

# The Ontic Probability Interpretation of Quantum Theory

## Part I: The Meaning of Einstein's Incompleteness Claim

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### ABSTRACT

Ignited by Einstein and Bohr a century ago, the philosophical struggle about Reality is yet unfinished, with no signs of a swift resolution. Despite vast technological progress fueled by the iconic EPR paper (EPR)<sup>1,2,3</sup>, the intricate link between ontic and epistemic aspects of Quantum Theory (QT) has greatly hindered our grip on Reality and further progress in physical theory. Fallacies concealed by tortuous logical negations made EPR comprehension much harder than it could have been had Einstein written it himself in German. It is plagued with preconceptions about what a physical property is, the 'Uncertainty Principle', and the Principle of Locality. Numerous interpretations of QT vis à vis Reality exist and are keenly disputed<sup>4,5,6,7,8,9,10,11</sup>. This is the first of a series of articles arguing for a physical interpretation called 'The Ontic Probability Interpretation' (TOPI). A gradual explanation of TOPI is given intertwined with a meticulous logico-philosophical scrutiny of EPR. Part I focuses on the meaning of Einstein's 'Incompleteness' claim. A conceptual confusion, a preconception about Reality, and a flawed dichotomy are shown to be severe obstacles for the EPR argument to succeed. Part II analyzes Einstein's 'Incompleteness/Nonlocality Dilemma'<sup>12</sup>. Future articles will further explain TOPI, demonstrating its soundness and potential for nurturing theoretical progress.

### List of Acronyms (Part I)

QT	Quantum Theory	EPR	The Einstein/Podolsky/Rosen Paper
TOPI	The Ontic Probability Interpretation	<i>PD</i>	Probability Distribution
<i>PI</i>	Physical Interaction	<i>GI</i>	Gauge Interaction
<i>TM</i>	True Measurement	TRC	The Reality Criterion
TCC	The Conceptual Confusion	<i>SD</i>	Standard Deviation of a <i>PD</i>
TRP1	The Reality Preconception 1	TFD	The Fallacious Dichotomy

## 1. Introduction

As a *realist*, Einstein wrote: “there is something like the ‘real state’ of a physical system, which independent of any observation or measurement exists objectively and which can in principle be described by means of physical terms”. However, *probability*-wise, Einstein was a *subjectivist* -- blaming the stochastic makeup of QT on its *incompleteness*. But more than *chance* as Nature's modus operandi, he obstinately detested its “spooky action at a distance” -- blaming again such “telepathy” predicted by QT on its *incompleteness*<sup>13</sup>.

Poorly understood even today, EPR<sup>1</sup> and Bohr's response<sup>2</sup> were published on May 15 and October 15, 1935 with identical titles: “Can Quantum Mechanics Description of Physical Reality be Considered Complete?”. Prior to his formal response, Bohr had sent a letter<sup>3</sup> to *Nature*. EPR

discussed thought experiments where the position and momentum of two correlated ‘particles’ were predicted by QT and ‘measured’. I put ‘particles’, and ‘measured’ in quotes because: (a) quantum objects are neither particles nor waves; and (b) most physical interactions are *not* measurements. John Bell advised for the word ‘measurement’ to “be banned altogether in quantum mechanics”<sup>14</sup>. Most physicists and philosophers did not listen.

## 2. Elements of a Physical Theory

Against the Logical Positivism in vogue at the time, EPR states:

EPR1: *Any serious consideration of a physical theory must take into account the distinction between the objective reality, which is independent of any theory, and the physical concepts with which the theory operates. These concepts are intended to correspond with the objective reality, and by means of these concepts we picture this reality to ourselves.*

A factual theory is an explanatory/predictive logico-mathematical formalism whose ultimate referent is Reality; ergo, it must be put to the empirical test. A theory consists of *Ontology*, *Foundation*, *Structure*, *Interpretation*, and *Evidence*. The *Ontology* includes the presumed *real* entities plus known *facts* about their properties and behavior. The *Foundation* comprises: a) *abstract* entities/attributes; and b) unexplained explainers: principles, postulates, hypotheses, etc. The *Structure* entails: a) non-factual formalisms (e.g. Logic, Calculus, Geometry); b) other factual theories (e.g. Space/Time, Relativity, Electromagnetism); and c) *laws* and *theorems* about the *abstract* entities. The elusive *Interpretation* attempts to grasp Reality by proposing *semantic rules* via which the *abstract* entities/attributes represent the *real* ones. The *Evidence* incorporates the *empirical* support the theory possesses to claim its verisimilitude. Measurements and observers are necessary for the *Evidence* but are not, and must not be, part of the theory.

