Zurek’s existential interpretation of quantum mechanics suffers from three classical prejudices, including the belief that space and time are intrinsically and infinitely differentiated. They compel him to relativize the concept of objective existence in two ways. The elimination of these prejudices makes it possible to recognize the quantum formalism’s ontological implications—the relative and contingent reality of spatiotemporal distinctions and the extrinsic and finite spatiotemporal differentiation of the physical world—which in turn makes it possible to arrive at an unqualified objective existence. Contrary to a widespread misconception, viewing the quantum formalism as being fundamentally a probability algorithm does not imply that quantum mechanics is concerned with states of knowledge rather than states of Nature. On the contrary, it makes possible a complete and strongly objective description of the physical world that requires no reference to observers. What objectively exists, in a sense that requires no qualification, is the trajectories of macroscopic objects, whose fuzziness is empirically irrelevant, the properties and values of whose possession these trajectories provide indelible records, and the fuzzy and temporally undifferentiated states of affairs that obtain between measurements and are described by counterfactual probability assignments.

Keywords: interpretation of quantum mechanics; macroscopic objects; objective existence; pointer states; quantum states; space; time.

1 Introduction

Detailed investigations of a large class of specific models, carried out over the past two decades, have demonstrated that the reduced density operators associated with sufficiently large and/or massive systems, obtained by partial tracing over realistic environments, become very nearly diagonal with respect to a privileged basis in very short times, and that they stay that way for very long times. In such systems environment-induced decoherence leads to einselection (environment-induced superselection) of a “pointer basis.” The special role played by (relative) positions in classical physics can be traced to the fact that all known interaction Hamiltonians are local (meaning that they contain δ functions
of relative positions). Because of this, the spreading of wave packets ordained by the uncertainty relations (and speeded up by non-linear dynamics) is counterbalanced by an ongoing localization relative to the environment. The result is a compromise between localization in position space and localization in momentum space. In the appropriate macroscopic limit the hallmark of classicality—localization in phase space—emerges. There is every indication that in linear systems these states form an overcomplete basis of (near) minimum-uncertainty Gaussian states defining position and momentum distributions that afford maximum predictability [1, 2, 3, 4, 5, 6]. These findings have motivated a new interpretation of quantum mechanics, the so-called “existential interpretation” [1, 2, 3], which has even been dubbed “the new orthodoxy” [7]. It is in large part the brainchild of Wojciech H. Zurek.

To say that physics is part mathematics and part philosophy is to state the obvious. Without the latter, physics would be nothing but a mathematical formalism; any statement purporting to address the relation of the mathematical formalism to the physical world is by nature philosophical. Philosophy of science comes in two broad categories. Empiricists defend the point of view that it is the business of science to make reliable predictions at the level of the observable. On this view, quantum mechanics encapsulates correlation laws, and the link between the formalism and the real world is measurement outcomes: they are (i) the correlata required by the formalism and (ii) real. Realists are more ambitious; they consider it the aim of science to discover a true description of the world.

In which category does Zurek’s interpretation belong? On the one hand, it is clearly more ambitious than the correlation interpretation [8] (a.k.a. “minimal instrumentalist interpretation” [9]) that satisfies the empiricist philosopher. According to Zurek, the existential interpretation completes the most straightforward, most literal, and therefore also most simple-minded realist interpretation of quantum mechanics: “Decoherence and einselection fit comfortably in the context of the Many Worlds Interpretation where they define the ‘branches’ of the universal state vector. Decoherence makes MWI complete” [3]. On the other hand, Zurek appears to want to remain noncommittal where the ontological status of quantum states is concerned: “There may be in principle a pure state of the Universe including the environment, the observer, and the measured system. While this may matter to some [10], real observers are forced to perceive the Universe the way we do: We are a part of the Universe, observing it from within. Hence, for us, environment-induced superselection specifies what exists” [3, emphasis in original].

What exists for us, according to Zurek, is predicated on decoherence and einselection, which is predicated on the deterministically evolving quantum state associated with a composite system that includes the environment and us. What exists for us, therefore, owes its existence (for us) to this deterministically evolving quantum state. If, following Zeh [10, 11], we attribute observer-independent reality to the universal state vector, we
have an ontological basis on which the “relative objective existence” that Zurek attributes to pointer states can be predicated. If we were to deny the reality of quantum states, we would effectively reduce the quantum formalism to an encapsulation of lawful statistical correlations between measurement outcomes. This would not necessarily put us inside the empiricist camp, inasmuch as it would allow us to attribute to the correlata an absolute objective existence, as the following will show. What makes it impossible to reconcile the mathematical formalism of quantum mechanics with the concept of a single objective existence is the construal of any one of the theory’s formal states as an evolving ontological state. One then has two kinds of reality, the bona fide reality of the universal state vector, and a reality in scare quotes—“In quantum physics ‘reality’ can be attributed to the measured states” [3]—which belongs to pointer states and to measurement outcomes indicated by pointer states. The fact that Zurek is unable to attribute to pointer states and measurement outcomes anything stronger than a relative objective existence, is to my mind a clear indication of his implicit faith in the absolute reality of the universal state vector.

The object of this article is to show how the mathematical formalism of quantum mechanics can be reconciled with an unqualified objective existence. Decoherence and einselection are as important to making sense of quantum mechanics as Zurek claims they are, but in order to arrive at an unqualified objective existence we must free ourselves from three classical prejudices: the belief that $|\psi(t)\rangle$ represents a physical state that evolves, the belief that $|\psi(t)\rangle$ evolves deterministically, and the belief that space and time are intrinsically and infinitely differentiated (Sec. 2). Only by doing so are we in a position to descry the ontological implications of the quantum formalism—in particular the relative and contingent reality of spatiotemporal distinctions and the extrinsic and finite spatiotemporal differentiation of the physical world (Sec. 3)—which are crucial for the wanted reconciliation (Sec. 4).

