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## Space is blue and birds fly through it

Carlo Rovelli

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# 'Space is blue and birds fly through it'

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Quantum mechanics is not about 'quantum states': it is about values of physical variables. I give a short fresh presentation and update on the *relational* perspective on the theory, and a comment on its philosophical implications.

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This article is part of the discussion meeting issue 'Foundations of quantum mechanics and their impact on contemporary society'.

## 1. A misleading notion: quantum state

In his celebrated 1926 paper [1], Erwin Schrödinger introduced the wave function  $\psi$  and computed the Hydrogen spectrum from first principles.

But the theory we call 'quantum mechanics' (QM) was born 1 year earlier, in the work of Werner Heisenberg [2], and had already evolved into its current *full* set of equations in a spectacular series of articles by Born *et al.* [3,4]. Dirac, following Heisenberg's breakthrough, got to the same structure independently, in 1925, the year before Schrödinger's work, in a work titled 'The fundamental equations of quantum mechanics' [5]. (See [6,7] for a historical account.) Even the Hydrogen spectrum had been computed by Pauli in [8], using the language of Heisenberg, Born and Jordan, based on the equations

$$[q, p] = i\hbar, \quad \frac{dA}{dt} = -\frac{i}{\hbar}[A, H] \quad (1.1)$$

and the relation between physical values and eigenvalues, with no reference to  $\psi$ .

So, what did Schrödinger do, in his 1926 paper?

With hindsight, he took a *technical* and a *conceptual* step. The *technical* step was to change the algebraic

54 language of the theory, unfamiliar at the time, into a familiar one: differential equations. This  
 55 brought ethereal quantum theory down to the level of the average theoretical physicist.

56 The *conceptual* step was to introduce the notion of ‘wave function’  $\psi$ , soon to be evolved into  
 57 the notion of ‘quantum state’  $\psi$ , endowing it with heavy ontological weight. This conceptual step  
 58 was wrong, and dramatically misleading. We are still paying the price for the confusion it has  
 59 generated.

60 The confusion got into full shape in the influential second paper of the series [9], where  
 61 Schrödinger stressed the analogy with optics: the trajectory of a particle is like the trajectory of a  
 62 light ray: an approximation for the behaviour of an underlying physical wave in physical space.  
 63 That is:  $\psi$  is the ‘actual stuff’, like the electromagnetic field is the ‘actual stuff’ underlying the  
 64 nature of light rays.

65 Notice that this step is entirely ‘interpretational’. It does not add anything to the predictive  
 66 power of the theory, because this was already fully in place in the previous work of Heisenberg,  
 67 Born and Jordan, where the ‘quantum state’ does not play such a heavy role. Schrödinger’s  
 68 conceptual step provided only a (misleading) way of reconceptualizing the theory.

69 The idea that the quantum state  $\psi$  represents the ‘actual stuff’ described by QM has pervaded  
 70 later thinking about the theory. This is largely due to the toxic habit of introducing students to  
 71 quantum theory beginning with Schrödinger’s ‘wave mechanics’: thus betraying at the same time  
 72 history, logic and reasonableness.

73 The founders of QM saw immediately the mistakes in this step. Heisenberg was vocal in  
 74 pointing them out [10]. First, Schrödinger’s basis for giving ontological weight to  $\psi$  was the claim  
 75 that quantum theory is a theory of waves *in physical space*. But this is wrong: already the quantum  
 76 state of two particles cannot be expressed as a collection of functions on physical space. Second,  
 77 the wave formulation misses the key feature of atomic theory: energy discreteness, which must  
 78 be recovered by additional ad hoc assumptions, because there is no reason for a physical wave to  
 79 have energy related to frequency. Third, and most importantly, if we treat the ‘wave’ as the real  
 80 stuff, we fall immediately into the horrendous ‘measurement’ problem. In its most vivid form  
 81 (due to Einstein): how can a ‘wave’, spread over a large region of space, suddenly concentrate on  
 82 a single place where the quantum particle manifests itself?