## 3. Elements of ‘The Ontic Probability Interpretation’ (TOPI)

An interpretation endows the *Foundation*, *Structure*, and *Evidence* with *physical* meaning, thereby characterizing the *Ontology*. Numerous interpretations/formulations of QT exist and are widely disputed<sup>4,5,6,7,8,9,10,11</sup>. Like Bunge<sup>15</sup>, I will refer to the abstract/real entities of QT as ‘quantons’. Per TOPI, an *abstract* quanton interacts with its *abstract milieu* and has: a) a *current abstract* state that corresponds to the *real* quanton’s state attained from the *last* interaction with its *physical milieu*; b) *current abstract* attributes that parallel *physical* properties of the *real* quanton in its *current real* state; and c) a probability distribution (*PD*) for the *transition* to its *next abstract* state/attributes, which is the predicted *ontic PD* for the *real* quanton to transition to its *next real* state/properties. Being a *PD*, the *next* state/property values are *defined* but *undetermined*. There are attributes a quanton does not possess (e.g. size, shape), i.e. they are not *defined* at all; and others that are *defined* only for some states (like the azimuthal angle is defined/undefined off/on the polar axis). Quantons are not punctiform objects. A property which is defined/undefined for the *current* state can be undefined/defined for the *next* state. If, for any state/property, the *PD* is as narrow as to effectively assign *determinate* values for all *next* states/properties, the theory is classically *deterministic*; otherwise, it is *stochastic*. QT is partly stochastic and partly causal, to which I call ‘quantically deterministic’. *Classical determinism* is a degenerate type of *quantic determinism*. TOPI is applicable to Classical Physics<sup>16,17,18</sup>.

A *composite* quanton can be in *product-states*, for which all sub-quantons are isolated; and in *entangled* states, for which the sub-quantons’ states are undefined per se. The same *current* state is expressible via different linear combinations of *next* eigenstates (different bases for the State-

Space). Quanton and milieu jointly determine the basis, with the *PD* for the *next* state/properties encrypted in the resulting linear combination<sup>18</sup>. Per TOPI, QT claims neither explicative nor predictive power between *current* and *next* states. Discrete and continuous systems are covered by QT/TOPI. A ‘Physical Interaction’ (*PI*) between a quanton and its milieu is, generally, reciprocal, i.e. both change states. A *PI* implemented by us to acquire *knowledge* will be called a ‘Gauge Interaction’ (*GI*); *GIs* were called ‘measurements’ by QT pioneers and, ignoring Bell’s advice, they still are by most researchers. If a *GI* is such that the milieu (the ‘measurer’) changes state and the quanton (the ‘measured’) does not, I call it a ‘True Measurement’ (*TM*). From a strictly physical viewpoint, the anthropic *GIs* and *TMs* occur all the time without human intervention. Only some properties may be experimentally accessible, creating the empirical *Evidence*. The *operationalist* believes a physical property has no meaning but the one given by its *measurement* protocol. This is not true because we must understand the *real* property before we can conceive a gauging technique and build and/or select the proper instrumentation.<sup>18</sup>