Contrary to a widespread misconception, viewing the quantum formalism as being fundamentally a probability algorithm does not imply that quantum mechanics is concerned with states of knowledge rather than states of Nature. On the contrary, unlike interpretations that transmogrify the quantal probability algorithm into an evolving physical state, it allows us to arrive at a complete and strongly objective description of the physical world that requires no reference to observers. What objectively exists, in a sense that requires no qualification, is the trajectories of macroscopic objects, whose fuzziness is empirically irrelevant, the properties and values of whose possession these trajectories provide indelible records, and the fuzzy and temporally undifferentiated states of affairs that obtain between measurements and are described by counterfactual probability assignments (Sec. 5).

Is it worth the trouble? Is it worth to engage in a struggle against prejudices that are hardwired into the neurobiology of perception [12, 13, 14], such as the belief that space
and time are intrinsically and infinitely differentiated? From the empiricist point of view, certainly not. For empiricist philosophers, the statement “there is a teapot on the table” means that anyone who cares to look will see a teapot on the table. The teapot has an intersubjective or weakly objective reality, and that’s all the reality they require.

Realists want more; they aim at a strongly objective reality independent of observers. If they see a teapot on the table then for them there is a teapot on the table whether or not anyone cares to look. It has been argued that standard quantum mechanics (unadulterated with spontaneous collapses [15, 16, 17] or Bohmian trajectories [18]) is inconsistent with a strongly objective reality, and that we must content ourselves with a weakly objective one [19, 20, 21]. (See, in particular, d’Espagnat’s assessment of Zurek’s philosophy [22].) These arguments suffer from at least three defects. The first is that nothing but a strongly realist conception of the world can explain the miraculous success of “the pinnacle of human thought” [23], quantum field theory. The second is that science owes its immense success in large measure to its powerful “sustaining myth” [24]—the belief that we can find out how things really are. Neither the ultraviolet catastrophe nor the spectacular failure of Rutherford’s model of the atom made physicists question their faith in what they can achieve. Instead, Planck and Bohr went on to discover the quantization of energy and angular momentum. If today we seem to have reason to question our sustaining myth, it ought to be taken as a sign that we are once again making the wrong assumptions, and it ought to spur us on to ferret them out. Anything else should be seen for what it is—a cop-out. The third defect is that these arguments implicitly accept at least one of the three classical prejudices mentioned above.

I make no apologies for the absence of equations in this article. For one thing, the quantitative results that underwrite its conclusions are the same as those that underwrite the existential interpretation. They are available elsewhere [1, 2, 3, 4, 5, 6]. For another thing, a physical interpretation of the mathematical formalism of quantum mechanics cannot be achieved by mathematical means; equations do not address the problem of making physical sense of equations.

2 Three classical prejudices

Every physical interpretation of the mathematical formalism of quantum mechanics has to spell out which of the formalism’s substructures or structural elements correspond to what actually exists. Zurek brings two Significant Insights to bear on this task, which I paraphrase by introducing two terms—“extrinsic” and “intrinsic”—that seem to me to be very useful in elucidating the ontological implications of quantum mechanics.

1. The values of observables are extrinsic: No value is a possessed value unless it is an indelibly recorded value—unless, this is to say, information about an observable’s
value is spread so abundantly across the environment that the resulting decoherence is irreversible, at least for all practical purposes.

2. Existence is predicated on persistence. In order to obtain something resembling the familiar macroworld, one must attribute objective existence to the maximally predictable pointer states. Since these provide their own records (on account of their predictability) they can be considered self-existent or intrinsic.

Zurek is compelled to qualify the first insight by turning the possession of a value into something that is relative to observers (via the environment in which they are embedded), and to qualify the second insight by attributing to the maximally predictable pointer states the highest degree of a nevertheless relative objective existence. This signals to me that Zurek’s insights are marred by three classical prejudices.

The first prejudice is that a vector in Hilbert space represents a state in much the same sense that a point in the classical phase space does. One way to surmount this prejudice is to look upon both the classical state (a point \( P \) in some phase space) and the quantum state (a vector \( |\psi\rangle \) in some Hilbert space) as probability measures. The difference is that a classical state assigns trivial probabilities (0 or 1) to the possible values (represented by subsets) of every measurable quantity, while a quantum state assigns nontrivial probabilities (greater than 0 and less than 1) to the possible values (represented by subspaces) of most measurable quantities.

The triviality of the classical probability measure permits its reinterpretation as an objective state of affairs: instead of taking \( P \subset E \) to mean that the probability of finding \( E \) is 1, one takes it to imply the truth of “system \( S \) is in possession of property \( E \)” or “observable \( O \) has value \( E \)” ; and instead of taking \( P \not\subset E \) to mean that the probability of finding \( E \) is 0, one takes it to imply the falsity of these propositions. If one countenances similar inferences for quantum states—\( |\psi\rangle \subset E \) implies the truth of these propositions, \( |\psi\rangle \perp E \) implies their falsity—one arrives at the most unwanted and unloved aspect of von Neumann’s axiomatization of quantum mechanics, the collapse postulate for repeatable ideal measurements.

Instead of addressing the root of the disease—the belief that \( |\psi(t)\rangle \) represents a physical state that evolves—Zurek contents himself with suppressing one symptom of the disease, the collapse postulate. This evinces his second classical prejudice, determinism. One way to surmount this prejudice is to accept that the phase space formalism of classical physics and the Hilbert space formalism of quantum physics both concern lawlike correlata. Here the essential difference is that classical physics deals with deterministic correlations while quantum physics deals with statistical/probabilistic correlations. From this essential difference further differences ensue.

