COGNITIVE ROOTS OF QUANTUM WEIRDNESS

1. Introduction

Science unfolds in the gulf between the noumenal world-in-itself and the parochial nature of embodied cognition, attempting to bridge them. Theories about physical reality are the cognitive strategies of an organism, rather than direct revelations of truth. They serve human aims, just as ordinary perception serves the interests of the organism. Sense-making is grounded in the expectations of daily experience.

Classical physics developed from experience on the familiar human scale, roughly halfway between the smallest and largest known things. While it is convenient to assume that physical laws as we know them should apply on other scales as well, there is no a priori guarantee of such a fit. That assumption is arbitrary if “laws” are not transcendent metaphysical principles (as they have often been considered), but simply pithy summaries of actual data gleaned on our scale. In perspective, it is hardly surprising that some classical concepts were found not to apply outside the domain of ordinary experience.

Quantum theory challenges our basic ideas concerning space, time, causality, and the role of the subject in relation to the object. The gulf between reality and cognition it obliges us to confront is characterized by the vast difference in size between the macroscopic and the microscopic realms. The quantum realm confounds ordinary expectations because we assume that notions based on ordinary experience should apply there as well. Yet, in truth, many of those expectations are not based on logically consistent notions even in the classical realm.

Just as light (or some other medium to convey information) is required for knowledge of astronomical objects, so some medium to convey information is required to probe the tiny reaches of the microscopic realm. In all cases, there is a relationship between subject and object, with an intermediary between them—a messenger or signal that interacts both with the observed and with the observer. The properties of this messenger must be taken into account. The small energy of visible radiation does not perceptibly affect the state of macroscopic objects it interacts with. In the micro realm, however, the energy of the messenger is comparable to that of the small entities with which it interacts. The interaction mutually disturbs the probe and the system probed.[1]

Just as the extreme speed of light renders negligible the effect of observation at everyday speeds, so the extremely fine grain of light renders its effect on normal interactions negligible. This is why quantum effects—like relativistic effects—remained undetected for so long. But, physics eventually had to take into account the finite velocity of light; it was obliged to by inconsistencies that arose because of the failure to do so. In the same way, it was obliged to confront the discontinuous structure of the world because of inconsistencies that arose from the assumption of continuity. Both these developments, which began in late 19th century, are effects

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[1] You can visually track the path of a billiard ball, for example, without light disturbing its position (path)—or that of your eye. Imagine, however, that the only way to gain information about the position of the ball was by means of another billiard ball that you roll to collide with it. Assuming you do not have the benefit of sight, this would give only ambiguous information about the location of the first ball, let alone its path after the collision, which might be assessed by how and where the probe rebounds to a curb of the table or falls into a pocket. Moreover, if the billiard table were nearly weightless, and mounted on frictionless wheels, striking the pocket or side of the table would affect *its* position in the room.

of scale with deep roots in ancient conundrums inherent in the logic and common sense derived from human cognition.

The paradigm of the quantum realm is the infamous wave-particle duality. Underpinning it are fundamental contradictions and inconsistencies in human thinking that have been there all along. For example, physical processes obviously take time; yet, the world appears instantaneously and transparently to the visual sense. Any intervening process, whether in the brain or in the external world, is not apparent. Nor is it apparent to us moderns, any more than it was to Zeno, exactly what it is that *takes* time in causal processes. Similarly, the substances that make up the world appear to be continuous and potentially divisible; yet they are also organized into discrete objects separated by apparently empty space. Then, is material reality ultimately continuous or discrete? Such questions, and the apparent contradictions behind them, perplexed and divided the ancients long before modern science could address them. Yet, the modern answers are no less perplexing and dividing. They defy reason perhaps because reason itself, like the biology underlying human cognition, has changed little over the course of millennia of adaptation.

The micro world is strange and baffling because it does not jive with the cognition that evolved for creatures dealing with mesoscopic objects and processes. To put that the other way around, the quantum world reveals the lengths to which human cognition has gone to adapt to the scale of its *umwelt*. The dilemmas of the quantum realm reflect the natural commitments of human cognition, including such notions as realism and causality. Yet, these commitments are hardly coherent among themselves. How, then, can they serve as the basis for a coherent vision of the world?