### 3.1. Heisenberg’s Inequalities vis à vis TOPI

QT predicts probabilities, not values. Under TOPI, probability is not epistemic but ontic<sup>15,16,17,18,19,20,21</sup>. Heisenberg’s inequalities have had more misinterpretations than any other formula in history. Per QT, given two properties with *noncommutative* operators  $\mathcal{P}_1$  and  $\mathcal{P}_2$  ( $[\mathcal{P}_1, \mathcal{P}_2] = \mathcal{P}_1\mathcal{P}_2 - \mathcal{P}_2\mathcal{P}_1 \neq 0$ ), and depending on the quanton’s *current* state, only one of the properties may have a single value ( $SD \rightarrow 0$ ) while the other is undefined. As for the *next* state and properties, only their *PDs* are univocally defined. Thus, for any common current state, it is impossible to jointly assign determinate current/next values to both properties. Per TOPI, it is the *probability distribution* for the values, not the values themselves, that constitutes the *physical* property of a quanton/milieu system and, hence, no single *GI* can characterize the property. **Inequalities (1)** express the so-called ‘Uncertainty Principle’ for generic properties  $\mathcal{P}_1$  and  $\mathcal{P}_2$  and for momentum  $\mathcal{P}$  and position  $Q$ :

$$\Delta\mathcal{P}_1\Delta\mathcal{P}_2 \geq (1/2)|\langle[\mathcal{P}_1, \mathcal{P}_2]\rangle| \quad \Rightarrow \quad \Delta\mathcal{P}\Delta Q \geq \hbar/2 \quad (1)$$

Under TOPI, these inequalities neither express a ‘principle’ nor involve ‘uncertainty’, not even ‘indeterminacy’. They do not entail ‘measurements’ either. They constitute a *theorem* of QT relating the *SDs* of two random variables for the *next* state. The narrower one *PD* is, the broader is the other. This is only true when the quanton *current* state is the same for both properties.<sup>18</sup>

## 4. Correctness/Completeness/Elements of Reality

EPR asserts how to judge the correctness of a physical theory:

EPR2: *The correctness of the theory is judged by the degree of agreement between the conclusions of the theory and human experience. This experience, which alone enables us to make inferences about reality, in physics takes the form of experiment and measurement.*

A theory is *correct* because none of its central predictions has been empirically nullified. Prima facie, EPR appears to recognize the *correctness* of QT. A *correct* theory may be *incomplete* because it does not predict aspects of Reality (facts) we expected it to predict. Despite being its leitmotif, EPR does not define *completeness*, proposing only a *necessary* condition:

EPR3: *Whatever the meaning assigned to the term complete, the following requirement for a complete theory seems to be a necessary one: every element of the physical reality must have a counterpart in the physical theory.*

Being **EPR3** just *necessary*, only *incompleteness* can be proven. To do so, an element in the *Ontology* must have no counterpart in the *Foundation*, viz we must identify a **fact** the theory **cannot predict**. EPR admits it is us who identify the **ontic** entities/properties (“elements of the physical reality”) which we *expect* the theory to describe/explain. Thus, *completeness* relates to both Reality (facts) and our *expectations*, which could be rooted in prejudices and/or a priori philosophical views. No unexplained explainer in the *Foundation* (not even a *principle*) belongs to the *Ontology*: if predictions defy our prejudices, *experiment* must rule. EPR agrees:

**EPR4**: *The elements of the physical reality cannot be determined by a priori philosophical considerations, but must be found by an appeal to results of experiments and measurements.*

To identify an ‘element of physical reality’, EPR proposes ‘The Reality Criterion’ (TRC):

**EPR5**: *If, without in any way disturbing a system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity... Regarded not as a necessary, but merely as a sufficient condition of reality, this criterion is in agreement with classical as well as quantum-mechanical ideas of reality.*

#### 4.1. The Conceptual Confusion (TCC)

Palpably against **EPR4**, **EPR5** says that for a property to be real, it is enough that we can *predict* its value “with certainty” and “without in any way disturbing” the system. It is against **EPR4** because *measurement* is absent. Besides, a mere *prediction cannot* disturb anything physical, and the only way to know how *certain* our prediction was is to accurately *measure* the property so... I surmise EPR forgot to include ‘when measured’ after “the value of a physical quantity”.