The reason why the classical probability algorithm (represented by a point in some phase space) is capable of reinterpretation as an evolving physical state or a changing list
of possessed properties, is that it assigns only trivial probabilities, and the reason this is so is that the classical correlation laws are deterministic: if the state of the system is $P_1$ at the time $t_1$ then it has been or it will be $P_2$ at the time $t_2$. It is worth reminding ourselves that classical physics tells us nothing whatever about the state of the system at the time $t_1$, unconditionally, nor about the mechanism or process by which the state at $t_1$ determines (or is determined by) the state at $t_2$. (Progress in knowledge is often made possible by an admission of ignorance.)

Because the quantal correlation laws are irreducibly probabilistic, a factlike state at $t_1$ is not sufficient to determine a factlike state at $t_2$. Combined with a factlike state $|v\rangle$ at $t_1$ (a set $v$ of values possessed by a complete set of compatible observables) and with the measurement of a complete set of compatible observables at $t_2$ with possible value sets $w_i$, the relevant correlation law represented by the unitary operator $U(t_2,t_1)$ gives us the probabilities $|\langle w_k|U(t_2,t_1)|v\rangle|^2$ with which the factlike state at $t_2$ turns out to be $|w_k\rangle$. (As in the classical case, nothing needs to be said about the temporal order of $t_1$ and $t_2$.) Without assuming that a given set $W$ of compatible observables is successfully measured at a given time $t_2$, all we have is $|\langle \sqcup|U(\sqcup,t_1)|v\rangle|^2$, which has two input slots ($\sqcup$), one for a possible value set and one for the time of a measurement. This doesn’t tell us anything unless we assume the factuality of the value set $v$ at $t_1$, nor does it tell us anything about what exists, obtains, is factlike, or is real at any time other than $t_1$. (It bears repetition: progress in knowledge is often made possible by an admission of ignorance.)

Note that I am not saying anything to the effect that quantum states are states of knowledge rather than states of Nature. The fact that the fundamental theoretical framework of physics is an irreducible probability algorithm in no wise implies that quantum mechanics is an epistemic theory concerned with subjective probabilities. The notion that probabilities are inherently subjective is a wholly classical idea. The objective stability of matter (the fact that there are stable objects consisting of finite numbers of unextended particles and nevertheless occupying finite volumes) does not rest on a subjective uncertainty about the position or the momentum of an atomic electron. Quantum mechanics concerns objective probabilities (not to be confused with relative frequencies) which have nothing to do with how much we know. Subjective probabilities arise if relevant data are ignored; they disappear when all relevant data are taken into account. The “uncertainty” relations guarantee that quantum-mechanical probabilities are objective: they can’t be made to disappear.

The fact that the fundamental theoretical framework of physics is an algorithm for computing objective—and hence fundamentally nonclassical—probabilities, ought to tell us something of paramount importance about the physical world, which cannot possibly be understood if one treats it so cavalierly as to postulate a fundamentally unobservable, unverifiable, and predictively useless determinism. This takes me to Zurek’s third classical prejudice, which is all but universally shared.
It strikes me as odd that the ontological status of $|\psi\rangle$—state of knowledge or state of Nature?—has been the focus of a lively controversy for three quarters of a century, while the ontological status of the coordinate points and instants on which the wave function depends has remained largely unquestioned. (Exceptions are found in the literature on quantum gravity, where it is occasionally observed that a fuzzy metric conflicts with the postulation of a manifold of points that are sharply localized relative to each other.) If the wave function evolves deterministically, it evolves in an intrinsically and infinitely differentiated (partitioned) spacetime manifold. If it turned out that the idea of such a manifold corresponds to nothing in the physical world, the idea of deterministic evolution would share the same fate. Determinism thus implies that space and time are—indeed of their material “content”—intrinsically and infinitely differentiated. This is what makes it possible to treat them as point sets or as a single manifold. But if this is how one conceives of the spatiotemporal aspects of the physical world, one is in no position to recognize the ontological implications of the fact that the fundamental theoretical framework of physics is an algorithm for computing objective probabilities, as I will show.

If $|\psi\rangle$ represents a physical state, and if it evolves beyond the measurement at $t_2$ without being reset in accordance with the outcome, this outcome (if it exists at all) only exists relative to the environment in which it is recorded. For if the quantum state of the observed system, the observer, and the environment evolves deterministically and contains one possible outcome then it contains all possible outcomes (as a superposition). The quantum-mechanical correlation laws ensure that observers who exist in the same “branch” of the universal state vector and are therefore capable of communicating with each other, agree about the outcome. While this saves the classical appearances, it obliges Zurek to qualify Significant Insight #1 by turning the existence of an outcome and the possession of a value into something that is relative to the state of the environment and the observers it contains. If predictability is the sole criterion for objective existence then all possible outcomes exist, each in a separate branch of the universal state vector.

To my way of thinking, treating possible outcomes as actually existing ones is simply a category mistake. Possibilities just aren’t actualities. I agree with Zurek that predictable correlations play a crucial role in the search for those substructures or structural elements of the quantum formalism that correspond to what objectively exists: pointer positions have values only because their values are predictably correlated (except when they serve to record unpredictable values). But predictability of correlations is not sufficient for an objective existence that is absolute rather than relative. To arrive at an absolute objective existence, one needs to show that objective existence can consistently be attributed to a single possible history of the universe. To be able to do this, one needs a criterion for deciding when possibilities can “re-interfere” and when they cannot. Unless the classical prejudices mentioned in this section are eliminated, the possibility of “re-interference”
always exists, at least in principle. But if “re-interference” can be ruled out only for all practical purposes, no truly indelible record exists, and no value is ever possessed in an absolute sense. This obliges Zurek to qualify Significant Insight #2 by making objective existence quantitatively dependent on the likelihood of “re-interference” and thus relative in a second, quantitative sense. This likelihood can be quantified by counting the number of times information about a value is replicated by the environment, or the number of parts of the environment that become correlated with the possible values of an observable.