2. Wave-Particle Duality

The wave-particle duality corresponds to the ancient conundrum of the discrete versus the continuous, the part and the whole, the one and the many.[2] A discrete object can be conceptually integral, a whole with no parts; yet the objects we know can be divided into parts. Perfectly elastic collision between integral objects is not a logically consistent notion either. For, a physical particle cannot have volume and also be a perfectly rigid body; collision would have to be instantaneous, involving no internal forces. But neither can it be a dimensionless point. The transmission of forces—whether within the object or across space between objects—presumably must take time. But how can such transmission itself be understood, except in terms of smaller parts acting at a distance, or in terms of a disturbance conveyed through a medium, which simply regresses the problem and still does not answer the question of why time is involved in the transmission of force?

The wave-particle duality expresses the idea that the world consists of discrete things separated in space *and* is an indefinitely divisible continuum. What is often lacking in discussions of what the world *is*, however, is discussion of what the observer *does*. Quantum entities appear in some contexts to be wave-like and in others to be particle-like. These are appearances *to observers*, whose nature must also be taken into account, along with that of the medium of observation and of the equipment involved.

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[2] "In fact, a thorough scholarly study of the history of the logical relationship between these two notions [wave and particle]…still remains a project for future research." [Max Jammer, *the Conceptual Development of Quantum Mechanics* 1966/AIP 1989, p24]

As mesoscopic creatures, we naturally organize our perception of the world as consisting of objects separated in space. Continuity between them is no more perceptibly obvious than the air we breathe. Yet something—light—obviously bridges the gulf to connect objects in our perception. Rather circularly, we are inclined to think of this connecting agent itself in the objective terms established by ordinary perception: things moving in space, whether the thing (light) is considered a particle or a wave front. The real mystery here cannot be unraveled in such terms alone. For, it is hardly possible to see the thing by means of which you see, using that thing itself.

The theoretical challenge of the wave-particle duality is framed as the problem to understand how apparent objects can manifest interference patterns; or, to understand how apparent waves (spreading in space) can suddenly be absorbed by an atom at a single location. Yet *particle* and *wave* are not straightforwardly objective facts. They are rather metaphors drawn from common experience of things seen. They implicate the very concepts of 'thing' and 'space' and 'continuum' as categories of thought. What category does light belongs in? If it is not a thing seen, but the means of seeing, is it a thing at all? Of course, light is classed as a boson in the Standard Model. But perhaps that simply reflects the general commitment of science to unify phenomena in a common ontology. That commitment in turn reflects the general outward orientation of the mind, an arrangement that is a product of natural selection.

Quantum phenomena appear to be particles in detection but waves in propagation.[3] Macroscopically, "particleness" and "waviness" seem to be disjunct properties, and we are certainly unfamiliar with anything ordinary that appears to be both wave and particle or a cross between them. Yet, that is what seems implied by the wave-particle duality, which suggests that a photon is a localized indivisible whole (a particle that can pass through only one of two apertures), but is also dispersed in space (a wave that can pass through both). We have no ordinary experience of this in the world at fingertips. It is the logic derived from familiar experience that tells us the wave-particle duality is a contradiction.

While the quantum world is strange and unfamiliar, if it is the *fundamental* level of physical reality, as physicists often claim, then it must nevertheless be truer to reality than our familiar experience. Yet, it is the latter we take for granted as how the world *is*. The micro world presents a challenge to our understanding because it does not conform to that familiar image as described by classical physics. The early quantum physicists naturally tried to grasp the quantum world in the terms of concepts successful in the classical realm, which in turn were derived from common experience. As such attempts became ever more problematic, however, the formalisms of quantum theory were accepted to the extent they *worked*, regardless of whether they made intuitive sense or aligned with classical concepts.

