introduced and explored in this chapter is intended to be comprehensible to readers unfamiliar with mathematics. Some familiarity with the Pythagorean theorem and the addition of vectors will be useful, but not necessary.

THE FORMAL DESCRIPTION OF QUANTUM MECHANICAL STATE EVOLUTION

As mentioned earlier, we refer to the "state" of a system as a maximal specification of the facts or actualities comprised by the system. (These facts/actualities are typically referred to by physicists as "observables" or "collective observables," even though most are, for all practical purposes, unobservable; for this reason, we will use the terms "facts" and "actualities" instead.) For the sake of simplicity, let us consider an idealized system consisting of nothing other than an old-fashioned traffic signal—the type with two lights, red and green. Let us further suppose that the signal always functions normally, such that neither of the lights is burned out and that both will never be illuminated simultaneously. And finally, let us ignore everything other than the status of the two lights—the wiring, the casing, and so on—such that the state of our idealized traffic-light system entails but one fact: The status of the signal, which is either green or red.

The state of any system in quantum mechanics is represented by a vector of unit length in Hilbert space—an abstract linear vector space that, in our idealized example, can be depicted via a simple *x–y* Cartesian coordinate system. The benefit of using Hilbert spaces in quantum mechanics is that these spaces are capable of representing, in a mathematically useful way, potentia as well as actualities and their relationship in a given system. This representation is based on two simple principles:

(i) Every physical system can be represented by a unique Hilbert space $\mathscr{H}_s$, and the state S of a given physical system (again, "state" being the maximal specification of the facts/actualities/observables associated with the system) can be represented by a single vector $|u\rangle$ of unit length in the system's Hilbert space.

(ii) In a measurement interaction involving the system, there is a one-to-one correspondence between the number of probability-valuated outcome system states and the number of dimensions comprised by the Hilbert space.

In the case of our highly idealized traffic-light system, which has two potential states S, then, the associated Hilbert space has only two dimensions: One represents "S = *green*," and the other "S = *red*." This particular two-dimensional Hilbert space is therefore easily represented by simple *x–y* coordinate axes, where a vector of unit length $|u_{green}\rangle$ along the *x*-axis represents "S = *green*" and a vector of unit length $|u_{red}\rangle$ along the *y*-axis represents "S = *red*."

As regards our idealized system, one can at this point see the logical need for Principle 2: It guarantees, in satisfaction of the logical principles of non-contradiction and the excluded middle, that there exist *some* potential states that are mutually exclusive and exhaustive, as represented by the mutual orthogonality of the *x* and *y* dimensions (where "mutually orthogonal vectors" are vectors at right angles to one another). To generalize this somewhat, we can say that in a Hilbert space of *n* dimensions, there are only *n* mutually orthogonal vectors, representing only *n* mutually exclusive states. If, for example, we were dealing with a more modern traffic-signal system with a green, a red, and a yellow light, our Hilbert space would require three dimensions, represented by *x*, *y*, and *z* coordinate axes. It

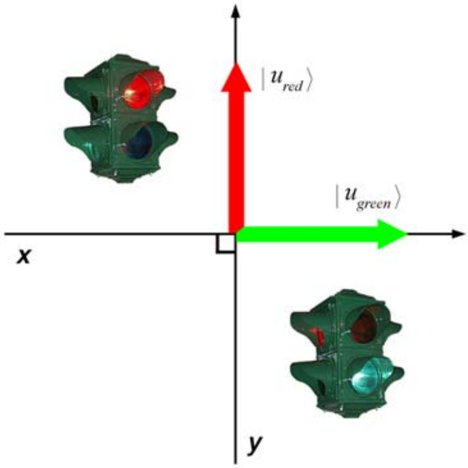

FIGURE 3.1 The two potential states S of a traffic signal represented by orthogonal vectors of unit length in a Hilbert space of two dimensions. The vector $|u_{green}\rangle$ along the *x*-axis represents "S = *green*," and the vector $|u_{red}\rangle$ along the *y*-axis represents "S = *red*."

is only by means of this third dimension that we are guaranteed three mutually exclusive and exhaustive states: S = *green*, S = *yellow*, or S = *red*, represented by the mutual orthogonality of the vectors along the *x*, *y*, and *z* axes. An added benefit of mutually orthogonal vectors representing mutually exclusive and exhaustive states is that such vectors can be grouped so that, as regards a modern traffic-signal system, we can specify the three possible states thus: S is either *green*, represented by $|u_{green}\rangle$, or S is *not green*, represented by the plane formed by $|u_{red}\rangle + |u_{yellow}\rangle$; S is either *red* $|u_{red}\rangle$ or *not red* $|u_{green}\rangle + |u_{yellow}\rangle$; S is either *yellow* $|u_{yellow}\rangle$ or *not yellow* $|u_{green}\rangle + |u_{red}\rangle$.

Such groupings are referred to as "subspaces" of the Hilbert space, and their usefulness becomes readily apparent when considering nonidealized systems with manifold—even innumerable—potential states, each with a multiplicity of associated facts/actualities/observables. Consider, for example, the state of "System *You*" as you read this chapter. As is the case for most physical systems, a maximal specification of the facts/actualities/observables associated with you is far too unwieldy to calculate, so let us focus, as is typically done in quantum mechanics, on just one fact/actuality/observable: the location of System *You* in the universe. We first represent the state of

END OF CHAPTER SAMPLE

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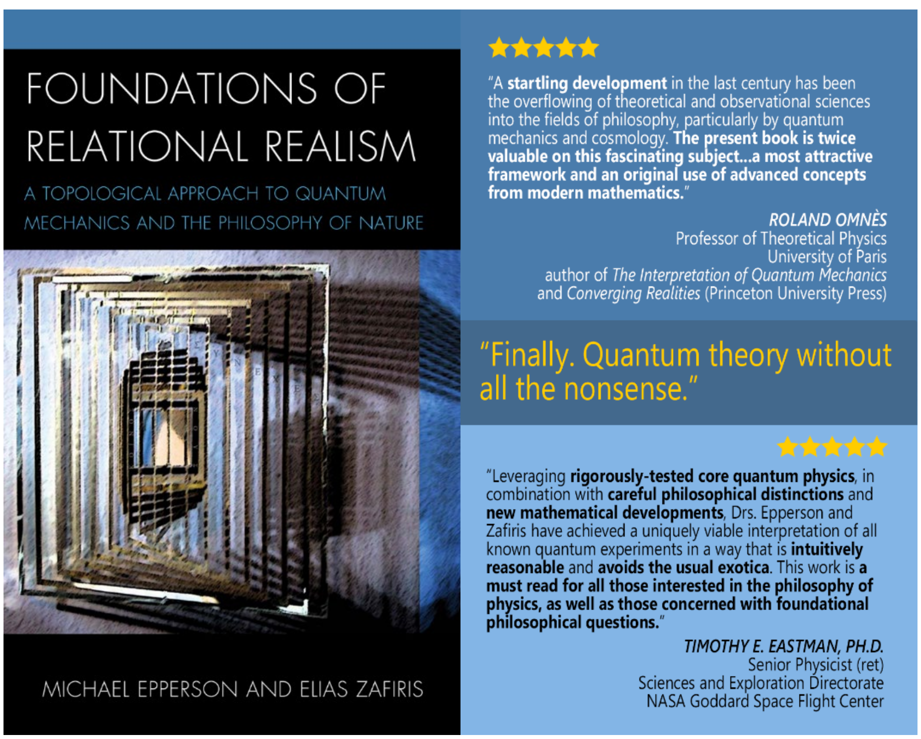

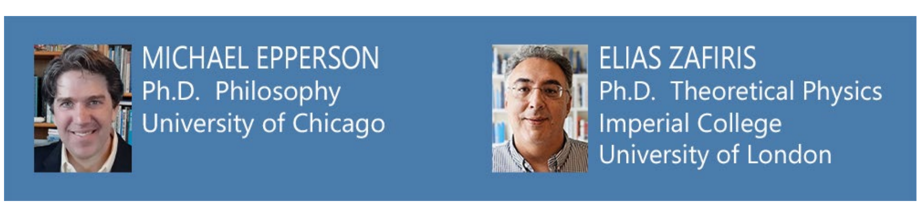

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Interlude

The Philosophy of Alfred North Whitehead

ALFRED NORTH WHITEHEAD was as much a mathematician as he was a metaphysician, and so it should come as no surprise that whereas some have characterized his metaphysical system as intuitive, others have found it to be frustratingly complicated and difficult to understand. If mathematics is indeed intuitively simple at some level, it is because mathematics always abides by the fundamental desiderata of logic, coherence, applicability to human experience, and adequacy in that applicability such that one cannot conceive of a type of experience where mathematics is fundamentally inoperative. These are, of course, the same four desiderata Whitehead assigns to his metaphysics, and the manner in which they are fulfilled by the latter is similar to the manner they are fulfilled by mathematics—a manner demonstrative of a deep complexity but married to a fundamental, intuitive simplicity. This is not to suggest that Whitehead proposed a metaphysical scheme intended to be wholly definable by mathematics (and by implication reducible to mathematics); the significance of these shared desiderata is, rather, the implication that Whitehead's metaphysical scheme might at some level be describable by mathematics.

For both mathematics and Whitehead's metaphysics, the requirement of empirical adequacy is particularly evident in the case of theoretical physics, for which Whitehead's metaphysics was intended to supply a suitable ontological framework. In this sense, the applicability and adequacy of any speculative metaphysical framework intended to accommodate physical phenomena is, for Whitehead, measured in part by its empirical exemplification. The traditional philosophical opposition of the terms "empirical" and "metaphysical," then, is a dualism Whitehead would likely correlate with the Cartesian dualism of matter and mind, the repudiation of which lies at the root of his philosophy. The traditional philosophical notion of "empirical" as understood to mean based upon observation or experience alone without regard for system and theory, then, is not the notion Whitehead intends in his use of the term. Rather, the empirical side of his metaphysical scheme as expressed in the desiderata "applicability" and "adequacy" is to be thought of as the bridge by which the principles of Whitehead's metaphysics are connected with human experience. The soundness of the underlying framework, then, derives not only from the logical and coherent applicability of the metaphysics to distinct, often exclusive realms such as those that define physical and microphysical experiences, but rather from its logical and coherent applicability to human experience itself.

With each passing year, modern physics becomes increasingly relevant to our everyday lives. Breakthroughs in cosmology continually make their way into the morning newspapers, and breakthroughs in technology continually make their way onto our desktops, into our living rooms, into us; and in all of these cases, quantum mechanics has become more and more prominent with each leap forward, as has the need for an ontology capable of accommodating the quantum theory logically, coherently, and adequately. Since his death in 1947, the influence of Whitehead's metaphysics has grown steadily, if not rapidly. And in the coming years, as quantum mechanical phenomena grow to become the very heart of our everyday technology in the form of quantum transistors, superconducting devices, and quantum computers, the popularity of Whitehead's philosophy is likely to undergo a rapid expansion. For the regnant classical mechanical worldview is simply incapable of accommodating quantum mechanical phenomena without glaring paradox, ontological inconsistency, and arbitrary dispensations from important classical mechanical laws and principles. And as these quantum mechanical phenomena grow to become more and more integral to our lives, these paradoxes and inconsistencies will become less and less tolerable.

One goal of the present work is to demonstrate how Whiteheadian metaphysics can be heuristically useful in understanding modern ontological interpretations of quantum mechanics, such that the physics can be interpreted logically, coherently, and empirically adequately as an exemplification of the metaphysics; but just as important is the converse demonstration that modern ontological interpretations of quantum mechanics can be heuristically useful to an understanding of Whiteheadian metaphysics. *Process and Reality,* the opus in which Whitehead's metaphysical system is given in its most complete and systematic form, presents this system in an infamously nonlinear format, wherein the entire scheme is essentially presupposed with each elucidation of a particular aspect. In this sense, rather than proceeding in linear fashion from beginning to middle to end, with each part presupposing its antecedents, *Process and Reality* proceeds in an almost inward-spiraling fashion, each revolution presupposing the overall curvature, with repeated visitation of each quadrant along the way to an ever-retreating center. By mapping a linear treatment of quantum mechanics onto this nonlinear treatment given in *Process and Reality,* I hope to make each treatment mutually illuminative of the other.

For indeed, the overall theme driving Whitehead's metaphysical scheme is the same theme driving modern ontological interpretations of quantum mechanics as discussed in Part I—the repudiation of fundamental mechanistic materialism and the redefinition of such materialism as a mathematical abstraction that ought not be mistaken for a fundamental description of the "concrete" reality of nature. Whitehead refers to this as the "fallacy of misplaced concreteness," and, as discussed in Part I, Heisenberg held a similar view. For Whitehead, classically described objects are more fundamentally described as historical routes of atomic events, where past events influence but do not determine future events. The universe is a multiplicity of such events, each of which evolves or becomes via a process of prehending and integrating all the antecedently actualized events (data) that the universe comprises. Some data are, of course, more relevant than other data; and indeed, most data once brought together by prehension are further integrated largely by elimination. Conceptually, such integration of data through elimination can be thought of in the same sense that mathematical terms brought together in an equation are eliminated through cancellation. The function and importance of these terms as constituents in the equation is in no way vitiated by their cancellation; cancellation is simply the proper mode of their integration with the other terms of the equation.