But here is the striking EPR confusion: the text in parentheses shows that **EPR5** conflated three distinct concepts: (a) the *prediction certainty* (predicted vs. real); (b) the *measurement accuracy* (measured vs. real); and (c) the *probability* for a property to assume one of its values. It is vital to understand that it is (c) what QT is all about, **not** (a); and that (b) is outside QT, serving only to test its *correctness*. Predicting something with a probability is not the same as predicting a probability for something. Predicting a value “with probability equal to unity” amounts to a perfect prediction (predicted = real), and it is utterly different to predicting ‘a probability equal to unity for a value’. Whether *correct* or not, if the theory is classically *deterministic*, all *predicted* probabilities are equal to unity. Instead, for a state/property, QT predicts a *PD* over the next states/property values, i.e. they are all random variables. Predicting a probability *less* than one can be as accurate (vis à vis Reality) as predicting a probability **equal** to one. I call this muddle ‘The Conceptual Confusion’ (TCC). It could be cogently argued that TCC invalidates EPR arguments and conclusions at the outset. That would be unfair -- considering the enormous technological and philosophical impact EPR has had.

QT predicts a unity probability **only** when the quanton is in an eigenstate of the property’s *operator*. Only then an ideal *GI* delivers the value the property had pre-*GI*, i.e. the *GI* is an *ideal TM*. But a *real TM*, if repeated, never delivers a single value but a distribution of them -- for classical and quantic systems. We use a single value because the error-distribution is exceptionally narrow. However, most *GIs* are not *TMs*, i.e. the initial state is not an eigenstate, with QT predicting a broad *PD* for the next state/properties. Ergo, estimating the *prediction accuracy* (“certainty”) requires comparing two *PDs*: predicted vs. **real**, with the latter assessed

by *measurement*. In sum, EPR confuses the nil *SD* of the *predicted PD* for a property (when the system is in an eigenstate) with the *prediction* and *measurement* accuracies for its single value.

How do we then interpret **EPR5**? It cannot be literally, i.e. per **(a)**, because QT does *not* predict the *certainty* of its predictions. Clearly, it must be **(c)** for *prediction* plus **(b)** for Reality. Thus, from now on, TRC means EPR5 so interpreted and, if I refer to **(a)** to rephrase EPR rationale, I will use quotes, viz “with certainty”. Only doing so can we be fair to EPR, despite TCC.

With this caveat, and a negligible *measurement error*, TRC implies that if a ‘particle’ is in a *momentum* eigenstate, the ‘momentum is real’ and if it is in a *position* eigenstate, the ‘position is real’. Otherwise, TRC is mute. Under TRC, Reality might oddly depend on the ‘particle’ state.

## 5. The Reality Preconception 1 (TRP1)

EPR verbalizes Heisenberg’s *Inequalities* using the operationalist language:

**EPR6**: *A definite value of the coordinate [position], for a particle in the state given by Eq. (2) [an eigenstate of the momentum operator], is thus not predictable, but may be obtained only by a direct measurement. Such a measurement however disturbs the particle and thus alters its state. After the coordinate is determined, the particle will no longer be in the state given by Eq. (2). The usual conclusion from this in quantum mechanics is that **when the momentum of a particle is known, its coordinate has no physical reality.***

Per QT, because *position* and *momentum* operators do not commute, the *momentum* eigenstate is *not* a *position* eigenstate; hence, *position* in such a state is *undefined* while a *PD* is predicted for its *next* value under a *position-GI*. By stating that a definite value of the coordinate is “thus not predictable, but may be obtained only by direct measurement”, EPR reveals an a priori belief in *classical determinism*: such a *position* must exist and it could have been provided by its direct ‘measurement’ had the previous ‘measurement’ of the *momentum* not altered the system state.

When a ‘particle’ is in a *momentum* eigenstate, a *momentum-GI* is a *TM* so, per **TRC**, the *momentum* is *real*. As for a *position-GI*, being the prediction a *PD*, **TRC** is mute so it is a non sequitur to infer that if the *momentum* is *real* the *position* is *not*. **EPR6** recites the Copenhagen Interpretation of QT. **TRC** was purposely devised as “merely” *sufficient* lest, having assumed QT *correct*, **TRC** would imply that the “coordinate has no physical reality” at all. EPR believed the *position* was *real* but only if it had a definite value, which is nothing but an a priori philosophical belief (violating **EPR4**). For Einstein, using *probability* amounted to confessing *ignorance* of the underpinning *causal* processes. I call this ‘The Reality Preconception 1’ (TRP1).