3. Interpretation and *Anschaulichkeit*

The mathematical formalisms of quantum theory have proven highly successful, especially in developing new technology, which no doubt encourages further concept formation in that realm. However, there remains a gap between practical utility and intuitive comprehension, with an insistent psychological need to bridge the gap. Perhaps, in some ways, this parallels the

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[3] "In a nice twist of history, G. P. Thompson won the Nobel prize for showing that the electron is a wave whereas, 31 years earlier, his father J. J. Thompson had been awarded the Nobel prize for showing that the electron is a particle!" [Jim Baggott *The Meaning of the Quantum Theory* Oxford UP, 1992, p19]

unresolved explanatory gap between the mental and the physical, which never prevents people from conducting their lives. Just so, physics can charge ahead to manipulate the invisible micro world because of benefits on the human scale. Yet, intuitive comprehension lags behind, precisely because it is bound to the realm of direct experience.

Questions of interpretation of the formalism certainly occupied the early protagonists of the quantum theory, beginning with Planck, who saw the need to quantize energy but was reluctant to believe in the quantum as a real object.[4] The famous debates between Einstein and Bohr, and the competition between Schrödinger and Heisenberg, concerned essentially how to reconcile, through the use of visualizable models, classical concepts with the strange aspects of the micro realm. One could, for example, picture a spherical wave-front of radiation as consisting of myriad discrete parcels; yet each such parcel seemed to retain the wave-like property demonstrated in interference, as well as the particle-like ability to be absorbed at a singular location.

Schrödinger thought that the discrete energy levels of electrons, which Bohr had proposed to account for atomic spectra, could better be understood as harmonic resonances of standing waves (in a continuous energy field), rather than as orbits of particles on the analogy of planets. Schrödinger himself admitted that his wave function was defined in "configuration space" and could not be interpreted literally in real space. Moreover, while Heisenberg's alternative matrix formalism tried to skirt the issue of interpretation, Schrödinger's formalism embroiled the wave picture in a troublesome implication subsequently known as the "collapse of the wave function." Even when the wave equation was reinterpreted by Born as describing a probability rather than literal standing waves, there seemed no explanation for why mere probability shifted to actuality when radiation was absorbed or detected at a particular location. We see in such struggles the persistent desire of theoreticians to metaphorize invisible processes in familiar terms.

The intuitively comprehensible or visualizable[5] aspect of a model was of ongoing concern to the early quantum physicists—which we can understand as a natural desire to ground physics concepts in macroscopic experience. In that regard, to compete with the more intuitive appeal of Schrödinger's wave conception, Heisenberg introduced his microscope thought experiment, in part to establish a more visual basis for his matrix conception. It was this exercise that led to the famous relations that became known as the Uncertainty Principle.[6]

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[4] Planck was taken aback by his own discovery, which contradicted the classical axiomatic idea of continuity. He thought that "oscillators" could absorb or emit radiation only in discrete amounts, while the radiation itself might be continuous in space. It was Einstein who took the further step to claim that radiation consisted of discrete parcels (photons) even in free space.

In seeking a radiation formula that fit experimental data for a wide range of wavelengths, Planck in effect interpolated between two expressions, one of which leads to Wien's formula and the other to the Raleigh-Jeans formula; in effect this amalgamated the wave and particle aspects of radiation. [Max Jammer, *Conceptual Development* op cit, p34]

[5] *Anschaulich*, in the German literature of the time.

[6] However, "Heisenberg never seems to have endorsed the name 'principle' for his relations. His favourite terminology was 'inaccuracy relations' (*Ungenauigkeitsrelationen*) or 'indeterminacy relations' (*Unbestimmtheitsrelationen*)." [Note that the latter German term can mean indeterminacy or uncertainty. The connotation of 'indeterminacy' is ontological; that of 'uncertainty' is epistemic.] Furthermore, while the uncertainty relations are a central aspect of quantum theory, a satisfactory derivation of quantum theory from them has apparently never been carried out, and actual experiments in support of the uncertainty relations have only been performed relatively recently. [Stanford Encyclopedia of Philosophy: Uncertainty Principle, sec 2.4] It might be thought that the uncertainty concerned is a consequence of the