Most significantly, however, the data prehended, while objectively real, can be objectified by an occasion in any number of potential ways. Data can be objectified by simple reproduction, for example, and Whitehead's Category of Conceptual Reproduction lies at the heart of what we perceive to be the "enduring objects" that dominate our classical worldview—our conceptions of atoms, molecules, rocks, planets, suns; and sometimes the reproductions take a more rhythmic form characteristic of electromagnetic waves, probability functions, and so forth. The Category of Conceptual Reproduction as it applies to macroscopic "enduring objects" is closely associated with Whitehead's Category of Transmutation, whereby manifold microcosmic prehensions of data are "transmuted" into a single, macrocosmic perception of an integrated datum or "collective observable" in the language of quantum physics—a process analogous to looking at a photo in the newspaper and seeing a single image rather than a multiplicity of individual dots.

But data are not always objectified by simple reproduction, nor are their transmutations necessarily inherited from and consistent with antecedent transmutations. Data are also integrated according to the Category of Conceptual Reversion—that is, according to novel potential forms and transmutations that were not simply inherited from the historical route, but instead ingressed into the becoming occasion from somewhere else—from some other actuality apart from that particular historical route. In this way, each occasion, and the societies they form, has the potential for novel growth. Even the most rudimentary electromagnetic occasions enjoy such reversions from time to time, and this is evinced, for example, by indeterministic quantum mechanical phenomena.

For Whitehead, the potentia driving novelty constituted a different species of reality, as they did for Heisenberg—realities that do not derive entirely from some particular antecedent actual datum but rather from a spatiotemporally generic, and therefore primordial, actuality. The fact of any possibility, in other words, necessarily derives from a more fundamental actuality, and this reasoning requires the concept of a supremely fundamental, primordial actuality. In Kant's 1762 work *The Only Possible Ground for a Demonstration of God's Existence*, he argues that this reasoning from *possibility as a consequence* to God's existence as the *ground of this possibility* is the only sound demonstration of the existence of God. And for Whitehead, this same reasoning is central to his own conception of God's necessary existence and relations with the world.

Whitehead was indeed an atomist, then—a realist, but not in the materialist sense; for his atomic actualities are not substances, indivisible and symmetrically interrelated such that their interactions are strictly deterministic and time-reversal invariant (i.e., actualities formative of a clockwork universe); Whitehead's atomic actualities are, rather, individual occasions, asymmetrically related (past occasions being settled, future occasions being open) such that each new occasion embodies a common past and, once actualized, contributes to this past, recreating it by its augmentation of it. The many occasions of the past become one in each new occasion, and are thus increased by one.

Central to Whitehead's atomism, however, is a repudiation not just of fundamental mechanistic materialism, but also of the Cartesian "bifurcation of nature" that typically accompanies it. Mentality and materiality are mutually implicative, interrelated modes of reality for Whitehead, not separate species of reality, one more fundamental than the other. For Whitehead, each atomic occasion is dipolar, with (i) a physical pole that entails the actual occasion's relationship with its antecedent data that are thereby causally efficacious in its becoming—that is, its "public," real physical relations with its universe; and (ii) a mental pole, which entails the actual occasion's evolving forms of definiteness—the "private" workings of reproduction, reversion, transmutation, and other categories that describe the evolution of the occasion from potentiality to actuality (the term "mental pole" should not be misunderstood to imply conscious mentality, however, which in Whitehead's metaphysics is a higher-order function inoperative in the vast majority of actual occasions). For Whitehead, each pole is incapable of abstraction from the other, in the same way that the concept of potentiality is incapable of abstraction from the concept of actuality. The traditional philosophical distinction between primary and secondary qualities of an object is thus replaced by a more subtle and complex scheme revolving around these two interrelated poles of the atomic actual occasion.

For Whitehead, then, these dipolar entities, their relations and their actualizations, are typically analyzed in one of two ways: One way is by "coordinate analysis," where emphasis is given to the physical pole for which relations among occasions are primarily relations of causal efficacy. Coordinate division gives emphasis to the physical pole in the sense that it is in the physical pole that the data of the actual world are initially appropriated according to their nature as concrete, spatiotemporally "coordinated" quanta. Such relations are well described by classical physics, chemistry, biology, and other sciences; coordinations of data according to special relativity, for example, have significance only in the physical pole.

The second type of analysis is "genetic analysis," where emphasis is given to the mental pole. The spatiotemporal coordination of data in the physical pole often manifests as nexūs and societies of occasions whose loci and other defining characteristics ("congenial uniformities") are vague and ill defined. "Presentational immediacy" in the mental pole contributes a precision to such nexūs and societies—a precision perceived as the occasion's "contemporary world," which is inoperative in the physical pole because of the limiting spatiotemporal coordination of the data prehended in that pole. (Special relativity, for example, requires that data prehended in the physical pole lie in the subject occasion's past light cone. Thus, contemporary occasions cannot be mutually causally efficacious.) Presentational immediacy presupposes the causally efficacious relations of the physical pole, and projects upon them a sharp, well-defined "contemporary" state—that is, one of the mutually exclusive and exhaustive precisely defined alternative system states described in quantum mechanics, among which one will become actual. In the mental pole, a prehending subject's "presented locus" (or "strain-locus") is the subjectively "immediate" spatial, geometrical coordination of its actual world in terms of subjectively "contemporaneous" temporally coordinated actualities organized into a "presented duration"—a contemporary nexus, perceived in the mode of presentational immediacy.

Whereas data are coordinated in the physical pole, they are integrated in the mental pole, and the integration entails reproductions, reversions, negative prehensions, and transmutations, among other processes, which project sharp, well-defined forms of definiteness upon the data inherited from the physical pole. The result is a matrix of alternative, valuated potential forms of definiteness. Whitehead's genetic analysis, then, is the type of analysis with which quantum mechanics is primarily concerned; for quantum mechanics describes the evolution of a system of actual occasions from an initial state to a final state—an evolution that entails the integration of antecedent data according to a matrix of potential forms of definiteness. And just as the physical and mental poles are mutually implicative, so are coordinate and genetic analyses. This mutually implicative dipolarity is evinced in quantum mechanics by the problem of state reduction, which is easily solved when one acknowledges that the actualization of potentia is presupposed by quantum mechanics; the physical pole is presupposed by the mental pole, and therefore cannot be accounted for by it. Potentiality, in other words, is nonsensical apart from presupposed actuality. At the same time, however, the dipolarity of concrescence entails that the spatiotemporal coordination operative in the physical pole cannot occur apart from the presupposed genetic operations in the mental pole of a prior occasion. For apart from these operations, the prior occasion would not exist, and there would be no data to coordinate. Thus, in Whitehead's dipolar metaphysical scheme, coordination presupposes genesis as much as genesis presupposes coordination. In the same way, a quantum mechanical state evolution presupposes logically and temporally prior actualized evolutions as data (that is, there must be an initial state that evolves); and the quantum mechanical actualization of a potential outcome state (the final state) presupposes the evolution from whence it came—and also a subsequent evolution for which it will serve as datum. (Recall that in quantum mechanics, all outcome states are necessarily confirmed retrodictively, via a subsequent measurement or state evolution.)

For Whitehead, both genetic and coordinate analyses are governed by the cooperation of two fundamental principles: the Principle of Relativity, according to which "the potentiality for being an element in a real concrescence of many entities into one actuality is the one general metaphysical character attaching to all entities . . . [such that] it belongs to the nature of a 'being' that it is a potential for every 'becoming' ";[1] and the Ontological Principle (or "Principle of Efficient and Final Causation"), according to which "every condition to which the process of becoming conforms in any particular instance has its reason *either* in the character of some actual entity in the actual world of that concrescence, *or* in the character of the subject which is in process of concrescence."[2]

According to the Ontological Principle, writes Whitehead, "there is nothing which floats into the world from nowhere."[3] Coordinate analysis of any actual occasion has as its object the conditioning influences derived from the spatiotemporally coordinated antecedent actualities of its actual world; and genetic analysis has as its object the conditioning influences derived from the "nonactualized" yet real world of potentia. These nonactual potentia revealed by genetic analysis are the formative elements of the actual, temporal world, and apart from their participation in the actual world, we would know nothing of them. Further, the genetic analysis of an actual occasion reveals two important implications with respect to how nonactual yet ontologically significant "real" potentia contribute to the formation of any actual occasion: first, that the actualization of potentia is a creative process, such that the actual world is most accurately seen as an historical route of creations whose logically ordered relations reveal an overall trajectory of ongoing novelty—of creative advance; second, that in a genetic analysis of any particular occasion one can trace the lineage of particular constituent potentia back through a particular logically ordered, historical route of occasions.

But one is also able to discern potentia that are not derivable in this way, and indeed, it is these "pure" potentia that drive the creative advance, lest the novelty of the future be reducible to the possibilities of the past. And yet by the Ontological Principle, these "pure potentia" must derive from somewhere—some actual yet nonhistorical, or better, nontemporal, primordial source. This primordial actual entity is God in Whitehead's philosophy—the metaphysical source of pure potentiality and true novelty in the universe. This novelty is continually manifested in the creative advance of the world—an advance that is both indeterminate, yet by the Ontological Principle, conditioned by the actual world temporally (via historically derivable "real" potentia) and nontemporally (via the "pure" potentia that drive true novelty, originating in God).

Thus with the Ontological Principle and the Principle of Relativity, the valuable concepts given by postmodern subjectivism (those that emphasize the private, autonomous, and creative aspects of existence) and the valuable concepts of classical realism (those that emphasize the public, heteronymous relations with an objectively real universe) are brought together in the dipolar unification of the mental and physical poles in each atomic actual occasion. Each actuality is thus creative of itself, but based in large part upon the real data of the universe, as well as the generic pure potentia or "eternal objects" that ingress into the concrescence—potentia that must derive from God, the supremely fundamental, primordial actuality.

Whitehead called his metaphysical scheme the "philosophy of organism," and this, coupled with the operation of the mental pole in even the most basic electromagnetic occasions, might lead one to believe that Whitehead considered the universe to be "alive" or held that objects such as stones or trees enjoy the same kind of mentality that human beings enjoy. Both of these are misapprehensions of Whitehead's metaphysics. For although every occasion entails a mental pole, "mentality" in this sense is not synonymous with consciousness, intellectually informed free will, or mind. There are "low-grade" occasions such as electromagnetic ones for which the operations of the mental pole are limited solely to reproduction of antecedent data, with rare, rudimentary reversions and transmutations restricted to the integration of potentialities—integrations of the sort described by quantum mechanical indeterminacy, for example. For these occasions, the conformal, causal operations of the physical pole dominate, and the rudimentary conceptual reproductions, reversions, and transmutations of the mental pole constitute the whole of their "mentality."

In contrast, "high-grade" occasions, such as those associated with the human mind, entail an enhanced mental pole where advanced conceptual reversions and transmutations may be just as operative, if not more so, than the mere reproduction of antecedent data. In the actual occasions of the human mind, conceptual reversions and transmutations transcend the form of mere "potential fact" (mere eigenstate in quantum mechanics) and take the more complex and intense forms of proposition, of hypothesis, of imagination, of dream.

Whitehead's distinction between "high-grade" and "low-grade" occasions in terms of the operations of the mental pole is particularly important in qualifying the "aliveness" of occasions and—more significantly as regards modern complexity theory—societies of occasions. For Whitehead, the lower-grade occasions constitute the more fundamental species of "physical purpose" that forms the basis of microphysics—occasions related to transfers of electromagnetic energy and the like. This species of occasion, rather than creating by "private experience," instead "receives the physical feelings, conforming their valuations according to the [public] 'order' of that epoch. . . . [Their] own flash of autonomous individual experience is negligible."[4] Our cosmic epoch consists primarily of these low-grade electromagnetic occasions,[5] which form structured societies. These structured societies subsume both (i) subordinate societies, whose definition and integrity are largely independent of their environments (i.e., the molecules of a cell); and (ii) subordinate nexūs, whose definition depends largely on their environments (the cytoplasm of a cell, the organs of the human body, and so on). The former are thus typically less "specialized" than the latter, and in general, "a structured society may be more or less 'complex' in respect to the multiplicity of its associated sub-societies and sub-nexūs and to the intricacy of their structural pattern."[6]

So "the problem for Nature," writes Whitehead, "is the production of societies which are 'structured' with a high 'complexity,' and which are at the same time 'unspecialized.' In this way, intensity is mated with survival."[7] This is accomplished in two ways for Whitehead: The first way is via the "lower-grade" physical purposes characteristic of quantum mechanical evolutions where conceptual reproduction is primary, and the operation of the mental pole is mainly limited to negative selection associated with decoherence—that is, the massive average objectification of a nexus, and the elimination of detailed diversities from it. The result is the "low-grade" structured societies such as crystals, rocks, planets, and suns, the "most long lived of the structured societies known to us."[8]

The second way nature accomplishes unspecialized complexity is "an initiative in conceptual prehensions, i.e., in appetition. . . . In the case of the higher organisms, this conceptual initiative amounts to thinking about the diverse experiences. . . . This second mode of solution also presupposes the former mode. . . . Structured societies in which the second mode of solution has importance are termed 'living.' A structured society in which the second mode is unimportant, and the first mode is important, will be termed 'inorganic.'"