Let us take stock. I have pointed out three classical prejudices and shown how they compel Zurek to relativize objective existence in two ways. The first prejudice—the belief that $|\psi(t)\rangle$ represents a physical state that evolves—all but implies the second—the belief that $|\psi(t)\rangle$ evolves deterministically—for the consequences of the alternative—instantaneous “collapses” of physical states—are too preposterous for consideration, at least in a relativistic world governed by standard quantum mechanics (unadulterated with nonlinear modifications of the “dynamical” equations [15]). The second prejudice entails the third, the belief that space and time are intrinsically and infinitely differentiated.

I advocate that theorists think of quantum states the way experimentalists use them, namely as algorithms for computing probabilities of possible measurement outcomes on the basis of actual measurement outcomes. The quantum “dynamical” laws encapsulate correlations between measurement outcomes. The expression $|\langle\mathcal{U}\mid \mathcal{U}(\mathcal{U}, t_1)\mid v\rangle|^2$ is meaningless unless a possible measurement outcome is plugged into the first slot and the time of measurement is plugged into the second. I advocate this for several reasons:

(i) It prevents us from getting mired in disputes over pseudoquestions [12], such as how to extract probabilities from the quantum formalism if this is not fundamentally a probability algorithm [25].

(ii) The axioms of standard quantum mechanics (including the infamous projection postulate, stripped of the notion that quantum states are evolving physical states) become transparent if the quantum formalism is viewed as an algorithm for calculating objective probabilities describing an objective fuzziness such as that on which the stability of matter rests [25, 26, 27]. An algorithm for assigning probabilities to possible measurement outcomes on the basis of actual measurement outcomes has two perfectly normal dependences. It depends continuously on the times of measurements: if you change the time of a measurement by a small amount, the probabilities assigned to the possible outcomes change by small amounts. And it depends discontinuously on the results that constitute the assignment basis: if you take into account information that was not previously taken into account, the assignment basis changes unpredictably as a matter of course.

(iii) It becomes possible to recognize ontological implications of the quantum formalism that cannot possibly be seen if one starts with metaphysical assumptions that contradict them, such as the assumption that the physical world is infinitely differentiated spacewise and timewise (Sec. 3).
It becomes possible to reconcile quantum mechanics with a single absolute objective existence (Sec. 4).

3 The spatiotemporal differentiation of the physical world

In this section I assume that we can talk unambiguously about objective records, measurement outcomes, and possessed values. In so doing I do not take any liberties, for if the quantum formalism is fundamentally concerned with correlations between measurement outcomes, records, or possessed values then it presupposes the objective existence of these things and none of the formalism’s ontological implications can compel us to qualify or relativize it. One of these ontological implications is that the physical world is not infinitely differentiated either spacewise or timewise, as I proceed to explain.

If quantum mechanics is fundamentally an algorithm for computing objective probabilities then these probabilities as the formal expression of an objective fuzziness and no object ever has a sharp position relative to any other object, except nonrelativistically in the unphysical limit of infinite momentum dispersion and infinite mean energy. (The proper formalism for dealing quantitatively with fuzzy variables is a probability algorithm. Saying that a variable $Q$ lacks a sharp value is the same as saying that there are finite intervals $I$ for which the proposition “the value of $Q$ is in $I$” lacks a truth value; consequently, no trivial probability can be assigned to the outcome of a measurement of the truth value of such a proposition. Note that the meaning of such a proposition is not that $Q$ has a precise value somewhere in $I$ but that $I$ itself is a measured and therefore possessed value of $Q$.)

Consider the probability distribution $|\psi(x)|^2$ associated with the position of the electron relative to the nucleus in a stationary state of atomic hydrogen. Imagine a small region $V$ for which $\int_V |\psi(x)|^2 dx$ differs from both 0 and 1. While the atom is in this state, the electron is neither inside $V$ nor outside $V$. (If it were inside, the probability of finding it outside would be 0, and if it were outside, the probability of finding it inside would be 0.) But being inside and being outside are the only relations that can possibly hold between a region $V$ and an unextended (“pointlike”) object like the electron (or the center-of-mass position of an extended object like a $C_{60}$ molecule [28]). If neither of these relations holds this region simply does not exist for the electron. It has no reality as far as the electron is concerned.

Conceiving of a region $V$ is tantamount to making the distinction between “inside $V$” and “outside $V$.” Hence instead of saying that $V$ does not exist for the electron, we may say that the distinction we make between “inside $V$” and “outside $V$” is a distinction that the electron does not make. Or we may say that the distinction we make between “the electron is inside $V$” and “the electron is outside $V$” is a distinction that Nature does not make. It corresponds to nothing in the physical world. On the other hand, if the truth
values of these propositions (at a given time $t$) are measured or recorded (in which case one is “true” and one is “false”) one of the possible relations between the electron and $V$ holds at the time $t$, and the distinction between “inside $V$ at $t$” and “outside $V$ at $t$” is real as far the electron is concerned.