In his 1927 paper,[7] Heisenberg proposes an imaginary gamma-ray microscope to precisely determine the position of an electron, noting that its momentum will be changed by the interaction with the gamma radiation. But, has the position in fact been precisely determined? His argument trades on the ambiguity of 'determine'—a term that might refer either to a posited interaction event or to a *detection event* presumably caused by it. In the ontological (causal) sense, the event of the interaction happens at a definite place and time with respect to some reference frame. From the observer's viewpoint, however, what is actually observed is a separate event taking place somewhere else at a slightly different time—on the retina or a photographic plate, for example, or perhaps in the brain of the observer. The electron's objective position at the moment of the interaction must be inferred from this. That interaction is a theoretical event, distinct from the detection event actually observed. To produce the latter, the scattered gamma photon must subsequently interact with a molecule on a detection screen (or equivalent, such as the retina), amplified somehow to become visible. It is the position of *that* molecule which is "determined."[8] It is not possible to simply illuminate the electron and look at it under the microscope, in the literal manner we are used to and as suggested by the thought experiment. Similarly, the electron's momentum cannot be directly observed, but only through its effects in some detection device. Just as mass cannot easily be disentangled from velocity in observing distant macroscopic events, so also in the micro realm, when what is observed is momentum or the result of a transfer of energy, which is relative to the dynamical state of the observer.[9] It is no more possible to directly weigh electrons than to weigh planets. Though literally invisible, should the quantum event be visualized as an occurrence like the collision of two ordinary objects? Or is it rather an occurrence in a measuring apparatus, visible because it happens on our scale?

4. Eye of the Beholder

Since all experience, thought, and action reflect both object and subject, the fact that quantum objects defy intuitive expectations must inhere as much in our context as embodied organisms as it does in the physical world itself. It may reflect the natural tendency to organize experience in terms of "objects" separated in "space," for example. While something in the world-in-itself must correspond to "objectness," it is also an adaptive feature of cognitive organization, which spills over into the ontology of science. Moreover, inconsistency in human concepts does not necessarily mean that *nature* is inconsistent. Rather than gloss over apparent inconsistencies in nature, it is more honest and fruitful to acknowledge that science has no consistent conceptual

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wave-like nature of quantum phenomena. That is circular reasoning, however, since "wave" metaphorically describes the same epistemic effect as the uncertainty principle. (That is, waves are literally vague, at least in French!)

[7] Werner Heisenberg "The Actual Content of Quantum theoretical Kinematics and Mechanics", 1927 (archived by NASA 1983 in translation). Note that "actual" content, like "visualizable" is a translation of the German *anschaulich.*

[8] Alternatively, the electron itself must interact with a detection screen, in which case *its* (scattered) position registered there is not its position at the putative time of interaction with the photon.

[9] According to the de Broglie equation, the wavelength of a particle is a function of its momentum, which (as in Special Relativity) is relative to the dynamic state of the observer. [Taha Sochi *The Epistemology of Quantum Physics* 2022, p109 (Sec 5.3.1.2)]

basis underlying it and can hardly present a coherent picture, let alone absolute truth. Rather, like cognition generally, science "enables us to orientate our activities by anticipating the outcome of each act we perform…"[10]

On the one hand, an "object" is integral, a coherent whole, an individual. On the other hand, it is extended in space, and may endure in time. Intuition tells us that extended things or processes consist of functional parts or potential conceptual subdivisions that can in turn be subdivided. (Hence the mathematical notion of the continuum, and the problems of infinities and infinitesimals that have beset mathematicians ever since Zeno.) While intuitions about integrity, infinity, and indefinite divisibility extrapolate experience gleaned on the human scale, there is no *a priori* reason to assume they hold in unfamiliar domains. If we are tempted to regard some particles as truly elementary, for example, it may be only because we do not have the energy resources to break them into something more fundamental. Yet, perhaps it may also be that we balk mentally at the idea of unending complexity all the way down, not to mention infinity all the way up.