## 6. The Fallacious Dichotomy (TFD)

Endeavoring to prove QT *incomplete*, EPR condenses **TRC**, **TCC**, and **TRP1** into a dichotomy:

**EPR7**: *From this follows that either (1) the quantum-mechanical description of reality given by the wave function is not complete or (2) when the operators corresponding to two physical quantities do not commute the two quantities cannot have simultaneous reality. For if both of them had simultaneous reality—and thus definite values—these values would enter into the complete description, according to the condition of completeness. If then the wave function provided such a complete description of reality, it would contain these values; these would then be predictable. This not being the case, we are left with the alternatives stated.*

The phrase “For if both of them had simultaneous reality—and thus definite values—...” is now unequivocally asserting **TRP1**: only attributes with definite values are *real*, so two

conjugate properties cannot be “simultaneously real” (unless QT is incomplete). **EPR7** also says that the definite value of a real property must be “predictable”: the “mere” *sufficient* character of **TRC** has now become also *necessary*. Thus, for EPR, a theory cannot be *complete* if, in most cases, it predicts a mere *PD*. **EPR7** dogmatically removes *probability* from the *Ontology* and, inevitably, preordains QT’s *incompleteness*: *Petitio Principii* at work. It is baffling why Reality was not so ‘defined’ at the outset. A plethora of convoluted logic could have been saved: QT would be *incomplete* simply because only rarely does it predict definite values. However, the inclusion of a priori philosophical considerations into the *Ontology* (against **EPR4**) would have been obvious.

**EPR7** dichotomy boils down to: either (1) the two quantities *do* have “simultaneous reality” (determinate values) and QT is *incomplete* because it does not *predict* them, or (2) the quantities *do not* have “simultaneous reality” (at least one has a *PD*) and QT is *complete* because it predicts so. EPR conflates the joint reality of two physical properties with joint predictability and measurability of *single* values for them. This dichotomy is fallacious because it is predicated on a priori philosophical beliefs regarding Reality. It has only *analytic* value (as opposed to *synthetic*) because QT completeness or incompleteness depends on the ad hoc definition of “simultaneous reality”, not on experimental evidence.

As for **EPR7** phrase “..., it would contain these values; these would then be predictable”, it is obviously intimating the well-known idea of ‘hidden variables’ which, having zero dispersion ( $SD = 0$ ), would restore *Classical Determinism* to Physics, reaffirming **TRP1**. Future articles in this series will deal with hidden-variable theories and other QT interpretations/formulations.

## Conclusions

To honor the spirit of EPR, because of the conceptual confusion (**TCC**), I reinterpreted its reality criterion (**TRC**). In violation of its own dictum for identifying the ‘elements of reality’ (**EPR4**), EPR revealed its commitment to *classical determinism*, associating *probability* only with human *ignorance* and, thereby, relying on a Reality preconception (**TRP1**). Combining **TRC**, **TCC**, and **TRP1**, EPR proposed a mutually exclusive disjunction (**TFD**), whose truth value is only analytic (*not synthetic*) because it depends upon an ad hoc ‘definition’ of Reality.

Despite the above logical flaws, EPR strived to prove that option (1) in **TFD** was true, i.e. that the two quantities did have “simultaneous reality”. But, because (in most cases) a ‘measurement’ (*GI*) disturbs the state and **TRC** was mute regarding the property’s reality, EPR needed to conceive a way of ‘measuring’ without “in any way disturbing the system”. In our TOPI jargon: a way of making a *GI* to effectively work as a *TM*. Such a scheme to prove QT’s *incompleteness* was proposed by EPR, and it is dissected and proven also inadequate in Part II.<sup>12</sup>

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