Whitehead continues:

> In accordance with this doctrine of "life," the primary meaning of "life" is the origination of conceptual novelty—novelty of appetition. Such origination can only occur with the Category of Reversion. Thus a society is only to be termed "living" in a derivative sense. A "living society" is one which includes some "living occasions." Thus a society may be more or less "living" according to the prevalence in it of living occasions. Also an occasion may be more or less living according to the relative importance of the novel factors in its final satisfaction.[9]

The universe, then, is for Whitehead most fundamentally a structured society of electromagnetic occasions that contains both subordinate societies and subordinate nexūs, the vast majority of which are "inorganic," "nonliving" societies whose mentality is limited to conceptual reproduction and rudimentary transmutation and reversion. Hence, for Whitehead, the universe for the most part is not "alive." Clearly, then, without proper attention to the Whiteheadian distinctions between organic and inorganic, living and nonliving, conscious and merely mental, the correlation of Whitehead's metaphysics with the physical sciences will be a needlessly uneasy one, likely to inspire either the complete excising of the mental pole on the grounds that it cannot be relevant to physics—or even worse, attempts to use quantum mechanics to "explain away" the human mind and other higher-order mentality.

Either would be terribly unfortunate. For Whitehead's drive was never to explain away existence, nor was it to define one type of experience solely in terms of another more fundamental type. His drive was instead to show how traditionally incompatible areas of inquiry such as modern physics, philosophy, and even religion, could be brought together in a mutually illuminative way within the framework of a logical, coherent, empirically applicable, and empirically adequate metaphysical scheme. Existence was not to be explained away; it was to be enjoyed through adventures in understanding. But for Whitehead, the first step in a proper understanding, apart from embracing the four desiderata just mentioned, was to set an asymptotic course instead of the steep, head-on trajectory typical of both philosophy and science throughout history. Whitehead saw the advent of quantum mechanics, and its characterization by its innovators as *die endgültige Physik*; and it was most certainly not lost upon him that Newton had taken his own physics to be the final word as well. For Whitehead, philosophical and scientific dogmatism would lead to nothing but intellectual death from an unchecked craving for a head-on crash into Truth. Better to glide down in a gentle curve, satisfied to skim the surface and enjoy the view.

Notes

1. Alfred North Whitehead, *Process and Reality: An Essay in Cosmology, Corrected Edition*, ed. D. Griffin and D. Sherburne (New York: Free Press, 1978), 22.

2. Ibid., 24.
3. Ibid., 244.
4. Ibid., 245.
5. Ibid., 98.
6. Ibid., 100.
7. Ibid., 101.
8. Ibid., 102.
9. Ibid., 102.

II

Quantum Mechanics and Whitehead's Metaphysical Scheme

4

The Correlation of Quantum Mechanics and Whitehead's Philosophy

> It is a remarkable characteristic of the history of thought that branches of mathematics, developed under the pure imaginative impulse, thus controlled, finally receive their important application. Time may be wanted. Conic sections had to wait for 1800 years. In more recent years, the theory of probability, the theory of tensors, the theory of matrices are cases in point.
>
> Alfred North Whitehead, *Process and Reality*

THE ONTOLOGICAL INTERPRETATION of quantum mechanics explored thus far in this essay can be distinguished from other interpretations by two primary characteristics: First, it is an interpretation that attempts to describe, via imaginative hypothetical deduction, the form among the facts of experience, rather than both the form *and* the facts, as is the case with many other interpretations of quantum mechanics—those, for example, that attempt to account for the actualization of potentia by way of the mechanics. The existence of facts by this interpretation is accepted a priori, such that the mechanics and its interpretation both presuppose and anticipate the facts of actuality as described in the quantum mechanical evolution of system states. The "problem of the actualization of potentia" is thus no problem at all by this interpretation, which merely seeks to describe the underlying form, and implications, of the quantum mechanical process by which actuality evolves to actuality, mediated by given potentia.

Second, it is an interpretation that, via the decoherence effect and its required mutual interrelations between the measured system and all facts environmental to it, explicitly makes use of the requirements of logic, coherence, and universal applicability and adequacy typically lacking in most interpretations of quantum mechanics. For these desiderata are satisfied with the explicit recognition of the universe in its entirety as the only truly closed system to which quantum mechanics might apply, and it is this recognition that guarantees the necessary, mutual interrelations among all facts. The implications of quantum mechanics by this interpretation are thus universal and therefore ontologically significant; and indeed, this interpretation of quantum mechanics constitutes the exemplification of a clear ontological principle, rather than merely an epistemological principle such as Bohr's principle of complementarity. The ontological principle is: Every fact is a determinant in the becoming of every new fact, such that the evolution of any fact entails both temporally prior facts and logically prior potentia as data, and an integration of these data that is unique to that evolution.

The interpretation of quantum mechanics described in Part I is a fundamental physical exemplification of this ontological principle; and given that, one might infer that it is an exemplification of some much broader metaphysical scheme that must flow from this principle. It would have to be a scheme wherein the universe is characterized as an ongoing process of actualizations (described by quantum mechanics as an historical route of state evolutions of $|\Psi\rangle$). Each actualization is itself a process, comprising the following phases as exemplified by quantum mechanics:

(i) An initial phase, consisting of the integration of all facts relative to a particular fact belonging to a particular subsystem of facts (e.g., the "indexical eventuality" belonging to the measuring apparatus) into potential forms or states. Since the process of actualization is described mechanically as an "evolution" of the state of the system of facts relative to a particular fact, the latter must therefore have two natures: (*a*) that of the *subject* of the state evolution, partially characterized by its inclusion in and relation to S_{init} (e.g., in quantum mechanics, the system state always evolves relative to the indexical eventuality and its associated preferred basis); (*b*) that of the product of the state evolution, partially characterized by its inclusion in and relation to S_{final}—a novel integration of facts which includes the newly evolved indexical eventuality. The relativity of this integration is both objective and subjective. It is objective in that it is an integration of facts, and it is subjective in that the uniqueness of the indexical eventuality, together with the objective actuality of the facts interrelated, conditions the particular form of the integration. The latter is reflected in quantum mechanics by the fact that a preferred basis is always associated with any indexical eventuality.

(ii) A supplementary phase, whereby potential facts incapable of integration are eliminated via negative selection, yielding a reduced matrix of mutually exclusive, valuated potential integrations—that is, a matrix of potential states or potential forms of facts, valuated as probabilities. These forms are subjective insofar as they are integrations of facts relative to a unique indexical eventuality; but they are also objective insofar as they are integrations of facts.

(iii) The actualization of one of these integrations according to the valuations qualifying each, in satisfaction of the evolution and its aim—the latter as evinced by the probabilistic nature of these valuations.

Readers familiar with the cosmological scheme developed by Alfred North Whitehead in his "philosophy of organism" have likely already inferred a number of correlations between the Whiteheadian scheme and the interpretation of quantum mechanics described in Part I. The explication of these correlations is the task of the remainder of this book.

It should be noted that the development from 1924 to 1930 of the "new" quantum theory of Heisenberg, Bohr, Schrödinger, et al., and its philosophically troublesome innovations—many of them hashed out at the Solvay Conferences of 1927 and 1930—took place during the same years that Whitehead developed his cosmological scheme, presented in its most complete, systematic form—*Process and Reality*—in his 1927–1928 Gifford Lectures, published in 1929. (Whitehead had presented an earlier version of this scheme in the 1925 Lowell Lectures, as well as in *Science and the Modern World*, published the same year.) One is left to wonder, then, whether Whitehead was aware of the troubling philosophical implications of the "new" quantum mechanics—as opposed to the "old" quantum mechanics consisting of Einstein's and Planck's theories of quantized transference of electromagnetic energy combined with Bohr's 1913 model of the atom.

Whitehead occasionally refers to the quantum theory in presenting his metaphysical scheme, and it is clear that some, if not most, of these references refer to the "old" quantum theory:

> The treatment of cosmology in the philosophy of organism . . . contains the discussion of the ultimate elements from which a more complete philosophical discussion of the physical world—that is to say, of nature—must be derived. In the first place an endeavour has been made to do justice alike to the aspect of the world emphasized by Descartes and to the atomism of the modern quantum theory. Descartes saw the natural world as an extensive spatial plenum, enduring through time. Modern physicists see energy transferred in discrete quanta.[1]

But Whitehead also refers to concepts inherent in the quantum theory as developed by Heisenberg, Bohr, Schrödinger, et al.—the "new" quantum theory, which is formulated, for example, in precisely the same terms Whitehead uses in the quotation from *Process and Reality* that begins this chapter: Namely, "the theory of probability, the theory of tensors, the theory of matrices." (Recall that the combined Hilbert spaces representing a composite system-apparatus-environment are tensor product spaces; and that sets of probability-valuated potentia are grouped into matrices, etc.) His references to this terminology aside, Whitehead also refers to the "new" quantum theory in terms of two fundamental conceptual innovations primarily associated with it: First, the refutation of fundamental materialism as given in Whitehead's "fallacy of misplaced concreteness":

> This fallacy consists in neglecting the degree of abstraction involved when an actual entity is considered merely so far as it exemplifies certain categories of thought.[2]

Material substance is one such category, through which the fallacy of misplaced concreteness (and the related "fallacy of undifferentiated endurance") has led to the doctrine of materialism in which

> the notion of continuous stuff with permanent attributes, enduring without differentiation and retaining its self-identity though any stretch of time however small or large, has been fundamental. The stuff undergoes change in respect to accidental qualities and relations; but it is numerically self-identical in its character of one actual entity throughout its accidental adventures. The admission of this fundamental metaphysical concept has wrecked the various systems of pluralistic realism. This metaphysical concept has formed the basis of scientific materialism. . . . But this materialistic concept has proved to be as mistaken for the atom as it was for the stone.[3]

Whitehead here refers to the quantum mechanical description of the atom—a description which many physicists, in their debates concerning the proper formulation of the "new" quantum theory, attempted to fit into a materialistic framework. Of these attempts Heisenberg, echoing Whitehead's words above, writes: "It would, in their view, be desirable to return to the reality concept of classical physics or, to use a more general philosophic term, to the ontology of materialism. They would prefer to come back to the idea of an objective real world whose smallest parts exist objectively in the same sense as stones or trees exist." According to the Copenhagen Interpretation, Heisenberg continues, "modern atomic theory no longer allows any reinterpretation or elaboration to make it fit into the naive materialistic conception of the universe."[4] Thus, as Whitehead points out, "the field is now open for the introduction of some new doctrine . . . which may take the place of the materialism with which, since the seventeenth century, science has saddled philosophy."[5]

> What has vanished from the field of ultimate scientific conceptions is the notion of vacuous material existence with passive endurance, with primary individual attributes, and with accidental adventures. Some features of the physical world can be expressed in that way. But the concept is useless as an ultimate notion in science, and in cosmology.[6]

> The simple notion of an enduring substance sustaining persistent qualities, either essentially or accidentally, expresses an abstraction useful for many purposes of life. But whenever we try to use it as a fundamental statement of the nature of things, it proves itself mistaken.[7]

The second conceptual innovation of the "new" quantum theory to which Whitehead refers is closely related to the first: the concept of concrescent state evolution, wherein the final state of a system of facts evolves from the interrelations of its potential facts with the antecedent facts described by the initial system state. This is an exemplification of Whitehead's Ontological Principle:

> Every condition to which the process of becoming conforms in any particular instance, has its reason either in the character of some actual entity in the actual world of that concrescence, or in the character of the subject which is in process of concrescence.[8]

> The actual world is the "objective content" of each new creation.[9]

Whitehead thus characterizes these interrelations between concrescing potentia and the world of actualities antecedent to them as having, in his words, a "vector character"[10] in the sense that each potential fact in the process of concrescence "has its reason" in some particular antecedent fact or facts.[11] Further, the serial evolution of these concrescences—the historical route of state evolutions—manifests itself in the "ultimate vibratory characters of organisms and to the potential element in nature":[12]

> The atom is only explicable as a society with activities involving rhythms with their definite periods. Again the concept shifted its application: protons and electrons were conceived as materialistic electric charges whose activities could be construed as locomotive adventures. . . . The quanta of energy are associated by a simple law with the periodic rhythms which we detect in the molecules. Thus the quanta are, themselves, in their own nature, somehow vibratory; but they emanate from the protons and electrons. Thus there is every reason to believe that rhythmic periods cannot be dissociated from the protonic and electronic entities.[13]

Similarly, in *Modes of Thought* Whitehead writes, "There is a rhythm of process whereby creation produces natural pulsation, each pulsation forming a natural unit of historic fact."[14] The natural unit of historic fact, as applied to quantum mechanics, is the newly evolved, fully determinate system state—a "society" of facts actualized from among a matrix of potential states that have themselves evolved from a society of antecedent facts; and the rhythm is the alternation between the newly evolved, unitary, actual system state and the multiplicity of antecedent facts (and their associated potentia) from which the novel state evolves. Thus, the "many" antecedent facts and their associated potentia become "one" novel state (a novel fact), and are increased, historically, by one—a process which repeats itself "to the crack of doom in the creative advance from creature to creature."[15]

Whitehead's references to the quantum theory as an exemplification of his cosmological scheme, then, pertain to three related concepts—the first one best associated with the "old" quantum theory of Planck and Einstein as applied to Bohr's 1913 atomic model, and the other two best associated with the "new" quantum theory of Heisenberg, Schrödinger, Bohr, et al., typically referred to as the Copenhagen Interpretation:

1. ("old" quantum theory): The transference of electromagnetic energy in discrete quanta and the "vector" relationship between such transference and photonic emissions (Einstein's photoelectric effect). "The mysterious quanta of energy have made their appearance, derived, as it would seem, from the recesses of protons or of electrons. Still worse for the concept, these quanta seem to dissolve into the vibrations of light. Also the material of the stars seems to be wasting itself in the production of the vibrations."[16]

2. ("new" quantum theory): The fallacy of misplaced concreteness (and undifferentiated endurance) as it applies to the doctrine of materialism—successful since the seventeenth century, but unable to accommodate the quantum theory.[17] The latter instead characterizes material substance in terms of "systems" of rhythmically evolving actualities, such that "The atom is only explicable as a society with activities involving rhythms and their definite periods." Thus, "we diverge from Descartes by holding that what he has described as primary *attributes* of physical bodies, are really the forms of internal relationships *between* actual occasions, and *within* actual occasions. Such a change of thought is the shift from materialism to organism, as the basic idea of physical science."[18] This concept is closely related to the next.