Classical properties are thought to inhere in things themselves.[11] As in relativity, however, quantum properties implicate the role of the observer as well. Even in the classical realm, it is only scale that permits the role of the observer to be disregarded. The disproportionate size, energy, mass, or slowness of ordinary objects in relation to the medium of investigation permits the latter to be ignored, so that the object can be considered in its own right. This bracketing of the observer, with focus on the observed, is what makes science possible. Yet, the circumstance of scale is but a contingent fact of the world we live in, to which we have adapted with an appropriate stance we call realism. While this anthropocentric stance works, in context and for its purposes, we cannot logically assume that ideas formed on the scale of human life are universally valid at every scale or in every circumstance. Moreover, classical properties can typically be *measured* by means distinct from how they are *produced*. For example, motion can be tracked visually, though it must be produced through some applied force. In contrast, quantum properties (e.g., polarization or spin) are measured by the same sort of apparatus (e.g., crystal or magnet) that reveals their existence, raising the question whether it is the act of measurement itself that creates the property.

In the early 20th-century, it began to be clear that the reality of nature as a whole cannot be embraced from the restricted point of view of the putative realism of classical physics, whose concepts are actually severe idealizations. While classical laws stand as universal generalizations, they actually apply only in special conditions. While such idealizations purport to represent the objective reality of the systems studied, they are, after all, intentional creations that draw liberally upon the power of the subject to define those systems, and ultimately upon the observer's biological nature and situation as a cognitive agent.

5. Identity, Individuality, and Statistics

The fact that elementary particles cannot be marked or tagged as individuals leads to a characteristically different statistical accounting for quantum entities. In fact, it is not *objects* that

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[10] Michel Bitbol "Some steps towards a transcendental deduction of quantum mechanics," sec4. Published in: Philosophia Naturalis, 35, 253-280, 1998

[11] The etymology of the very word *property* refers literally to the thing itself and not to relationships. Spatial location is then not a property but a relationship to a frame of reference—that is, to other objects.

are counted, but *detection events*—which may represent quantities rather than things. Is an electron a tiny object or a tiny quantity of electric charge? When quantity does not refer to individuals with distinguishable characteristics, it makes no more sense to speak of *this* electron as opposed to *that* one than it does to speak of *this* dollar as opposed to *that* one. "You can never point to the same particle twice" seems as true for microscopic objects as for Heraclitus' river. The river, like a bank account (or an electric current), is not itself a stable object, and what flows through it does not consist of identifiable things. This is relevant to conservation of mass, which has two possible meanings: conservation of a continuously variable *quantity*, or conservation of the *number* of massive particles. That is, conservation of a continuum or of a discrete collection of objects, again reflecting an ancient conundrum.

At the quantum scale, it seems there are not distinguishable individuals, only examples of *kinds*. A macroscopic object is identifiable as an individual thing, distinct from others, either by some distinguishing feature or else by its unique space-time location in relation to other identifiable things or some imposed framework. Ball bearings, for example, though made to be identical in principle, have slight deviations or imperfections of manufacture or incidental markings acquired through wear, which allow them to be identified as individuals.

Whether there can be objects of a kind that are identical in every respect but location has long been a matter of philosophical debate. Modern atomic theory is based on the supposition that all elementary particles of a kind are perfectly identical.[12] This notion defies experience on the macro scale, where it is acknowledged that real objects are never perfectly identical, in contrast to their idealized theoretical counterparts. In the micro realm, there is no way to tell electrons one from another. The difference between the intrinsic being of something and how it is distinguished is moot there, since the individual object cannot be perceived in the ordinary sense, and the only way to verify anything about its theoretical counterpart is through experimental data that are statistical, involving many individuals. Indeed, elementary particles of a kind are simply *defined* to be identical.

Individuality also implies impenetrability, for otherwise an object could not uniquely occupy a momentary position. Two ordinary solid objects cannot occupy the same space at once; otherwise, they could not be counted distinct on the basis of spatial separation. (Waves, on the other hand, can interpenetrate but lack identity.) The numerical separateness of physical things rests conceptually on their impenetrability. Some things are *relatively* penetrable; they can be compressed and rebound like a spring. Penetrability depends on elastic forces, which might be completely overcome in extreme conditions: for example, in degenerate matter or unification of forces at high energy. Here, too, the intuitive concept of an impenetrable, substantial, individuated particle comes into conflict with the notion of the continuous action of forces communicated through some medium or field.