It follows that the reality of spatial distinctions is relative and contingent—“relative” because the distinction we make between the inside and the outside of a region may be real for a given object at a given time, and it may have no reality for a different object at the same time or for the same object at a different time; and “contingent” because the existence of a given region $V$ for a given object $O$ at a given time $t$ depends on whether the proposition “$O$ is in $V$ at the time $t$” has a (measured or recorded) truth value.

Suppose that $W$ is a region disjoint from $V$, and that there is a record of $O$’s presence in $V$. Isn’t $O$’s absence from $W$ implied by this record? Are we not entitled to infer that the proposition “$O$ is in $W$” has a truth value (namely, “false”)? Because the reality of spatial distinctions is relative and contingent, the answer is negative. The distinction we make between “inside $W$” and “outside $W$” has no physical reality per se. If $W$ is not realized (made real) by being the sensitive region of an actually existing detector, it isn’t available for attribution to $O$, and the same holds for the spatial complement $W'$ of $W$. If neither $W$ nor $W'$ is the sensitive region of an actually existing detector, the proposition “$O$ is in $W$” cannot have a truth value. Therefore all we can infer from $O$’s recorded presence in $V$ is the truth of a counterfactual: if $W$ were the sensitive region of a detector $D$, $O$ would not be detected by $D$.

It follows that a detector—a perfect detector, to be precise, since otherwise the absence of a “click” does not warrant the falsity of “$O$ is in $W$”—performs two necessary functions: it indicates the truth value of a proposition of the form “$O$ is in $W$,” and by realizing $W$ (or the distinction between “inside $W$” and “outside $W$”) it makes the predicates “inside $W$” and “outside $W$” available for attribution to $O$. Much the same applies to spin measurements: the apparatus is needed not only to indicate the value of a spin component but also to realize an axis by means of the gradient of a magnetic field. The apparatus presupposed by every quantum-mechanical probability assignment is needed not only for the purpose of indicating or recording the possession, by an observable, of a particular value but also for the purpose of realizing a set of values and thereby making them available for attribution. This amply justifies Bohr’s insistence that, out of relation to experimental arrangements, the properties of quantum systems are undefined: positions and orientations need to be possessed in order to exist, and they need to exist as properties of measuring equipment in order to be attributable as measurement outcomes.

Let $IR^3(O)$ be the set of unpossessed exact positions relative to some object $O$. Since no object has a sharp position relative to any other object, we can conceive of a partition of $IR^3(O)$ into finite regions that are so small that none of them is the sensitive region of an actually existing detector. Hence we can conceive of a partition of $IR^3(O)$ into
sufficiently small but finite regions $V_i$ of which the following is true: there is no object $Q$ and no region $V_i$ such that the proposition “$Q$ is inside $V_i$” has a truth value. In other words, there is no object $Q$ and no region $V_i$ such that $V_i$ exists for $Q$. But a region of space that does not exist for any material object, does not exist at all. The regions $V_i$ represent spatial distinctions that Nature does not make. They correspond to nothing in the physical world. They exist solely in our heads. Upshot: The physical world is not infinitely differentiated spacewise. Its spatial differentiation is finite—it doesn’t go “all the way down.”

The same goes for time. The times at which observables possess values, like the possessed values themselves, must be recorded in order to exist. Clocks are needed not only to measure or record time but also, and in the first place, to make times available for attribution to measured or recorded values. Since clocks realize times by the positions of their hands, and since exact positions do not exist, neither do exact times. (Digital clocks indicate times by transitions from one reading to another, without hands. The uncertainty principle for energy and time however implies that these transitions cannot occur at exact times, except in the limit of infinite mean energy [29].) Exact times are not available for attribution. And since the physical world is differentiated timewise by the temporal relations (or relative times) that exist in it, its finite temporal differentiation follows from the fuzziness of times in exactly the same way that its finite spatial differentiation follows from the fuzziness positions.

It follows that physical space cannot be something that exists “by itself,” independently of its material “content,” and that is infinitely differentiated. $IR^3$ is not an aspect of the physical world but an aspect of the quantum-mechanical probability algorithm, useful for describing the fuzziness of any existing relative position by a distribution over $IR^3$. Physical space is something else altogether. It does not “contain” matter (which stands to reason, since containers have boundaries while space, presumably, has none) but instead is an aspect of it. We ought to think of space as the system of spatial relations that hold between the world’s material constituents (including their relative orientations). There is no such thing as empty space, not because space is “filled with vacuum fluctuations” but because where there is nothing (no thing) there is no there. There are no “unoccupied” positions because there are no unpossessed positions.

How is it that while we readily agree that red, or a smile, cannot exist without a red object or a smiling face, we just as readily believe that positions can exist without being properties of material objects? We are prepared to think of material objects as substances (things that exist “by themselves,” without being properties of other things), and we are not prepared to think of their properties as substances—except for their positions. The reasons for these disparate attitudes are to be found in the neurobiology of perception [12, 13, 14]. They concern the construction of what psychologists and philosophers of mind call the “phenomenal world.” They have nothing to do with the
physical world, other than making it hard to make sense of it.

The view that all existing positions are possessed relative positions—positions of material objects relative to material objects—is well-known and fully consistent with the deterministic correlation laws of classical physics [30, 31]. Quantum mechanics (considered as being fundamentally a probability algorithm) adds to this the fuzziness of all existing relative positions, and this makes the relational view of space mandatory, as we have just seen. The spatial extension of the physical world, accordingly, is not an attribute of a substantial expanse in which spatial relations are embedded but a shared attribute of every spatial relation—the quality to which each owes its spatial character.