3. ("new" quantum theory): The "vector relationship" between potential facts (or systems/societies of facts) in the process of actualization and all antecedent facts, such that the latter contribute in a specific way to the definiteness of the former, in exemplification of the ontological principle: Every actualization of a potential fact is partially determined by its specific relations with all facts antecedent to it, constituting the entire extant universe relative to the actualization at hand. In this way, "the actual world is the 'objective content' of each new creation."[19] The universe is thus characterized as a closed system, as required by any ontologically significant interpretation of the Schrödinger equation, such that any actualization within it necessarily involves all other actualities. This is reflected in Whitehead's "Principle of Relativity," according to which *every actuality* is a potential determinant in the becoming of every new actuality—a principle closely related to his Ontological Principle. The latter is echoed by Heisenberg when he writes, "the transition from the 'possible' to the 'actual' takes place as soon as the interaction of the object with the measuring device, *and thereby with the rest of the*

world, has come into play" (emphasis added).[20] Similarly, the epistemological implications of this fundamental characterization of nature given in the "new" quantum mechanics—the Heisenberg uncertainty relations and Bohr's principle of complementarity—are echoed by Whitehead when, in his commentary on the quantum theory cited above, he writes: "We are now approaching the limits of any reasonable certainty in our scientific knowledge."[21]

Whitehead's references to the quantum theory in *Process and Reality* always reflect what appears to be a distinction between the implications of the "old" quantum theory and those of the "new" quantum theory. Consider the following passages, where concepts best pertaining to the "old" quantum theory are printed in italics, and those best pertaining to the "new" quantum theory are printed in boldface:

> In the language of physical science, the change from materialism to "organic realism"—as the new outlook may be termed—is the displacement of the notion of static stuff by the notion of fluent energy. Such energy has its structure of action and flow, and is inconceivable apart from such structure. **It is also conditioned by "quantum" requirements. These are the reflections into physical science of the individual prehensions, and of the individual actual entities to which these prehensions belong. Mathematical physics translates the saying of Heraclitus, "All things flow," into its own language. It then becomes, All things are vectors.** *Mathematical physics also accepts the atomistic doctrine of Democritus. It translates it into the phrase, All flow of energy obeys "quantum" conditions.*[22]

And:

> [If we] remember that in physics "vector" means definite transmission from elsewhere, we see that this metaphysical description of the simplest elements in the constitution of actual entities agrees absolutely with the general principles according to which the notions of modern physics are framed. **The "datum" in metaphysics is the basis of the vector-theory in physics; the quantitative satisfaction in metaphysics is the basis of the scalar localization of energy in physics.**[23]

And:

> In the language of science, [the philosophy of organism] describes **how the quantitative intensity of localized energy bears in itself the vector marks of its origin, and the specialities of its specific forms;** *it*

> *also gives a reason for the atomic quanta to be discerned in the building up of a quantity of energy.* In this way, the philosophy of organism—as it should—appeals to the facts.[24]

It should be emphasized here that the "new" quantum theory is, in one sense, a more complete systematization of the "old" quantum theory such that the old theory is wholly subsumed within the new theory; therefore, the preceding passages, though they might best apply to either the "old" or the "new" quantum theory, fundamentally apply to both. In the last passage, for example, the "vector marks of [a localized energy's] origin, and the specialities of its specific forms" could also apply to the photoelectric effect of the "old" quantum theory, where energy in the specific form of an emitted photon has a vector relationship to the electron-nucleus interrelation originating the emission.

Discussions of the applicability of Whitehead's philosophy to quantum mechanics typically address whether or not the "new" quantum theory and the "Copenhagen Interpretation" of this theory, formulated contemporaneously with Whitehead's development of his cosmological scheme, might have perhaps influenced the latter in some way. Abner Shimony, for example, states that "Whitehead never refers to the new quantum theory, and it would be unreasonable to expect that even so imaginative a philosopher and scientist as he could have anticipated it except in the most general terms."[25] Shimony proceeds to argue that "the discrepancies . . . between Whiteheadian physics and current microphysics constitute strong disconfirmation of Whitehead's philosophy as a whole."[26] And Henry Folse argues, conversely, that "the philosophy of organism provides a natural context for the acceptance of the Copenhagen Interpretation of quantum theory, especially with the ideas of Bohr and Heisenberg."[27] Folse goes on to say:

> Quite naturally there are many aspects of the philosophy of organism which find no counterpart in the philosophical extrapolations of the Copenhagen Interpretation. . . . There is no reference to the equivalents of "feeling," "satisfaction," or "conceptual prehension." Yet Whitehead would have anticipated this, for the physicists' interpretation of theory is based on a very small segment of experience; Whitehead's system aims at far greater compass. . . .
>
> The Copenhagen position has come under considerable criticism in recent years, much of which draws its strength upon an appeal to

> the classical ontology of mechanistic materialism. It would seem that the Copenhagen Interpretation and process philosophy would make good allies in any battle against resurgent substantival materialism. However, the fate of any potential alliance is in jeopardy so long as current discussions of the subject insist on concentrating on the fine points of quantum interpretation rather than its broader more general ramifications.[28]

These points are well taken; however, it has been the purpose of this introductory section to demonstrate that Whitehead did indeed anticipate that the quantum theory would be an exemplification of his cosmological scheme, and not merely vaguely compatible with it. Indeed, to counter Folse's first point above, Whitehead goes so far as to suggest specific correlations between the nomenclature of his scheme and that of quantum theory:

> If we substitute the term "energy" for the concept of a quantitative emotional intensity, and the term "form of energy" for the concept of "specific form of feeling," and remember that in physics "vector" means definite transmission from elsewhere, *we see that this metaphysical description of the simplest elements in the constitution of actual entities agrees absolutely with the general principles according to which the notions of modern physics are framed.* The "datum" in metaphysics is the basis of the vector-theory in physics; the quantitative satisfaction in metaphysics is the basis of the scalar localization of energy in physics; the "sensa" in metaphysics are the basis of the diversity of specific forms under which energy clothes itself. . . . *The general principles of physics are exactly what we should expect as a specific exemplification of the metaphysics required by the philosophy of organism.*[29] (emphasis added)

Whitehead's claim here should not be overlooked; the metaphysical scheme he presents in *Process and Reality* and in other writings was absolutely intended to be a fundamental characterization of nature as exemplified by the theoretical physics of his time, which included the development of modern quantum mechanics. Aside from his explicitly saying so, the overwhelming detail in which he presents his cosmological model is more than indicative of that intention. For how could it be that the fundamental features of his philosophy are reflected and analyzable in practically every aspect of human experience, as thoroughly elaborated upon in his writings, *except* that of the physics of his time? If any aspect of human experience closely correlates with the specific features of Whitehead's metaphysical scheme, it should certainly be the latter—especially given that the quantum theory is a purely mathematical theory, and therefore clearly within the technical scope of Whitehead's expertise.

It is the purpose of this chapter to demonstrate how quantum mechanics, as given by the modern decoherence-based interpretations described thus far[30] is, in the most specific terms of the mechanics, an extremely precise, phase-by-phase exemplification of Whitehead's cosmological model. It is an exemplification both conceptually and mechanically, and in terms of physical nature, quantum mechanics is thus the most fundamental exemplification of Whiteheadian metaphysics currently capable of analysis.

The most general correlation between quantum mechanics and the Whiteheadian cosmological system pertains to the concept of state evolution in the former, and concrescence in the latter. These terms describe the same process as elaborated in Part I, wherein:

(i) A world of existing, mutually interrelated facts (Whitehead's "actual occasions") is presupposed.

(ii) The inclusion of these facts (Whitehead's "positive prehension" or "feeling" of facts as "data") in the act of measurement or state specification of them—by their necessary mutual interrelations, somehow entails:

(*a*) All other facts and their associated potentia—either in their inclusion in the specification, or their necessary exclusion from specification. This requirement is reflected in Whitehead's "Principle of Relativity" and his "Ontological Principle," and in quantum mechanics, by the Schrödinger equation's exclusive applicability to closed systems, with the universe being the only such system.[31] The exclusions relate to the process of negative selection productive of the decoherence effect described earlier, and Whitehead refers to these eliminations as "negative prehensions." Their form and function with respect to environmental degrees of freedom are, as we shall see, identical to those related to the process of decoherence.

(*b*) The evolution of the system of all facts into a novel fact—namely, a maximal specification (the "state" specification) of the relevant facts (those not excluded by decoherence or "negatively prehended" in Whitehead's terminology). State specification—the maximal specification of many facts via the necessary exclusion of some facts—thus entails the evolutionary production of a novel fact—namely, a unification of the facts specified.

(*c*) The requirement that this evolution proceed relative to a particular fact, typically belonging to a particular subsystem of facts. In quantum mechanics, these are referred to, respectively, as the "indexical eventuality" and the "measuring apparatus"; Whitehead's equivalent term is, simply, the prehending "subject." This requirement is given in Whitehead's "Ontological Principle" and "Category of Subjective Unity"; their correlates in quantum mechanics—the necessary relation of a state evolution to some "preferred basis" characteristic of the measuring apparatus—has often been misapprehended as a principle of sheer subjectivity, the source of the familiar lamentations that quantum mechanics destroys the objective reality of the world.

(iii) Measurement or state specification thus entails, at its heart, the anticipated actualization (or "concrescence") of one novel potential fact/entity from many valuated potential facts/entities which themselves arise from antecedent facts (data); and it is understood that the quantum mechanical description of this evolution terminates in a matrix of probability valuations, anticipative of a final unitary reduction to a single actuality. Ultimately, then, concrescence/state evolution is unitary evolution from actualities to unique actuality. But when analyzed into subphases, both concrescence and state evolution entail a fundamental nonunitary evolution, analogous to von Neumann's conception of quantum mechanics as most fundamentally a nonunitary state reduction productive of a unitary reduction.[32] It is an evolution from:

(*a*) a multiplicity of the actual many—that is, $|\Psi\rangle$, to

(*b*) a matrix of potential "formal" (in the sense of applying a "form" to the facts) integrations or unifications of the many (Whitehead's term is propositional "transmutations" of the many—a specialized kind of "subjective form"—and he also groups these into "matrices"[33]). Each of these potential integrations is described in quantum mechanics as a projection of a vector representing the actual, evolving multiplicity of facts onto a vector (or subspace) representing a potential "formally integrated" eigenstate. The Whiteheadian analog of the actual multiplicity's "projection" onto a potential integration is "ingression"—where a potential formal integration

> arises from the ingression of a specific "potentiality of definiteness"[34] via a "conceptual prehension" of that specific potentiality of definiteness (Whitehead also refers to these potentia as "eternal objects," and explicitly equates the two terms[35]). But whereas in quantum mechanics, the state vector representing the actual multiplicity of facts is *projected onto* the potential integration (the eigenvector representing the eigenstate), in Whitehead's scheme it is the latter which *ingresses into* the prehensions of the actual multiplicity. This difference reflects Whitehead's concern with the origin of these potentia; according to his Ontological Principle, if they ingress into the evolution, they must be thought of as coming from somewhere. The eigenstate, or object of projection in quantum mechanics, is, in contrast, simply extant. This difference aside, Whiteheadian vector "ingression" and quantum mechanical vector "projection" are conceptually equivalent—as are the terms "eternal object" and "potential fact."

There are, furthermore, two important characteristics shared by both the quantum mechanical and Whiteheadian notions of potentia. First, there is a sense in which both are "pure" potentia, referent to no specific actualities. For Whitehead, "eternal objects are the pure potentials of the universe; and the actual entities differ from each other in their realization of potentials."[36] "An eternal object is always a potentiality for actual entities; but in itself, as conceptually felt, it is neutral as to the fact of its physical ingression in any particular actual entity of the temporal world."[37] In quantum mechanics, this pure potentiality is reflected in the fact that the state vector $|\Psi\rangle$ can be expressed as the sum of an infinite number of vectors belonging to an infinite number of subspaces in an infinite number dimensions, representing an infinite number of potential states or "potentialities of definiteness," referent to no specific actualities and potentially referent to all. Many of these are incapable of integration, forming nonsensical, interfering superpositions, and are eliminated as negative prehensions in a subsequent phase of concrescence.

Second, quantum mechanical projections are also "inherited" from the facts constituting the initial state of the system (as well as the historical route of all antecedent states subsumed by the initial state) such that preferred bases in quantum mechanics are typically reproduced in the evolution from state to state. Similarly, in Whitehead's scheme, antecedent facts, when prehended, are typically "objectified" by one of their own historical "potential forms of definiteness"—usually the potential forms that were antecedently actualized at some point in the historical route of occasions constituting the system measured.