If all sub-atomic particles of a kind are by definition perfectly identical, there is no causal basis for why one individual particle should decay at a particular moment and another not, since there is no difference upon which a cause could act. (Hence the notion of randomness, indeterminacy, or unpredictability.) To maintain the causal picture would require a deeper description that includes individual identity—in other words, "hidden variables." But then the problem is to understand the causal basis for *kinds* of particles at all—why those of a kind are

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[12] Jammer *Conceptual Development* op cit, p358: "The atomic theory of the nineteenth and early twentieth centuries accepted… the qualitative identity of particles—but denied their indistinguishability!... For it was claimed that two particles, once 'told apart' can always be 'told apart', for they can always be reidentified thanks to the uniqueness of [their four-dimensional world-lines]."

defined by common properties and are not utterly unalike (in the way that planets could be). Ideally, the laws of physics should be able to explain the existence of kinds and predict the kinds that exist.

The challenge of distinguishing between two things of the same kind merges with the task of establishing the continuity of a single thing. The individual identity of something is relational, depending also on the observer's ability to identify it. A distinguishable characteristic must be observable. To the degree that 'particle' suggests a distinguishable object, it may be a misnomer from the start to call quantum entities particles.

If the quantum world consists of perfectly identical *units*, these are analogous, for example, to the units of value we call money. Without the distinguishing features of individual objects, they are circularly *defined* to be discrete, identical to each other and to their theoretical representations. As a physical coin, a given penny may have identifying marks and can be located in physical space. It's meaningful to talk of the probability of finding it somewhere. As a unit of value, however, it is meaningless to speak of finding a given cent in your bank account. To say that the state of a quantum system becomes real only when it is measured is like saying your bank account is real only when you check your balance. How should one regard the units of electricity called electrons—as tiny objects or as units of charge?

Some elementary particles have mass and locality: fermions (e.g., protons), which can be "at rest" or have a variable speed relative to an observer. Others are apparently massless: bosons (e.g., photons), without locality or a definable rest state, with speed relative to all observers curiously fixed. Except for quantization, it seems these are less like objects than like a bridge through space between objects. Yet, even a fermion cannot be an extended rigid object because, as such, it would transmit force within itself faster than light; on the other hand, neither can it be point-like, because the concentration of mass would be infinite and it would disappear in its own black hole.[13] Such conundrums point to enduring chaos in our basic categories of thought.

The concept of entanglement similarly indicates an inconsistency in the ordinary meaning of part and whole, which are matters of definition. Two apparent "things" (such as particles) are entangled when they are not actually individual things but an inseparable whole. That could mean that the only feature distinguishing them is spatial separation (with reference to a framework). Or, the difference could be some property that is defined to be complementary (and conserved) between them, such as momentum, spin, or polarization. Does that mean it is properties, rather than entities, which are entangled?

Two billiard balls which collide would have classically "entangled" momenta until they interact with something else. Because of conservation, to know the momentum of one can reveal the momentum of the other without changing it. However, this is not the case for two entangled quantum particles. To measure either can completely alter its state *and that of its pair*.

From the point of view of wave theory, entanglement is no surprise. By definition, a spreading (coherent spherical) wave front has the same properties at each locale at a given time. Rather, the mystery is how this wave can be absorbed in a discrete amount, at a particular location, defying the attenuation from expansion. While this is the essence of the wave-particle conundrum, it depends on an artificial construct (a coherent wave). The concept of coherence

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[13] Carlo Rovelli "Halfway through the woods: contemporary research on space and time" in John Earman and John D. Norton (eds) *The Cosmos of Science* U. of Pittsburg Press, 1997, p192-3

itself should be put in context as an artificially-induced state. The natural state on the human scale is “decoherence,” thermal agitation that destroys the possibility of interference.[14]

Like objectness and solidity, wave action and elasticity are concepts derived from experience on the scale of ordinary experience. So is the notion of a medium in which waves travel. These too illustrate logical inconsistencies within our metaphors. Solid objects can be broken apart, and the parts can be broken apart, but—unless it is “turtles all the way down”—at some point we must arrive at something with no further parts. But then how to understand the nature of those indivisible things, since our explanations typically rely on an analysis in terms of interacting parts? How to explain the properties of integral wholes themselves, the irreducible ultimate parts?