To recap. The fuzziness of all possessed relative positions implies (i) that the reality of the spatial distinctions that we make (equivalent to the objective existence of the regions of space that we imagine) is relative and contingent, and (ii) that the physical world is not infinitely differentiated either spacewise or timewise. There is no need to relativize objective existence; what is relative—not relative to the components of the universal state vector nor relative in a quantitative sense but relative to physical objects—is the reality of the distinctions that we make.

The fuzziness of physical observables further implies the extrinsic nature of their values. For one thing, if a predicative proposition may or may not have a truth value, a criterion for the possession of a truth value is needed. The existence of a (recorded) measurement outcome is a sufficient criterion, and in the context of standard quantum mechanics (unadulterated with, spontaneous collapses [15, 16, 17], Bohmian trajectories [18], or the modal semantical rule [32, 33]) it is also the necessary criterion. For another thing, if the possible values of positions and orientations do not pre-exist as aspects of an intrinsically differentiated space—the same goes for the values of the corresponding momenta—then experimental arrangements are needed not only to indicate or record values but also to realize them—to make them available for attribution to measured systems.

4 One unqualified objective existence

The existential interpretation postulates deterministic evolution for the state vector or the wave function associated with the environment, an observer or observers, and a measured system. As we have seen, this entails that the physical world is infinitely differentiated both spacewise and timewise, and it compels Zurek to relativize objective existence in two ways. The present interpretation (a.k.a. “the Pondicherry interpretation of quantum mechanics” [34, 35]) aims at unpacking the presuppositions and implications of the quantum formalism, regarded as being fundamentally a probability algorithm. One of the presuppositions is the unqualified objective existence of (recorded) measurement outcomes—the correlata of the formalism’s correlation laws. The nature or degree of their objective exis-
tence is not an issue. Among the formalism’s implications are the relative and contingent reality of spatial distinctions and the finite spatiotemporal differentiation of the physical world. These implications make it possible to resolve the issues peculiar to this approach by adducing the same quantitative results that Zurek adduces in support of the existential interpretation, as I proceed to show.

As said, any physical interpretation of the quantum formalism has to identify those substructures or structural elements that correspond to what exists. For the empiricist it suffices to attribute objective existence to measurement outcomes: everybody knows that measurements have outcomes, and quantum mechanics tells us how they are correlated. But once the extrinsic nature of the values of observables is taken seriously, a seemingly vicious regress arises. No value is a possessed value unless it is an indelibly recorded value, and pointer positions are no exception; they have values because their values are inscribed in the possessed values of other pointer positions. This seems to send us chasing objective existence in never-ending circles, like a dog trying to catch its tail. It is the essence of “von Neumann’s catastrophe of infinite regression,” which has convinced many that it takes an extra-physical ontological principle like consciousness to break out of the vicious circle or regress [36, 37, 38, 39, 40, 41, 42].

The key to the problem of identifying those substructures or structural elements that correspond to what exists, without invoking consciousness, lies in the following facts: while all existing positions are fuzzy, some objects have the sharpest positions in existence. This has the consequence that the correlations between the recorded positions of most of these objects are deterministic in the following sense: the fuzziness of the positions of these objects never evinces itself through outcomes or records that are inconsistent with predictions that are based on a classical law of motion and earlier outcomes or records.

Let me elaborate. There can be evidence of the departure of an object \( O \) from a precise trajectory only if there are detectors that can probe the region over which \( O \)'s fuzzy position extends. This calls for detectors whose position probability distributions are narrower than \( O \)'s. Such detectors do not exist for all objects. For those objects that have the sharpest existing positions, the probability of obtaining a record that is inconsistent with a precise trajectory, is necessarily very low. (This follows from the detailed investigations mentioned in the Introduction, which underwrite the Pondicherry interpretation as well as the existential interpretation.) Hence among those objects there are objects of which the following is true: every one of their recorded positions is consistent with (i) every prediction that is based on their previous recorded positions and (ii) a classical law of motion. Such objects deserve to be called macroscopic. To enable a macroscopic object to record an unpredictable value, one exception has to be made: its position may change unpredictably if and when it serves to record such a value.

Since the positions of macroscopic objects—macroscopic positions, for short—are correlated deterministically (except when they serve to record unpredictable values) it is
possible to pretend that macroscopic objects follow precise trajectories, even during value-recording events, when at least one macroscopic position changes unpredictably. In reality, though, macroscopic positions are fuzzy like the rest. The difference is that their fuzziness never evinces itself through unpredictable records. (Remember that macroscopic positions are defined that way.) Macroscopic positions are only counterfactually fuzzy. Their fuzziness would evince itself through unpredictable records if the space over which they are “smeared out” were probed. But it never is. This space is undifferentiated; it contains no smaller regions. We may imagine smaller regions, but they lack counterparts in the real world. The distinctions we make between them are distinctions that Nature does not make. Hence when we have said that macroscopic objects follow trajectories that are only counterfactually fuzzy, we have said everything that can usefully be said about the positions of macroscopic objects. The way we have defined them guarantees that their fuzziness is empirically irrelevant.

Now recall that the extrinsic nature of observables is a consequence of their fuzziness, which requires a nontrivial probability algorithm for its description. If the fuzziness of macroscopic positions is empirically irrelevant then macroscopic positions do not require a nontrivial probability algorithm. The triviality of the classical probability measure, as we have seen, permits its reinterpretation as an objective state of affairs or a list of possessed properties, and so does the triviality of the quantal probability measure when applied to macroscopic positions. The reason this is so is not that the probability of finding a macroscopic object where classically it could not be, is strictly 0, but that macroscopic objects as we have defined them are never found where classically they could not be. The extraordinary smallness of said probability, which has been amply demonstrated by decoherence investigations, implies that such objects are in plentiful supply: a significant fraction of the objects that are commonly called “macroscopic” meet our stricter definition. It is therefore consistent with the quantal correlation laws to attribute to the (only counterfactually fuzzy) values of the positions of macroscopic objects the same objective existence that classical physics attributes to the positions of all objects.