> An actual entity arises from decisions *for* it and by its very existence provides decisions *for* other actual entities which supersede it.[38]

> Some conformation is necessary as a basis of vector transition, whereby the past is synthesized with the present. The one eternal object in its two-way function, as a determinant of the datum and as a determinant of the subjective form, is thus relational. . . . An eternal object when it has ingression through its function of objectifying the actual world, so as to present the datum for prehension, is functioning "datively."[39]

Whitehead's characterization of potentia as "relational" is exemplified by the manner in which potentia mediate the actuality of a measured system and the actuality of the outcome of the measurement—that is, the mediation of the initial and final system states.

The evolution thus continues into its next phase:

(*c*) A reintegration of these integrations into a matrix of "qualified propositional" transmutations,[40] involving a process of negative selection where "negative prehensions" of potentia incapable of further integration are eliminated. The potential unifications or propositional transmutations in this reduced matrix are each qualified by various valuations. Each potential transmutation relative to the indexical eventuality of the measuring apparatus (i.e., each potential outcome state relative to the apparatus and some prehending subject belonging to it) is thus a potential "form" into which the potential facts will ultimately evolve. Whitehead terms these "subjective forms" and as applied to quantum mechanics, the term "subjective" refers to the fact that the "form" of each potential outcome state is reflected in the preferred basis relative to the indexical eventuality of the measuring apparatus (i.e., the prehending subject). Again, it is only the form that is thus subjective—for any number of different devices with different preferred bases could be used to measure a given system, and any number of different people with their own "mental preferred bases" could interpret (measure) the different readings of the different devices, and so on down the von Neumann chain of actualizations. The potential facts to which each subjective form pertains, however, are initially "given" by the objective facts constitutive of the world antecedent to the concrescence at hand. Thus, again, the "subjective form" of a preferred basis is in no way demonstrative of sheer subjectivity—that is, the evolution of novel facts *as determined* by a particular subject; it is, rather, demonstrative of the evolution of novel facts *jointly* determined by both the world of facts antecedent to the evolution *and* the character of the subject prehending this evolution by virtue of its inclusion in it. Again, according to Whitehead's "Ontological Principle,"

> Every condition to which the process of becoming conforms in any particular instance, has its reason either in the character of some actual entity in the actual world of that concrescence, or in the character of the subject which is in process of concrescence.[41]
>
> The actual world is the "objective content" of each new creation.[42]

The evolution thus proceeds to and terminates with what Whitehead terms the "satisfaction" which in quantum mechanical terms is described as:

(*d*) The actualization of the final outcome state—that is, one subjective form from the reduced matrix of many subjective forms—in "satisfaction" of the probability valuations of the potential outcome states in the reduced matrix. In quantum mechanics, as in Whitehead's model, this actualization is irrelevant and transparent apart from its function as a datum (fact) in a subsequent measurement, such that the "prehending subject" becomes "prehended superject." Again, this is simply because both Whitehead's process of concrescence and quantum mechanics presuppose the existence of facts, and thus cannot account for them. For Whitehead, "satisfaction" entails "the notion of the 'entity as concrete' abstracted from the 'process of concrescence'; it is the outcome separated from the process, thereby losing the actuality of the atomic entity, which is both process and outcome."[43] Thus, the probability valuations of quantum mechanics describe probabilities that a given potential outcome state *will be actual* upon observation—thus implying a subsequent evolution and an interminable evolution of such evolutions. Every fact or system of facts in quantum mechanics, then, subsumes and implies both an initial state and a final state; there can be no state specification S without reference, implicit or explicit, to $S_{initial}$ and S_{final}. This is reflected in Whitehead's scheme by referring to the "subject" as the "subject-superject":

> The "satisfaction" is the "superject" rather than the "substance" or the "subject." It closes up the entity; and yet is the superject adding its character to the creativity whereby there is a becoming of entities superseding the one in question. . . .[44]
>
> An actual entity is to be conceived as both a subject presiding over its own immediacy of becoming, and a superject which is the atomic creature exercising its function of objective immortality. . . . [45]
>
> It is a subject-superject, and neither half of this description can for a moment be lost sight of. . . .[46]
>
> [The superject is that which] adds a determinate condition to the settlement for the future beyond itself.[47]

Thus, the process of concrescence is never terminated by actualization/satisfaction; it is, rather, both begun and concluded with it. The many facts and their associated potentia become one novel state (a novel fact), and are thus increased, historically, by one, so that "the oneness of the universe, and the oneness of each element in the universe, repeat themselves to the crack of doom in the creative advance from creature to creature."[48] "The atomic actualities individually express the genetic unity of the universe. The world expands through recurrent unifications of itself, each, by the addition of itself, automatically recreating the multiplicity anew."[49]

The Phases of Quantum Mechanical Concrescence

> The process of concrescence is divisible into an initial stage of many feelings, and a succession of subsequent phases of more complex feelings integrating the earlier simpler feelings, up to the satisfaction which is one complex unity of feeling. This is the "genetic" analysis of the

> satisfaction. The actual entity is seen as a process; there is growth from phase to phase; there are processes of integration and reintegration.
>
> Alfred North Whitehead, *Process and Reality*

The process of concrescence described here by Whitehead is exemplified by the process of quantum mechanical state evolution, which entails the evolution of a closed system of objectively extant facts (data) correlative to the concrescent evolution of a single subject-fact (the indexical eventuality of the measuring apparatus). This evolution consists of a succession of phases in which manifold potential specifications of each datum are integrated—relative to the measuring apparatus and, particularly, its preferred basis. This integration entails the elimination of incompatible and irrelevant specifications via a process of negative selection, productive of the decoherence effect. The result is a matrix of decoherent, mutually exclusive and exhaustive alternative, probability-valuated integrations or potential system states. Of these, one will become actual fact in satisfaction of these valuations as revealed retrodictively by future measurements in its role as datum for these measurements.

> The final phase in the process of concrescence . . . is termed the "satisfaction." It is fully determinate (a) as to its genesis, (b) as to its objective character for the transcendent creativity [i.e., as datum for subsequent actualizations], and (c) as to its prehension, positive or negative, of every item in its universe. . . .[50]

> The satisfaction is merely the culmination marking the evaporation of all indetermination.[51]

Furthermore, the evolution from phase to phase in a concrescence does not occur in asymmetrically modal "physical time," and this is exemplified in quantum mechanics by the time-independent Schrödinger equation which most fundamentally describes this evolution. Each phase, rather, presupposes the actualization as a quantum whole—further exemplified in quantum mechanics, for example, by the inability to specify "what happens between" one observation and the next. This principle, an infamously mystifying component of quantum mechanics for many, is entirely intuitive when interpreted according to the Whiteheadian scheme: For apart from facts, there is nothing to specify.

> This genetic passage from phase to phase is not in physical time: the exactly converse point of view expresses the relationship of concres-

> cence to physical time. The actual entity is the enjoyment of a certain quantum of physical time. But the genetic process is not the temporal succession: such a view is exactly what is denied by the epochal theory of time. Each phase in the genetic process presupposes the entire quantum, and so does each feeling in each phase. . . . It can be put shortly by saying, that physical time expresses some features of the growth, but *not* the growth of the features.[52]

Whitehead divides the process of concrescence into three "stages";[53] the first two stages, Stage I, the responsive stage or "physical pole," and Stage II, the supplementary stage, or "mental pole," entail the integrations of prehensions (or "concrete facts of relatedness") of antecedent facts, and it is these two stages that find their exemplification in quantum mechanical state reduction. Stage III is termed the "satisfaction," which is the actualization of one of the many potential integrations generated in the first two stages. Stages I and II together consist of three successive phases (see figure 4.1, back end sheet), which are precisely analogous to the three phases of state evolution (the valuation of potentia) in orthodox "Copenhagen" quantum mechanics: (i) initial state, which evolves to become (ii) an integration of potentia subsumed by the pure state density matrix, which evolves to become (iii) a reintegration of potentia subsumed by the mixed state, reduced density matrix. Phases (*b*) and (*c*) here, as given in the Copenhagen formalism, entail two concepts also present in Whitehead's Phase 2 and Phase 3 in the supplementary stage, as will be explored presently: (i) the transitional nonunitary state evolution suggested by von Neumann; (ii) the process of negative selection productive of the decoherence effect related to this nonunitary state reduction.

It must be emphasized that these two additional concepts in no way require the modification of the orthodox quantum formalism with any additional features (i.e., linear or nonlinear modifications of the Schrödinger equation as suggested by Wigner, for example, or more recently, as suggested in the Spontaneous Localization interpretation of Ghirardi, Rimini, and Weber). All that is required is the orthodox quantum formalism, but applied universally—in satisfaction of the requirement of ontological coherence and consistency—rather than as conventionally and instrumentally applied only to specific situations incapable of accommodation by classical mechanics or ontology.

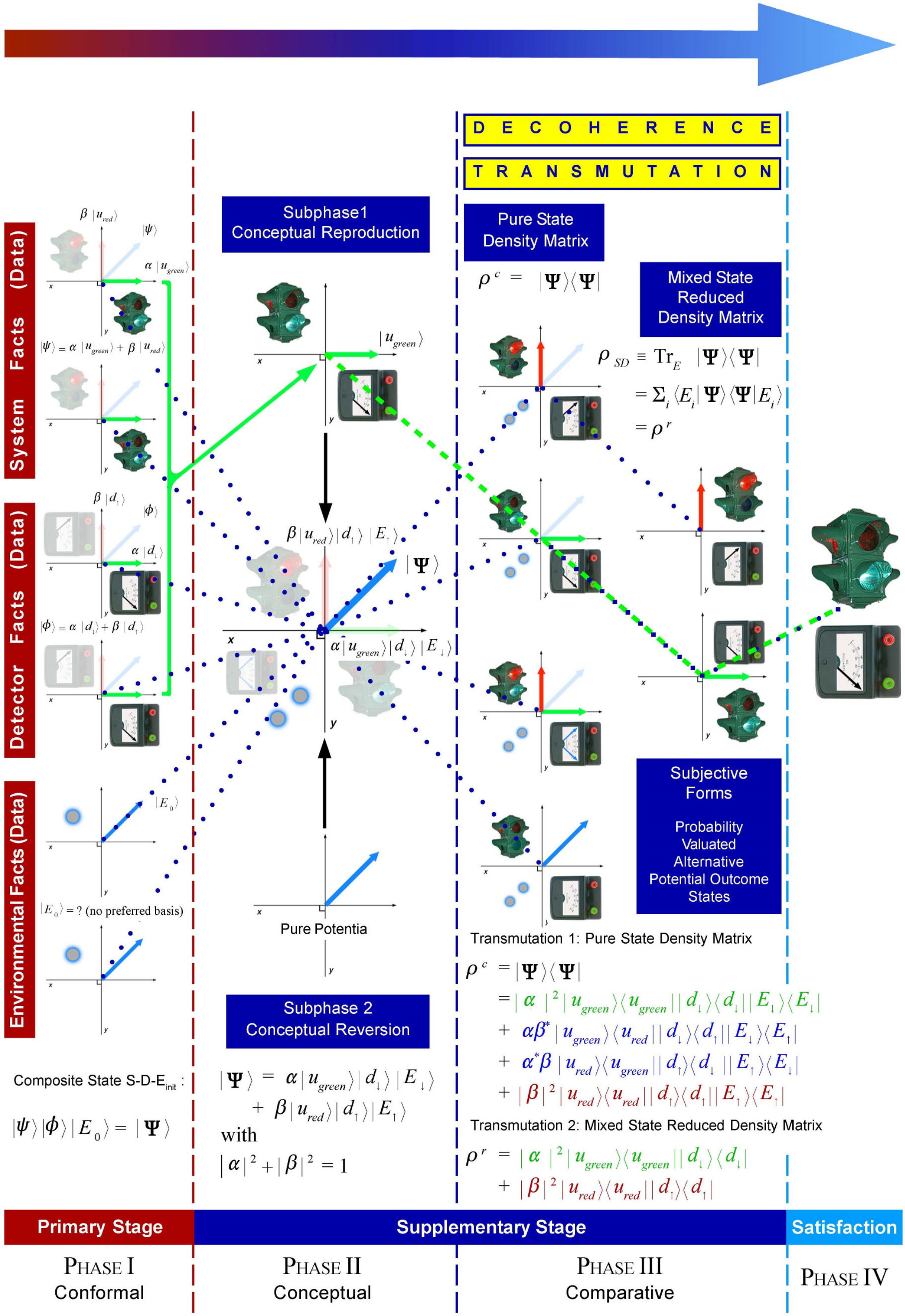

FIGURE 4.1. Whitehead's process of concrescence as exemplified by quantum mechanical state evolution.