6. Continuity

The idea of indefinitely precise measurement rests on continuity. Equally (and circularly), the idea of continuity rests on indefinite precision of measurement. The limits to precision encountered at the micro scale were initially nonplussing to a mentality trained on the apparent continuity of the macro scale. The idea of causal determinism rests on precise knowledge of initial conditions—an idealization it was assumed could be approached indefinitely. But this illusion depended on a relative gap in size between the measuring apparatus and the thing measured.

The idea of continuity is itself paradoxical even in macroscopic terms. For, if matter is truly a continuous substance, what accounts for the fact that materials can be broken apart or have a crystalline structure? On the other hand, if it is truly continuous, why should there be any limit to how finely a substance can be divided? Some classical physicists were understandably reluctant to abandon continuity by even admitting the existence of the atom!

A quantum need not be a particle, and a minimum threshold for the emission or absorption of energy (quantization) need not imply object-like particles. One could reasonably question what it means to claim, as in some modern experiments, that the intensity of light is reduced to a single photon emitted at a time.[15] For, how can it be established that this minimal intensity is emitted without simply *assuming* the corpuscular nature of light? How can an apparatus be controlled to emit or absorb a single photon without separately (and destructively) verifying that this is the case?

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[14] P. Jordan “On the Process of Measurement in Quantum Mechanics” Phil of Science, Oct 1949, vol. 16 no.4, p273

[15] Writing before the first two-slit experiments performed on single electrons, Landé asks, “where has a single electron ever displayed an intensity and phase? Both only occur in the statistical display of many electrons.” [Alfred Landé *From Dualism to Unity in Quantum Physics* Cambridge UP, 1960, pxii] Modern experiments emit single electrons in effect by controlling some macroscopic factor that regulates the intensity of a current; it is *assumed* that one quantum of charge is involved at a time, but there can be no independent verification (detection) of this without altering its state. It is the pattern of many actual detection events that emerges as an interference pattern, which is interpreted as each electron interfering with itself in a wave-like manner. While that interpretation is reasonable, it is not logically necessary. (If time were irrelevant, for example, the many independent electrons could be considered as two streams interfering with each other.) Landé’s interpretation, based on Duane’s research on electron diffraction by crystals, would be that the two slits somehow act mechanically on the electrons like the crystal does, to produce a distribution that resembles an interference pattern.

7. Determinism, Measurement, and Uncertainty

Macroscopic physical entities can be distinguished from each other and can differ from their idealized theoretical counterparts, to which they correspond only approximately. In contrast, it is presumed that microphysical entities are literally identical to their idealized theoretical counterpart, and therefore to each other. Since there can be no difference between the real entity and its theoretical version, uncertainty in measurement has a different meaning than in classical physics. Heisenberg's famous uncertainty relations might be interpreted as restrictions on the precision of individual measurements. But since even classical measurements are subject to such tradeoffs[16] (e.g., the time required to establish velocity blurs the position), uncertainty relations make more sense interpreted statistically, as minimum spreads of error in large runs. The notorious quantum indeterminacy has nevertheless often been reified as something deeper than a failure to gain the sort of certainty we feel entitled to on the mesoscopic scale. But if determinism is not a feature of physical reality at all, then it is no surprise that individual quantum events are unpredictable.

Determinism in the causal sense is wishful thinking even on the ordinary scale. Models, equations, and artifacts are deterministic but the natural world is not.[17] On the other hand, *randomness* only means that no explanatory precedent or ordered pattern has been found. The concept of randomness cannot refer to how effects are generated (which would be an oxymoron), but only to how they are perceived. (Hence, there can be no true random-number generators.) Patterns can appear random in the sense that no algorithm (pattern) can be identified. The very concepts of determinism and indeterminism are thus both observer-dependent. There is always an agent who can or cannot determine something.

8. Completeness

The classical difficulty of predicting individual events was excused as due to imperfect knowledge of "initial conditions," despite perfect equations. Only a description that enabled prediction of individual events (that is, a deterministic theory) could be considered complete. But description that is complete in this sense can be only be a description of theoretical artifacts—products of definition—not of nature. Classical determinism is precise theoretically, whereas the precision of the quantum realm is statistical and empirical, an effect of large samples.