Well, almost. While classical positions are intrinsic, in the quantum world even macroscopic positions are extrinsic, owing to the mutual dependence of all possessed positions. A macroscopic position does not exist “by itself.” It is not objective per se. Even the Moon has a position only because of the myriad of “pointer positions” that betoken its whereabouts. Yet the entire system of macroscopic positions is self-contained. There is no reason why it should depend on anything external to itself. It is therefore perfectly consistent with the quantal correlation laws to attribute to the totality of macroscopic positions—the macroworld—an unqualified and independent objective existence.

Given our definition of “macroscopic object,” it is clear that we cannot be one hundred percent sure that any given object $O$ falls in this category. Even if we had access to every
existing record of its past whereabouts and knew all relevant boundary conditions, we
could not completely rule out the possibility of finding it where classically it could not
be. Even maximally predictable Gaussian states assign small probabilities to such events.
It has been suggested that such an event would be considered as “a statistical quirk”
or “an experimental error” [43]. It ought instead to be regarded as confirmation that
positions are probabilistically correlated. (Such an event must not be confused with
the unpredictable changes that macroscopic positions undergo when they serve to record
unpredictable values.)

By our definition, macroscopic positions provide indelible records—not in the sense
that the theoretical probability of their “erasure” is strictly zero but in the sense that
they are never erased. We therefore have an unambiguous criterion for deciding which
possibilities can “re-interfere”: in principle all but those that are correlated with the
value of a macroscopic position. On the other hand, perfect correlation of an observable’s
possible values with the position of what is commonly called a “macroscopic object” is not
sufficient for the existence of an indelible record of the observable’s value. If the trajectory
of such an object can depart unpredictably from the trajectory predicted on the basis of
earlier data and a classical law of motion then it can also depart unretrodictably from
the trajectory retrodicted on the basis of later data and a classical law of motion. As a
consequence, the trajectory of a macroscopic object of common parlance may not always
retain information about an outcome.

This observation, however, fails to take into account that the positions of macroscopic
objects of common parlance are abundantly monitored. Suppose that at the time \( t_2 \) the
position of a macroscopic object loses information about an outcome obtained at the
earlier time \( t_1 \). Information about this particular macroscopic position in the interim will
be retained by the trajectories of a huge number of other macroscopic objects, and among
these there will be many that conform to our stricter definition of “macroscopic.” The
existence of an indelible record of the outcome of the measurement at \( t_1 \) (without which
there would be no outcome) is therefore not affected by the rare, non-classical behavior
of what is commonly called a “macroscopic object.”

To conclude: what objectively exists, in a sense that requires no qualification, is the
trajectories of macroscopic objects, whose fuzziness is empirically irrelevant, and those
values of observables of which these trajectories provide indelible records.

5 A quantum system between measurements

What can we say about the objective properties of quantum systems between successive
measurements? This question does not arise for a macroscopic object, inasmuch as its
recorded positions overlap extensively with regard to the times at which they are pos-
sessed: there is no time span during which no measurement is performed on a macroscopic
What about the objective properties of non-macroscopic quantum systems between successive measurements? The values of observables being extrinsic, all we can say, and all that needs to be said in order to provide an objective description of a quantum system between measurements, is what can be inferred from the relevant measurement outcomes. What obtains between successive measurements is a fuzzy state of affairs that is described—as befits a fuzzy state of affairs—by an algorithm for assigning probabilities to the possible results of measurements that might have been but were not performed in the meantime. The fact that the quantum formalism is fundamentally a probability algorithm thus in no wise implies that it concerns states of knowledge rather than states of Nature, for this algorithm describes Nature’s objective fuzziness rather than a subjective “uncertainty.” (The literal meaning of Heisenberg’s original term “Unschärfe” is “fuzziness.”)

The fact that the quantal correlation laws are time-symmetric implies that the fuzzy state of affairs that obtains between successive measurements, performed at the respective times $t_1$ and $t_2$, is determined not only predictively, by a density operator $\rho_P(t_1)$ that assigns probabilities on the basis of actual outcomes obtained at or before $t_1$ to the possible outcomes of measurements that could have been made after $t_1$, but also retrodictively, by a density operator $\rho_F(t_2)$ that assigns probabilities on the basis of actual outcomes obtained at or after $t_2$ to the possible outcomes of measurements that could have been made before $t_2$. In addition, probability assignments to measurement outcomes at $t > t_1$ made on the basis of $\rho_P(t_1)$ depend on $U(t, t_1)$, a unitary transformation that encapsulates the pertinent diachronic correlations and takes account of the relevant boundary conditions, and probabilities assignments to measurement outcomes at $t < t_2$ made on the basis of $\rho_F(t_2)$ depend on $U(t, t_2) = U^\dagger(t_2, t)$. While probability assignments based on earlier or later measurement outcomes are governed by Born’s rule, which makes use of either $\rho_P$ or $\rho_F$, probability assignments based on earlier and later measurement outcomes are governed by the ABL (Aharonov-Bergmann-Lebowitz) rule, which makes use of both $\rho_P$ and $\rho_F$.

Unless the relevant Hamiltonian is 0, the probability distributions describing the fuzzy state of affairs between successive measurements depend on the times of unperformed measurements. This is not the same as saying that the fuzzy state of affairs between actual measurements changes with time, for the counterfactual probability assignments describing this state of affairs are false not only because they affirm that a measurement is made but also because they affirm that this is made at a given time. (Counterfactuals are conditional statements whose antecedents are false.) For an unobserved quantum system there is no particular time.