Whitehead continues:

> There are three successive phases of feelings, namely, a phase of "conformal" feelings [Phase 1, which belongs to Stage I], one of "conceptual" feelings [Phase 2, which belongs to Stage II], and one of "comparative" feelings [Phase 3, which belongs to Stage II], including "propositional" feelings in this last species. . . . The two latter phases can be put together as the "supplemental" [stage].[54]

Phases 1, 2, and 3 and their relationship to Stages I, II, and III, have been diagramed on the back end sheet of this book in order to facilitate the following discussion. The first phase in Whitehead's scheme—the only phase in Stage I, the "responsive stage" or alternately, the "physical pole"—is termed the "primary phase." It is a "conformal," "responsive" phase, wherein the actual world as a multiplicity of facts is initially related to ("prehended" by) the subject. These facts constitute the whole of the antecedent universe relative to the concrescence—that is, facts comprised by the initial state of a measured system, together with that of its measuring apparatus and environment in accord with the closed-system requirement of the Schrödinger equation. This requirement in the ontological interpretation of quantum mechanics is an exemplification of Whitehead's "Principle of Relativity":

> The potentiality for being an element in a real concrescence of many entities into one actuality, is the one general metaphysical character attaching to all entities, actual and non-actual [i.e., actual and potential]. Every item in its universe is involved in each concrescence. In other words, it belongs to the nature of a "being" that it is a potential for every "becoming." This is the "principle of relativity."[55]

> The principle of universal relativity directly traverses Aristotle's dictum, "(A substance) is not present in a subject." On the contrary, according to this principle an actual entity *is* present in other actual entities. In fact if we allow for degrees of relevance, and for negligible relevance, we must say that every actual entity is present in every other actual entity. The philosophy of organism is mainly devoted to the task of making clear the notion of "being present in another entity." This phrase is here borrowed from Aristotle: it is not a fortunate phrase, and in subsequent discussion it will be replaced by the term "objectification."[56]

According to Whitehead's cosmological scheme as exemplified by the ontological interpretation of quantum mechanics, then, in every concrescence (or "actualization of a potential fact," or occasion of "state specification" in a measurement interaction) every fact constitutive of the universe is an initial datum which typically becomes "objectified" by one of its own historical potentia. Often, as in most cases of physical transmission of energy, the objectified potential is the one that was actualized in its own process of concrescence. (Recall from Part I that it is this regular reproduction of antecedent potentia throughout historical routes of facts that contributes to the "classicality" of high-inertia systems.) Objectified data are "positively prehended" in Whitehead's terminology, or equivalently, "felt." Thus, the primary phase is the seat of causal efficacy, via "simple physical feelings," in the process of concrescence.

> A simple feeling has the dual character of being the cause's feeling reenacted for the effect as subject. But this transference of feeling effects a partial identification of cause with effect, and not a mere representation of the cause. It is the cumulation of the universe and not a stage play about it. By reason of this duplicity in a simple feeling there is a vector character which transfers the cause into the effect. . . . Simple physical feelings embody the reproductive character of nature, and also the objective immortality of the past.[57]

Quantum mechanics echoes this conception of the causal interrelations between past facts and the becoming of novel facts. Recall the quote from Omnès:

> Past facts are not absolutely real; they only *were* real. One can never indicate a past fact by pointing a finger at it and saying "that." One must call for a memory or use a record, a note, a photograph. Nevertheless, the derivation of a unique past is possible because quantum mechanics allows for the existence of memory and records. . . . What we observe in reality is always something existing *right now*, even if we interpret it as a trace of an event in the past, whether it be a crater on the moon, the composition of a star atmosphere, or the compared amounts of uranium and lead in a rock.[58]

And in the same spirit, Charles Hartshorne comments, "It is quantum theory that has at last brought science to admit the contingency that qualifies every instance of becoming."[59]

In summary of the primary phase of concrescence, Whitehead writes:

> The primary stage in the concrescence of an actual entity is the way in which the antecedent universe enters into the constitution of the

entity in question, so as to constitute the basis of its nascent individuality. . . .[60]

The first phase is the phase of pure reception of the actual world in its guise of objective datum for aesthetic synthesis. . . .[61]

The actual world is the "objective content" of each new creation.[62]

The second and third phases of concrescence in Whitehead's scheme together constitute the "supplementary stage" or alternatively, the "mental pole,"[63] and whereas the primary stage/physical pole is the seat of causal efficacy, the supplementary stage/mental pole is the seat of causal indeterminism, via "conceptual prehensions" or prehensions of potentia, qualified as two types, "real potentiality" and "general potentiality" (also referred to as "pure potentiality"):

> Thus we have always to consider two meanings of potentiality: (a) the "general" potentiality, which is the bundle of possibilities, mutually consistent or alternative, provided by the multiplicity of eternal objects, and (b) the "real" potentiality, which is conditioned by the data provided by the actual world. General potentiality is absolute, and real potentiality is relative to some actual entity, taken as a standpoint whereby the actual world is defined.[64]

A "real potentiality" is potentiality conditioned by the extant facts of the universe to which they pertain—that is, potential facts historically embodied and thus conditioned by the actual universe from which they have evolved. The potential outcome of a measurement of the color status of our red-green traffic signal from Part I, for example, is conditioned by the inheritance of antecedent system states embodied by the history of the traffic-signal system, correlated with the histories of the measuring apparatus and the environment englobing both—that is, the history describing the universe itself. The two "real potentia" of this particular measurement are, then, "red light" and "green light" (assuming these are the only two potential colors to ever have been actualized throughout the history of that traffic signal). It is via such "real potentia" that the causal prehensions from the primary phase are objectified as "immanent," historically *realized* determinants of the facts prehended. But in the supplementary stage of the currently evolving concrescence, these potentia are now also transcendent capacities for determination; for if our traffic signal were determined via measurement to be red just prior to the current measurement, the outcome might nevertheless be green this time.

END OF CHAPTER SAMPLE

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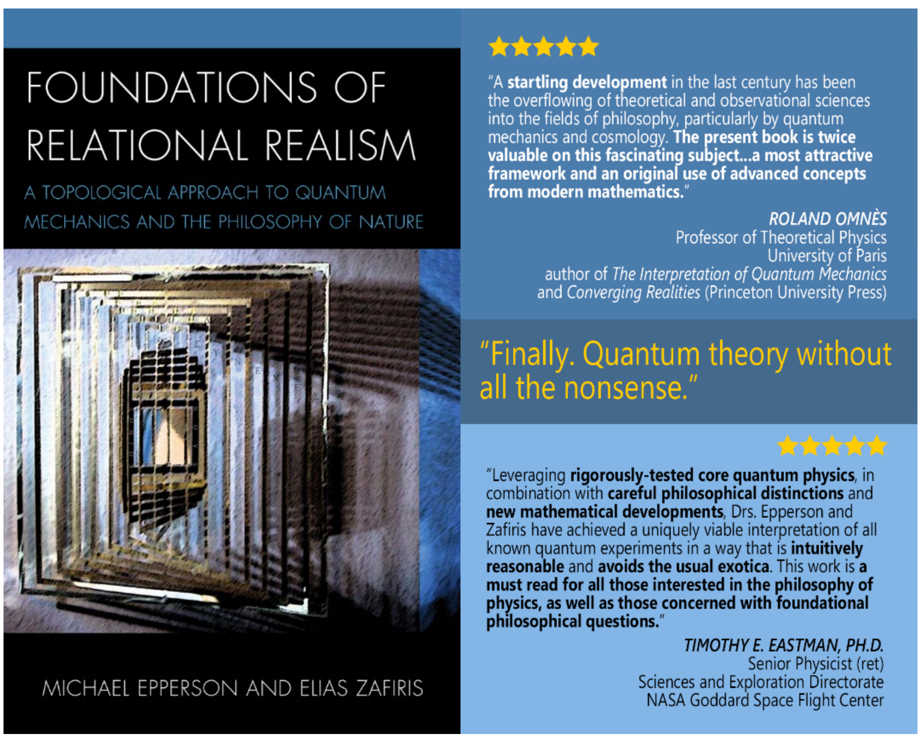

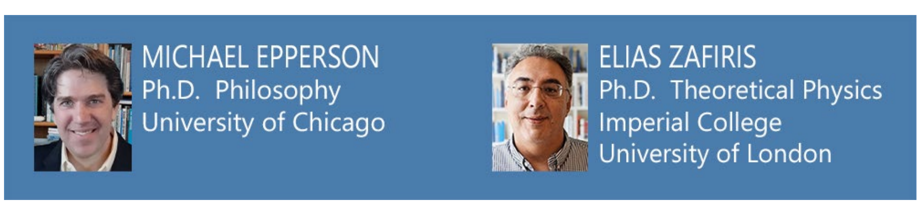

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5

Spatiotemporal Extension

FOR BOTH WHITEHEADIAN METAPHYSICS and the decoherence-based interpretations of quantum mechanics, physical objects—whether they be solid material bodies or localized fields of energy—are most fundamentally characterized as serial historical routes of quantum actual occasions. Nonlocal correlations among physical objects, such as those encountered in the EPR-type experiments discussed earlier, are described simply as logically necessary correlations among the *histories* constituting spatially well separated object systems. The logical necessity of these correlations derives from the understanding that any local system is necessarily participant in a broader environmental system, whose history subsumes those of all the local systems within it. In this way, the broader environmental history imposes consistency conditions, such as those first suggested by Robert Griffiths,[1] upon the manifold local histories it includes as these histories unfold, quantum event by quantum event. These consistency conditions are rooted ultimately in the logical principles of noncontradiction and the excluded middle.

The broadest conceivable system of actualities is the universe itself—the ultimate environment for any actuality and the ultimate history—and its provision of consistency conditions upon the histories of the local systems subsumed within it evinces a universal holism largely incompatible with the mechanistic materialism underlying classical physics. For it is not only a conceptual holism that one might confine to the realms of spiritual, philosophical, or theological tradition; it is also a physically significant holism—at least as regards the decoherence effect and those interpretations of quantum mechanics that employ it.

Because quantum mechanics exemplifies certain holistic features of the universe and divulges the logical historical relations among all actualities, it might be tempting to conclude that *any aspect* of physical relations among actualities must derive from, or reduce to, these holistic logically ordered features. What is emphasized in such a conclusion is the universal scope of any single, brute, quantum fact. When the local history describing a physical system is augmented by a novel quantum fact, the entire system history is changed, as is the history of any system included within it, or any system including it, irrespective of their spatiotemporal metrical topologies. The temptation, in other words, is to regard the spatiotemporal extensiveness of actualities and systems of actualities, as well as any theory describing such extensiveness (such as Einstein's special and general theories of relativity), as mere abstractions derivable entirely from fundamental quantum events, in the same way that the concept of "material body" is so derivable. Various information theoretic approaches to quantum mechanics emphasize these holistic features, some to the extent of redefining the whole of physics as a reduction entirely to relations among quantum events as sheerly logically ordered quantum "information bits."[2]

The logical, historical relation among all actualities and the associated holistic features of the universe are, as we have seen, essential components of Whiteheadian metaphysics—components that form the bulk of its connection to modern quantum theory. It is only natural, then, that information theoretic approaches to quantum mechanics that elevate these holistic features to primacy, and relegate spatiotemporal extension to mere abstraction, might be portrayed as being compatible with Whiteheadian metaphysics. The "fallacy of misplaced concreteness" would thus find its exemplification not only in the conventional notion of "fundamental materiality" but also in the conventional notion of "fundamental extensiveness in spacetime." But for Whitehead, the spatiotemporally *extensive* morphological structure ("coordinate division") of actualities and nexūs of actualities, as well as of spacetime itself, is as crucial to concrescence as the *intensive* features of their relations ("genetic division") emphasized by the information theoretic interpretations of quantum mechanics. The "intensive" features are the logical, historical, genetic relations operative in the supplementary stage of concrescence as described in quantum mechanical terms in previous chapters. "Intensity" is reflected in the valuations of subjective forms, or in quantum mechanical terms, in the probability valuations of potential outcome states. Indeed, there is a direct relationship between (i) the *extensive* morphological structure of actualities objectified as spatiotemporally coordinated data in the primary stage of concrescence (the "physical pole") and (ii) the *intensive* valuations of the subjective forms of these data in the supplementary stage (the "mental pole")—valuations that emphasize the logical, historical, genetic relations of the objectified data.

This close relationship is a key aspect of the dipolarity of concrescence and the avoidance of a Cartesian bifurcated Nature. The world is not merely a multiplicity of disembodied quantum physical facts upon which individual subjects project their own relativistic and vacuous spatiotemporal coordinations. For Whitehead, these extensive coordinations are local nexūs and societies of actual occasions—"relativistic" in the sense that these occasions *are* the relata—related to each other and to the prehending subject by virtue of their spatiotemporally coordinated objectification by this subject and according to the subject's own particular spatiotemporal morphology (i.e., its particular spacetime reference frame). And by the Category of Transmutation in the supplementary stage, these spatiotemporal coordinations in the primary stage contribute to the determination of "environmental" data to be eliminated as negative prehensions—an elimination key to the quantum mechanical decoherence effect discussed previously, and to the valuation of the subjective forms of potential quantum mechanical outcome states. The extensive relations of the physical pole and the intensive relations of the mental pole are, then, closely interwoven, such that the operation of neither pole can be abstracted from the operation of the other. Thus the logical coherence of the dipolarity of concrescence is evinced. The extensive coordination of actualities cannot occur apart from the logically prior historical genesis of the actualities coordinated; and the historical genesis of actualities cannot occur apart from the logically prior extensive coordination of the actualities ingredient in the novel genesis. The only ontology capable of accommodating such dipolarity is one wherein all beings are fundamentally historical and perpetual routes of quantum becomings.

Coordinate Division and Genetic Division

The relativistic extensive relations among the actualities disclosed by coordinate division are relations of causal efficacy; the phenomenon of local *causal influence of actualization by temporally prior actu-*

ality is derived from these extensive relations. And the phenomenon of nonlocal *causal affection of potentia by logically prior actuality* is derived from the logical, historical relations among actualities disclosed by genetic division as correlated with quantum mechanics in previous chapters. Whitehead tends to restrict the term "intensity of relations" to genetic division, in reference to the valuations (i.e., quantum mechanical probability valuations), adversions, and aversions of subjective forms in the supplementary stage of concrescence. This restriction of "intensity of relations" gives contrast to the "extensiveness of relations" pertaining to coordinate division operative in the primary stage. But because concrescence is dipolar, with the operations of both poles being mutually implicative (as opposed to "complementary" or "bipolar," where the operations of both poles would be mutually exclusive), it is clear that the intensive probability valuations in the supplementary stage/mental pole are closely related to the extensive spatiotemporal coordinations of the primary stage/physical pole.