Though both are formalisms, quantum physics differs from classical physics in being driven by observational results that seem irreducibly statistical. An interpretation in terms of entities is

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[16] According to a theorem in Fourier analysis, *any* "linear, time invariant system" will have an uncertainty principle of the same form as Heisenberg's. [R.W. Hamming "The Unreasonable Effectiveness of Mathematics" American Mathematical Monthly, 1980] Heisenberg's famous uncertainty formula says that the product of measurement error in position and error in momentum cannot be less than an amount set by h, Planck's constant. That these are "conjugate" variables means that one essentially entails the other (e.g., the velocity factor in momentum (mv) represents change of position and thus entails position, so that change of one implies change of the other by definition).

[17] Unless it happens to be a product of definition, as Creationists assert!

not strictly implied in the data themselves (detection events), any more than it *logically* follows in ordinary perception.[18] Quantum physics is thus profoundly empirical, if not "realist."

The famous debate between Einstein the realist and Bohr the positivist reflects the general philosophical question of whether physics describes nature or our knowledge of nature. Bohr's approach emphasized experimental results and allowed "complementary" descriptions, while Einstein—in quantum theory as in relativity—sought to preserve an ontological view that maintained causality and the overall integrity of physics.[19] No doubt both believed in an external reality; yet, for Bohr, its properties could be known only through interaction with different kinds of experimental equipment.[20]

A description can be complete in regard to the existing state of knowledge, while incomplete as a description of external reality. In that sense, Bohr and Einstein were talking at cross-purposes. A probabilistic description is incomplete from a realist perspective that seeks to predict individual events. The state within the unopened box, in the scenario of Schrödinger's infamous Cat, is understood differently in the two perspectives. For Einstein, it is common sense that there can be no intermediate state between an exploded and an unexploded bomb. Yet, even if we do not know what causes a given bomb to explode or not (or a cat to die or not), we can know how many bombs fail to explode in a series of tests of ostensibly identical bombs. On that basis, we can establish the probability that a given bomb will explode within a given time, however useful that may be.

9. Conclusion.

The scientific ideal of predictability surely reflects the biological need of the human creature to maximize control over its environment. This is achieved first by creating a mental environment of formalisms and idealizations, over which it *does* have control, being products of its own definitions. The conceptual inconsistencies underlying many of the apparent inconsistencies of nature, especially in the quantum realm, surely reflect the ad hoc nature of human thinking, cobbled of inconsistent but useful notions, and aimed less at logical coherence than at survival. One could begin instead with nature itself—revealed empirically—as the model of rationality. A

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[18] The detection events that occur on the retina, for example—in the firing of individual rods and cones—do not of themselves provide knowledge of objects in the world. Such knowledge requires complex mental processing of patterns involving many such events.

[19] One reason to introduce the Lichtquanta, as Einstein called them, was "to cure the asymmetry between matter and radiation if the latter is continuous… [T]his magisterial idea of Einstein, of denouncing unphysical asymmetries in classical physics was already used, equally successfully, in the starting paragraphs of the special relativity paper…" [Luis J. Boya "The Thermal Radiation Formula of Planck (1900)" (arXiv:physics/0402064v1 2004), p11] Moreover, Einstein's deeply theoretical considerations were an inspiration to his contemporaries. Heisenberg hoped to find in his operational analysis of position and momentum a solution analogous to Einstein's treatment of simultaneity in SR. [Max Jammer *The Philosophy of Quantum Mechanics* Wiley & Sons 1974, p58] In Bohr's conception, the role of frame of reference in relativity is taken over by the role of different experimental set-ups. [ibid, p201] De Broglie shows "mathematically that the Lorentz-Einstein transformation joined with the quantum relation leads us necessarily to associate motion of body and propagation of wave…" [Louis de Broglie "A Tentative Theory of Light Quanta" Philosophical Magazine, 1924, p457]

[20] Jonathan Powers *Philosophy and the New Physics* Methuen 1982, p134

more truly rational science might then be possible, but whether it would be as useful is another question.