Here our conclusion that the temporal differentiation of the physical world is finite takes on a concrete shape. As we have seen, if a region $V$ is to exist for an object $O$,
a relation must exist between $V$ and (the center-of-mass position of) $O$. By the same

token, if a particular time $t$ is to exist for $O$, a relation must exist between $t$ and $O$.

Time, however, is not an observable. It makes no sense to measure the time of $O$. What
can be measured is the time of possession, by $O$, of a property. Accordingly, a particu-
lar time $t$ exists for $O$ if and only if it is the (recorded) time of possession, by $O$, of
a property. The time between successive measurements also exists for $O$, but not as a
particular time. Instead, it exists as an undifferentiated whole. Recall: if the proposition
“$O$ is in $V$ at $t$” is true while for every $W \subset V$ the proposition “$O$ is in $W$ at $t$” lacks a
truth value, the distinction we make between $W$ and its complement in $V$ has no reality
for $O$ (at the time $t$). $V$ exists for $O$ as an undifferentiated whole. So does the interval
between successive measurements performed on $O$. Where $O$ is concerned, the state of
affairs that obtains between successive measurements is only counterfactually differenti-
ated. (It would be differentiated if there were a record of a property possessed by $O$ at a
particular time in the interim.) $O$ is temporally differentiated by the measurements that
are performed on it.

Obviously, none of these ontological implications of quantum mechanics (qua funda-
mental probability algorithm) can be seen as long as quantum states are regarded as
instantaneous physical states. An instantaneous physical state implies that the physical
world is infinitely differentiated timewise, while the quantum-mechanical correlation laws
imply that the physical world is not infinitely differentiated either spacewise or timewise.
In a quantum world, there is no such thing as an instantaneous state. Just as the spatial
aspect of the physical world is not “build up” from infinitely small parts (let alone points)
so the temporal aspect of the physical world is not “built up” from instantaneous states.

The conclusion that the state of a quantum system between measurements is tempo-
rally undifferentiated, and the conclusion that this state is both predictively and retro-
dictively determined, are exceedingly counterintuitive. Our successive experience of the
world’s temporal aspect makes it natural for us to embrace presentism, the view that
only the present is real, or that it is somehow “more real” than the future or the past.
Our self-experience as agents makes it natural for us to hold that the known or in prin-
ciple knowable past is “fixed and settled,” while the unknown and apparently unknowable
future is “open.” None of this has anything to do with the physical world—the world as
described by physics. It is impossible to consistently project the sole or greater reality of
the experiential now into the objective physical world. To philosophers, the perplexities
and absurdities entailed by the notion of a changing objective present are well known.
(See, e.g., the illuminating entry on “time” in Ref. [49].) To physicists, the subjectivity
of a temporally unextended yet persistent and persistently changing present was brought
home by the relativity of simultaneity. Much the same is implied by quantum mechanics,
inasmuch as this tells us that the temporal aspect of the physical world cannot be built
up from instantaneous states.
Nor does physics know anything about a preferred direction of causality. It is we who base on our sense of agency, our ability to know the past, and our inability to know the future, the figment of a causal arrow. The physical correlation laws are time-symmetric. They let us retrodict as well as predict. The fact that the undifferentiated and fuzzy state of affairs that obtains between measurements is determined retrodictively as well as predictively becomes incomprehensible only if we combine the figment of a causal arrow with the figment of an instantaneous state and project the result—an evolving instantaneous state—into the physical world. This leads to the well-known folk tale according to which causal influences reach from the nonexistent past to the nonexistent future through persisting “imprints” on the present. If the past and the future are unreal, the past can influence the future only through the mediation of something that persists. Causal influences reach from the past into the future by being “carried through time” by something that “stays in the present.” This evolving instantaneous state includes not only all presently possessed properties but also traces of everything in the past that is causally relevant to the future. In classical physics this is how we come to conceive of fields of force that evolve in time (and therefore, in a relativistic world, according to the principle of local action), and that mediate between the past and the future (and therefore, in a relativistic world, between local causes and their distant effects). In quantum physics, this is how we come to seize on a probability algorithm that depends on the time of a measurement and the results of earlier measurements and to transmogrify the same into an evolving instantaneous state.

6 Summary

Zurek’s interpretation of quantum mechanics suffers from three classical prejudices, which necessitate a twofold relativization of the concept of objective existence: the belief that $|\psi(t)\rangle$ represents a physical state that evolves, the belief that $|\psi(t)\rangle$ evolves deterministically, and the belief that space and time are intrinsically and infinitely differentiated. If instead the quantum formalism is viewed as an algorithm for calculating objective probabilities, describing an objective fuzziness, we are in a position to recognize its ontological implications—in particular the relative and contingent reality of spatiotemporal distinctions and the extrinsic and finite spatiotemporal differentiation of the physical world. This makes it possible to reconcile quantum mechanics with a single absolute objective existence. Contrary to a widespread misconception, viewing the quantum formalism as being fundamentally a probability algorithm does not imply that quantum mechanics is concerned with states of knowledge rather than states of Nature. On the contrary, it makes possible a complete and strongly objective description of the physical world that requires no reference to observers. What objectively exists, in a sense that requires no qualification, is the trajectories of macroscopic objects, whose fuzziness is empirically
irrelevant, the properties and values of whose possession these trajectories provide indelible records, and the fuzzy and temporally undifferentiated states of affairs that obtain between measurements and are described by counterfactual probability assignments. The quantitative results that underwrite these conclusions are the same as those that underwrite the existential interpretation.