Recall, for example, the story of the traveling salesman in Hong Kong whose wife in California is about to give birth. The question, "At what moment does the salesman become a father?" has only two significant possible answers: (a) at the moment his wife gives birth, for this moment is a common event in each of their histories; (b) as soon as a signal sent from the spacetime coordinates of the birth, traveling no faster than the speed of light, reaches the spacetime coordinates of the father; for prior to that, he cannot be causally altered by the event.

The first answer reflects the genetic analysis of the events—the logical, historical, and thus "nonlocal" relations between the salesman and his wife; it entails an implicit characterization of them as historically correlated quantum mechanical systems. The mutual nonlocality, or any other extensive qualities of these systems, has absolutely no bearing on the *fact* of the birth event augmenting each history in a correlated way; and once those potentia associated with the salesman's *history* are affected—his "history" defining him not only by his past, but also by the potentia associated with his future (what he might be, might do, might be able to do, might be for others, etc.)—then in some sense *he* is affected, whether he is aware of the affection or not. The phenomenon associated with this first answer and its analogous EPR-type nonlocal quantum mechanical correlations is "causal affection of potentia by logically prior actuality." (Again, an information theoretic approach to quantum mechanics would emphasize this feature over any spatiotemporally extensive qualifications of the systems.) But the *intensity* of the correlation, in quantum mechanical/Whiteheadian terms, derives in part from the extent to which (i) the wife-system and its birth event, and (ii) the salesman-system, are entangled *extensively*, that is, *spatiotemporally coordinately*, with a shared environment—another spatiotemporally coordinated system, whose global history subsumes their local histories, as well as the local histories of every other event or system of events within it.

Recall that apart from the logical consistency conditions provided by a global environmental history, crucial to the decoherence process, one would be left with a bare superposition of practically infinite potential outcome histories of negligible individual intensity, belonging to a practically infinite number of spatiotemporally disconnected events. But because of these historical environmental consistency conditions, a vast number of individual potential outcome histories are eliminated by negative selection and a process of mutual cancellation—a physical exemplification of the logical principle of noncontradiction. The superposition of this multiplicity of minimally intensive potential outcome states thus evolves, via the negative selection process of decoherence and transmutation, to become a reduced matrix of probability-valuated, mutually exclusive and exhaustive outcome states or propositional transmutations, each valuation reflective of a significant *intensity*. Thus, in both the decoherence-based interpretations of quantum mechanics and Whiteheadian metaphysics, the *intensive valuation* of the subjective forms of alternative outcome states is closely linked with the logically prior, spatiotemporally *extensive coordination* of the related data, such that the vast majority of these data are coordinated and qualified as "environmental" to the subject occasion or system of occasions.

Put another way, the term "intensity" as Whitehead uses it refers to the *qualitative intensity* operative in genetic division, represented by the probability-valuated subjective forms/potential outcome states of the reduced density matrix in the supplementary stage/mental pole. And this qualitative intensity is in part dependent upon a *quantitative intensity* which originates in coordinate division, operative in the primary stage/physical pole. The relationship between *coordinate extension* and *quantitative intensity* in the physical pole is evinced by the relationship between (i) the *number* of actualities extensively coordinated as "environmental" to the subject system, and (ii) the process of decoherence and transmutation in the supplementary stage. For apart from a sufficient number of actualities extensively coordinated as "environmental" to the subject system, there cannot be a sufficient number of negative prehensions to drive the process of decoherence/transmutation. Without this crucial negative selection process, there cannot be any subsequent qualitative valuation of intensities; there can be no reduction of the coherent superposition of the pure state density matrix to the decoherent set of probability-valuated, mutually exclusive and exhaustive potential outcome states/transmuted subjective forms in the reduced density matrix. Potential outcome states would instead remain locked in a coherent superposition; the data would persist as uncoordinated bare multiplicity, each datum superposed with all others, with some aspects of the superposition mutually consistent and others mutually contradictory. So long as the latter remain operative in the concrescence, there can be no reduction (transmutation) of the superposed multiplicity into a matrix of mutually exclusive and exhaustive, intensity-valuated transmutations. Thus the qualitative intensity operative in the mental pole cannot evolve apart from the extensive quantitative intensity that originates in the physical pole.

But the dipolarity of concrescence implies a conditioning in the opposite direction as well—a conditioning of the physical pole of a concrescence by the mental pole of an antecedent objectified actuality. Returning to the example of the salesman and his wife, consider answer (b), which emphasizes the extensive spatiotemporal coordination of the salesman-system and the wife-system. This coordination is relativistic, given the speed-of-light limitation of causal efficacy in the physical pole. Thus a speed-of-light communicative transmission from the wife to the salesman is the "fastest" way in which the salesman might be causally influenced by the birth event; for only events that fall within his past light cone are capable of causally influencing him. Whereas the EPR-type nonlocal causal phenomenon associated with the first answer was "causal affection of potentia by logically prior actuality"—a feature operative in the supplementary stage/mental pole and disclosed by the genetic analysis of concrescence—the causal phenomenon associated with answer

(b) is "causal influence of actualization by temporally prior actuality." It is a feature of concrescence operative in the primary stage/physical pole and disclosed by coordinate analysis. Since both salesman-system and wife-system are in the same general inertial reference frame relative to the Earth—that is, they are both relatively "stationary" on the Earth—the relativistic features of their spatiotemporal extensive coordinations do not pose much conceptual difficulty.

But suppose that the salesman were on a space transport on his way back to Earth from the Hong Kong Galaxy, twenty light years away, traveling at 0.8*c*. (*c* = the speed of light, approximately 186,000 miles per second). The fact that *c* is a constant in all reference frames means that there will be variances between (i) the spatial extensive coordinations from the salesman's inertial reference frame, relative to (ii) the spatial extensive coordinations from the wife's inertial reference frame. This will be evinced in the phenomenon of "length contraction" from the perspective of the salesman's inertial reference frame, such that the distance in the direction of his travel between the Hong Kong Galaxy and Earth will be twelve light years from the perspective of his inertial reference frame, and twenty light years from the perspective of his wife's inertial reference frame. Similarly, there will be variances between (i) the temporal extensive coordinations from the salesman's inertial reference frame, relative to (ii) the temporal extensive coordinations from the wife's inertial reference frame. This will be evinced in the phenomenon of "time dilation" from the perspective of the salesman's reference frame, such that the time interval of his travel between the Hong Kong Galaxy and the Earth will be fifteen years relative to his inertial reference frame, and twenty-five years relative to his wife's inertial reference frame.

Coordinate Division and the Decomposition of Invariant Spacetime Intervals

These variances in spatial extensive coordinations alone, and temporal coordinations alone, reflect the relativity of "simultaneity." The synchronization of the wife's watch and the salesman's watch, for example, would vary depending upon the reference frame from which the synchronization were measured. But the causal relationships between *serial routes of events* associated with the salesman and with his wife—events whose extensiveness is coordinated both spatially *and* temporally together as events in spacetime constitutive of *spacetime intervals*—are *invariant* regardless of reference frame according to Einstein's special and general theories of relativity.

From the perspective of Whiteheadian metaphysics, this relativistic invariance of spacetime intervals and the associated objectivity of causally related *spatiotemporally coordinated extensive events* is the key feature of Einstein's theory of relativity—not the phenomenon of time dilation with respect to merely temporally coordinated events, or length contraction with respect to merely spatially coordinated events. These phenomena may be pronounced when one considers nature's most fundamental constituents to be material particles existing in three-dimensional space and moving about this space in time. But when one considers nature's most fundamental constituents to be quantum actual events occurring in four-dimensional spacetime, the invariance of spacetime intervals and the objectivity of the causally related spacetime events constitutive of them are the truly important features of spatiotemporal extension and relativity theory. Relativity theory, in other words, is most importantly a theory of the objective invariance of spacetime intervals and the relations among events constitutive of them. It is not merely a theory of the subjective variance of spatial coordination and temporal coordination. Commenting on relativity theory at a public lecture in 1908, the mathematician (and onetime instructor of Einstein) Hermann Minkowski proclaimed, "The views of space and time that I wish to lay before you have sprung from the soil of experimental physics, and therein lies their strength. They are radical. Henceforth space by itself, and time by itself, are doomed to fade away into mere shadows, and only a union of the two will preserve an independent reality."[3]

The key to relativistic invariance is, of course, the constancy of the velocity of light regardless of reference frame. Because of this constancy, light cones are invariant for every event in spacetime, and thus the causal relationships among events within one event's past light cone will hold universally, for any event in any reference frame. It may be that for a given event located at a particular set of spacetime coordinates, two causally, historically related spacetime events will lie in the past light cone of the percipient event. The salesman might, for example, spill a cup of coffee and burn his hand, both events being historically related events in his past light cone. Thus, these events can be—and very likely are—causally influential of the salesman at his spacetime coordinates. But these events might lie outside the past light cone of his wife, and as such, their causal relations cannot be causally influential of her. They might lie in her future light cone, or they might lie outside both light cones in the hazy realm of "her contemporary universe." But the logical, asymmetrical, historical ordering of those two events nevertheless holds universally. There can be no reference frame, for example, wherein the event of the coffee spill is subsequent to the salesman's hand being burned by the spill. And in the same way, there can be no reference frame wherein the salesman becomes a father prior to his child being born. Indeed, one can imagine some percipient event at a particular set of spacetime coordinates for whom all of the aforementioned events lie in its past light cone—the spilling of the coffee, the burning of the hand, and the birth of the child. The asymmetrical, logical, causal order of these spacetime events will be maintained for this percipient—in its case as a temporal order—for the same reason they are maintained for any extensive, spatiotemporally coordinated percipient event: because of the relativistic invariance of spacetime intervals.

This does not mean, however, that there must be some "absolute reference frame" according to which *all* actualities are *universally temporally ordered*, or *universally spatially ordered*. Extensive spatiotemporal coordination of events does indeed yield invariant spacetime intervals among these events; but such intervals are always only *partially* ordered: their asymmetrical causal order is globally invariant, but the various temporal and spatial coordinations of events in an invariant spacetime interval entail manifold diverse potential decompositions of the invariant spacetime interval into different sets of potential timelike and potential spacelike intervals of varying magnitudes. There might be, for example, many different potential timelike intervals which include two causally related events *A* and *B*. Some potential timelike intervals will entail time dilation, some more than others, and some none at all, and so all of these potential timelike intervals will entail different magnitudes. But the asymmetrical causal order of *A* and *B* remains universally invariant. Thus, spacetime events are limited to *partial ordering,* such that causal order among actualities always holds universally, but there will be many *potential spacelike intervals* and *potential timelike intervals* of different magnitudes spanning any two actual events. The salesman's journey from Earth to the Hong Kong Galaxy and back again, for example, entails event A—his leaving, and event *B*, his return. If his wife is present at both events, then given the effects of time dilation referred to above, the timelike interval between events A and *B* from the salesman's reference frame has a magnitude of thirty years (fifteen years out, and fifteen years back). Whereas the timelike interval between events A and *B* from the wife's reference frame is fifty years (twenty-five years out, and twenty-five years back). Regardless, though, the asymmetrical causal order among events associated with the salesman and the wife along these intervals is universal. The fact of time dilations does not, in other words, entail the possibility of a causal effect temporally preceding its cause. Causal agent-events will always temporally precede their causal patient-events, universally and regardless of time dilation or any other relativistic phenomenon.

Spacetime intervals, then, can be decomposed or coordinately divided into diverse potential mixtures of (i) "timelike" intervals of temporally related events (where one event lies within the light cone of the other event), (ii) "spacelike" intervals of spatially related events (where one event lies outside the light cone of the other event), and (iii) "lightlike" intervals of luminally related events (where one event lies on the light cone of the other event, such as events spanning an ideal electromagnetic transmission in space).

Thus, according to Einstein's relativity theory, the constancy of the velocity of light in all reference frames yields two types of relations among extensive spatiotemporally coordinated actualities: (i) symmetrical spatial and temporal relations among actualities belonging to different inertial coordinate systems (as regards, for example, the relativity of "simultaneity"); (ii) asymmetrical spatiotemporal relations among spacetime intervals as historical routes of actual events. The famous "twins paradox" is a popular thought experiment which exemplifies this distinction between symmetrical and asymmetrical extensive relations. It is similar to the salesman-wife example above, so we can incorporate them: Imagine twin sisters, one on Earth and one riding with our salesman on his starship, traveling at .8 c to the Hong Kong Galaxy twenty light years away. They arrive, turn around, and return to Earth, again traveling at 0.8c. Because of the effects of time dilation described earlier, when the twins are reunited after the trip, the traveling twin will be younger than her sister.

The reason this has occasionally been considered paradoxical within the framework of special relativity is because according to this theory, spatial and temporal relations among actualities belonging to different inertial coordinate systems, such as the Earth and the ship, are *symmetrical*. For from the perspective of the starship, it is *Earth* that is moving away from the ship as it heads toward the Hong Kong Galaxy; and from the perspective of Earth, it is the ship that is moving. Special relativity thus holds that there is no way to objectively distinguish between uniform motion and rest when relating inertial coordinate reference frames. Therefore, it is argued, there is no reason why *both* the earthbound sister and the traveling sister should not experience the effects of time dilation. Why is it that only the traveling sister has aged less as the result of the trip, and not the earthbound sister, too?

Within the framework of special relativity, which applies only to inertial reference frames, the answer is simple, though not too satisfying: The starship does not travel with uniform motion throughout the trip. It undergoes acceleration—changes speed as well as direction—when it turns around at the Hong Kong Galaxy and heads back home (and also presumably when it departs and returns to Earth, speeding up as it leaves and slowing down when it returns). A more satisfying answer, however, is found within the framework of general relativity, which applies to *all* spatiotemporal reference frames, including those undergoing acceleration: The moments of acceleration are historically, asymmetrically, causally related *events* in spacetime, in the same sense that the salesman's coffee spill and burned hand were such events in the previous example. These spatiotemporally coordinated events associated with the spacefaring twin form spacetime intervals that are asymmetrically related to other spacetime intervals, such as those intervals describing the earthbound twin. Associated with each twin, then, is a "worldline" comprising historical routes of extensive spatiotemporally coordinated events and the invariant spacetime intervals spanning these events. The earthbound twin's worldline is thus asymmetrically related to the traveling twin's worldline, as well as to the worldline describing the historical route of any other spatiotemporally extensive actuality.

Thus the logical historical ordering of event data in the mental pole finds its reflection in the relativistic spatiotemporally extensive coordinations of event data in the physical pole—so long as these data are *extensively coordinated spatiotemporally*. The relativity of spatiotemporal extensive coordination in the physical pole is not in any way at odds with the logical, historical relations of events given in genetic analysis of the mental pole; concrescence is dipolar, with the operations of each pole implicative of those of the other. There are indeed symmetrical relativistic *spatial coordinations* and *temporal coordinations* in the physical pole that stand opposed to the asymmetrical logical relations of data in the mental pole. This is to be expected, as the poles *are* diverse despite their mutual implication. But the *spatiotemporal* extensive coordination of actualities yields invariant spacetime intervals comprising asymmetrically ordered causal relations among the events constitutive of these intervals. These asymmetrical causal relations are universal and absolute.

Hence, not *every* extensive coordination in the physical pole is noninvariant relative to various reference frames. There are, in fact, many relativistic invariants—objective absolutes—operative in Einstein's theories of special and general relativity. Most important for this discussion is the invariance of the spacetime interval spanning two spatiotemporally coordinated events, such that their asymmetrical causal order is maintained universally. This might be seen as a reflection in the physical pole of the logical asymmetrical, historical ordering of data in the mental pole, and vice versa. But four-dimensional spatiotemporal extensive coordination in the physical pole yields other relativistic invariants as well, including momentum-energy, where energy is the temporal extensive aspect of the coordination and momentum the spatial extensive aspect; electric charge–current density is another, where charge density is the temporal extensive aspect of the coordination, and current density is the spatial extensive aspect.

There are, then, two fundamental interrelated principles underlying all of these relativistically invariant relations: (i) the constancy of the velocity of light; (ii) the four-dimensional spatiotemporal extensive coordination of event data in the primary stage of concrescence. Other coordinations are possible—spatial extensive coordinations, temporal extensive coordinations—and these will yield noninvariant spatial relations, and noninvariant temporal relations relative to diverse reference frames. But with respect to those aspects of extensive coordination of data in the physical pole which find their implication in the asymmetrical logical ordering of data in the mental pole, the key lies in the four-dimensional spatiotemporal extensive coordination of objectified data in the physical pole, productive of relativistically invariant intervals spanning events in spacetime.

Empirical Adequacy and the Constancy of the Velocity of Light

It is clear that apart from constancy of the velocity of light, the invariance of spacetime intervals would be jeopardized. In this sense, this critical, constant velocity *c* provides a bridge between the logical order of actualities operative in the mental pole and the casual, spatiotemporal order operative in the physical pole. Were there velocities that exceeded *c*, there could be actualities existing simultaneously in numerous places, and the logical order and the directionality of time given by a closed past and an open future would be compromised. One could then posit, as Richard Feynman once playfully did, that there exists only one electron in the whole of the universe, zipping around in space and time from the past into the future and from the future into the past, such that whenever and wherever one observes an electron, one is really observing the same entity.

Thus, apart from the critical velocity *c*, the very identities of actualities would be as jeopardized as their logical order and their causal relations. And extensive spatial location would suffer the same fate as extensive temporal location: Nonlocal causal affection of potentia by logically prior actuality, of the sort exemplified by the EPR-type experiments, would be indistinguishable from local causal influence of actualization by temporally prior actuality. All notions of spatiotemporal extensive publicity and privacy would be lost.

But the constancy of the velocity of light is just one of the two fundamental principles from which Einstein deduced his theory of relativity—and the second is just as significant to Whiteheadian metaphysics as the first: *The laws of physics take the same form with* *respect to any inertial system of coordinates*.[4] Recall that Whitehead suggested four desiderata which any speculative metaphysical scheme must meet:[5] The scheme should be (i) *logical*; (ii) *coherent*, in the sense that its fundamental concepts are incapable of abstraction from each other; (iii) *empirically applicable*, meaning that the scheme must apply to at least some types of experience; and (iv) *empirically adequate*, in the sense that there are no types of experience conceivable that would be incapable of accommodation by the interpretation. The latter two desiderata (and indirectly the first) are clearly exemplified by the two principles from which Einstein deduced his theory of relativity: (i) The laws of physics take the same form with respect to any inertial system of coordinates; (ii) the speed of light is *c* with respect to any inertial system of coordinates.

As regards this latter principle, it should be emphasized that for Whitehead (and likely as well for Einstein) the critical importance of the constant *c* had little to do with its relation to the phenomenon of *light per se*; its significance, rather, lay in the derivative invariance of spacetime intervals and the associated possibility of (i) the asymmetrical, logical and causal ordering of events within spacetime reference frames, and (ii) the provision of a congruence relation that allows for the comparison of spatial and temporal extensive coordinations across diverse spacetime reference frames. In other words, the only reason that spacelike intervals and timelike intervals are *relatable* at all among diverse spacetime reference frames is that the velocity of light is constant in all frames. Indeed, for Whitehead, the speed of light in a vacuum was likely but a specific approximation of a generic critical velocity *c* operative in relativity theory:

> The critical velocity *c* which occurs in these formulae has now no connexion whatever with light or with any other fact of the physical field (in distinction from the extensional structure of events). It simply marks the fact that our congruence determination embraces both times and spaces in one universal system, and therefore if two arbitrary units are chosen, one for all spaces and one for all times, their ratio will be a velocity which is a fundamental property of nature expressing the fact that times and spaces are really comparable.[6]

> Both light and sound are waves of disturbance in the physical characters of events; and the actual course of the light is of no more importance for perception than is the actual course of the sound. To base the whole philosophy of nature upon light is a baseless assumption.

> The Michelson-Morley and analogous experiments show that within the limits of our inexactitude of observation the velocity of light is an approximation to the critical velocity "*c*" which expresses the relation between our space and time units.[7]

Coordinate Extensive Relations and Genetic Historical Relations: The Dipolarity of Relativity Theory and Quantum Mechanics

The dipolar relationship between (i) the spatiotemporally extensive, relativistic, coordinate analysis of concrescence, and (ii) the historically extensive, logical, genetic analysis of concrescence, entails an analogous relationship between relativity theory and quantum mechanics, respectively. At the heart of this relationship is the identification of invariant spacetime intervals with the quantum mechanical state evolution of the events comprised by these intervals. A null spacetime interval, then, would represent a single quantum state. The interval spanning the emission and absorption of a photon is such a null spacetime interval—which would imply that photon emission-absorption is, from the standpoint of both coordinate and genetic division, a single quantum event. Given this, and the invariance of *c*, one could characterize a photon of electromagnetic energy as a quantum interaction between two events along a null spacetime interval—that is, a concrescence whose subject and physical prehensions span this null spacetime interval. For Whitehead, in reference to the above two quotations, this would be preferable to the characterization of a photon as a luminous, "mass-less particle" which "travels" at the constant velocity *c* in a "vacuum." All three quoted terms imply a fundamental mechanistic-materialistic conception of nature.

The decomposition of an invariant spacetime interval yields relativistically noninvariant timelike and spacelike intervals. Actualities that lie in the past light cone of a given event—that is, actualities constitutive of a timelike interval—are logically and historically ordered, such that regardless of reference frame, local asymmetrical causal orders hold globally; but again, this constitutes only a *partial* extensive ordering of events, not a global ordering, for there are manifold potential spacelike and timelike intervals of varying magnitudes which might span any two events. As regards the example of the twins, two asymmetrically related events, "ship leaving Earth" and "ship returning to Earth" entail an invariant spacetime interval which can be decomposed into different potential spacelike and timelike intervals of varying magnitudes. The timelike interval associated with the spacefaring twin, for example, is dilated relative to that of the earthbound twin, even though these intervals span the same two events.

Put another way, the limitation of partial ordering among actualities in spacetime ultimately derives from the fact that not all events are merely timelike separated. There are spacelike separations to be considered as well. An event C might lie outside the past light cone of causally related events A and *B* (i.e., where A lies in the past light cone of *B*); thus C will be spacelike separated from, and essentially contemporaneous with *both* A and *B*. Nevertheless, the logical, asymmetrical order of A and *B* holds universally—*even for* C, despite the causal limitations inherent in its spacelike separation from A and *B*. This brings us back to the example of the salesman and his wife. Event C above is associated with the salesman; event A is associated with his wife just prior to the birth, and event *B* is associated with the birth. We saw earlier that quantum mechanically, event C is in fact logically and historically asymmetrically related to events A and *B*, despite the fact that in terms of spatiotemporal extension, the relations between C and A, and C and *B* are symmetrical. Again, this symmetry derives from the fact that spatiotemporal extensive coordination yields only a partial ordering among the events coordinated. The EPR-type experiments demonstrate this same distinction between (i) global, asymmetrical, logical-historical quantum mechanical relations among *spacelike* separated events, and (ii) local, asymmetrical, temporal-historical extensive relations among *timelike* separated events. Causal affection of potentia by logically prior actuality pertains to the former; and causal influence of actualization by temporally prior actuality pertains to the latter.

In some sense, then, the partial spatiotemporal ordering of events constitutive of invariant spacetime intervals is never exclusive of—that is, never merely complementary to—the global quantum mechanical historical ordering of events. If the significance to experience of *spatiotemporally extensive coordinate relations among actualities* is to maintain its reflection in modern physics, and if the significance to

END OF CHAPTER SAMPLE

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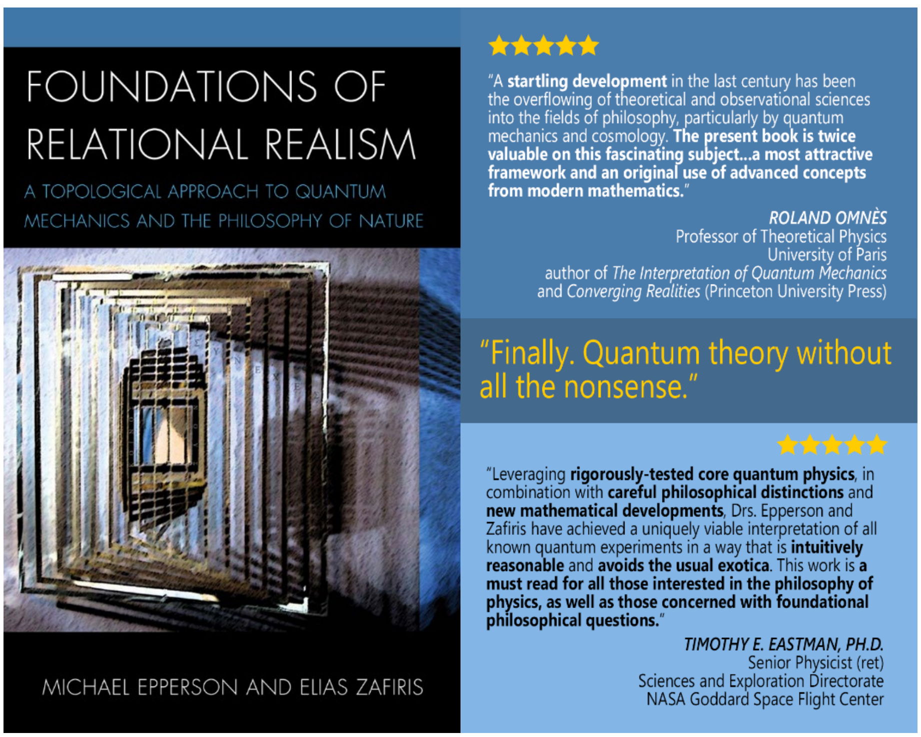

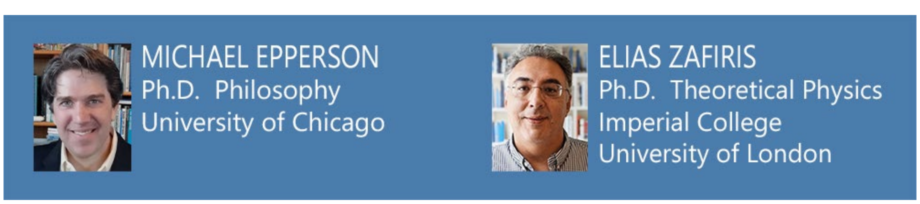

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