83 All these obvious difficulties, which render the ontologization of  $\psi$  absurd, were rapidly  
 84 pointed out by Heisenberg. But Heisenberg lost the political battle against Schrödinger, for a  
 85 number of reasons. First, all this was about ‘interpretation’ and for many physicists this was  
 86 not so interesting after all, once the equations of QM began producing wonders. Differential  
 87 equations are easier to work with and sort of visualize, than non-commutative algebras. Third,  
 88 Dirac himself, who did a lot directly with non-commutative algebras, found it easier to make  
 89 the calculus concrete by giving it a linear representation on Hilbert spaces, and von Neumann  
 90 followed: on the one hand, his robust mathematical formulation of the theory brilliantly focused  
 91 on the proper relevant notion: the non-commutative observable algebra, on the other, the weight  
 92 given to the Hilbert space could be taken by some as an indirect confirmation of the ontological  
 93 weight of the quantum states. Fourth, and most importantly, Bohr—the recognized fatherly  
 94 figure of the community—tried to mediate between his two brilliant bickering children, by  
 95 obscurely agitating hands about a shamanic ‘wave/particle duality’. To be fair, Schrödinger  
 96 himself realized soon the problems with his early interpretation, and became one of the most  
 97 insightful contributors to the long debate on the interpretation; but the misleading idea of taking  
 98 the ‘quantum state’ as a faithful description of reality stuck.

99 If we want to get any clarity about QM what we need is to undo the conceptual confusion  
 100 raised by Schrödinger’s introduction of the quantum state  $\psi$ .

101 The abstract of the breakthrough paper by Heisenberg reads: ‘The aim of this work is to set the  
 102 basis for a theory of QM based exclusively on relations between quantities that are in principle  
 103 observable.’ Only relations between variables, not new entities. The philosophy is not to inflate  
 104 ontology: it is to rarefy it.

105 Felix Bloch reports an enlightening conversation with Heisenberg [11]: ‘We were on a walk  
 106 and somehow began to talk about space. I had just read Weyl’s book *Space, Time and Matter*,

and under its influence was proud to declare that space was simply the field of linear operations. ‘Nonsense,’ said Heisenberg, ‘*space is blue and birds fly through it.*’ This may sound naive, but I knew him well enough by that time to fully understand the rebuke. What he meant was that it was dangerous for a physicist to describe Nature in terms of idealized abstractions too far removed from the evidence of actual observation. In fact, it was just by avoiding this danger in the previous description of atomic phenomena that he was able to arrive at his great creation of QM. In celebrating the 15th anniversary of this achievement, we are vastly indebted to the men who brought it about: not only for having provided us with a most powerful tool but also, and even more significant, for a deeper insight into our conception of reality.’

What is thus this ‘deeper insight into our conception of reality’ that allowed Heisenberg to find the equations of QM, and that has no major use of the quantum state  $\psi$ ?

## 2. Quantum theory as a theory of physical variables

Classical mechanics describes the world in terms of physical variables. Variables take values, and these values describe the events of nature. Physical systems are characterized by sets of variables and interact. In the interaction, systems affect one another in a manner that depends on the value taken by their variables. Given knowledge of some of these values, we can, to some extent, predict more of them.

The same does QM. It describes the world in terms of physical variables. Variables take values, and these values describe the events of nature. Physical systems are characterized by sets of variables and interact, affecting one another in a manner that depends on the value taken by their variables. Given knowledge of some values, we can, to some extent, predict more of them.

The basic structure of the two theories is therefore the same. The differences between classical and QM are three, interdependent:

- (a) There is fundamental *discreteness* in nature, because of which many physical variables can take only certain specific values and not others.
- (b) Predictions can be made only *probabilistically*, in general.
- (c) The values that a variables of a physical system takes are such only *relative* to another physical system. Values taken relatively to distinct physical systems do not need to precisely fit together coherently, in general.

I discuss with more precision these three key aspects of quantum theory, from which all the rest follows, below. The first—discreteness—is the most important characteristic: it gives the theory its name. It is curiously disregarded in many, if not most, philosophers’ discussions on quantum theory. The third is the one with heavy philosophical implications, which I shall briefly touch upon below.

This account of the theory is the interpretative framework called ‘Relational QM’. It was introduced in 1996 in [12] (see also [13–16]). In the philosophical literature it as been extensively discussed by Bas van Fraassen [17] from a marked empiricist perspective, by Michel Bitbol [18,19] who has given a neo-Kantian version of the interpretation, by Mauro Dorato [20] who has defended it against a number of potential objections and discussed its philosophical implication on monism, and recently by Laura Candiotti [21] who has given it an intriguing reading in terms of (Ontic) Structural Realism. Metaphysical and epistemological implications of relational QM have also been discussed by Matthew Brown [22] and Daniel Wolf (né Wood) [23].

### (a) Discreteness

I find it extraordinary that so many philosophical discussions ignore the main feature of quantum theory: discreteness.

Discreteness is not an accessory consequence of quantum theory, it is its core. Quantum theory is characterized by a physical constant: the Planck constant  $h = 2\pi\hbar$ . This constant sets the scale of

the discreteness of quantum theory, and thus determines how bad is the approximation provided by classical mechanics. Several ‘interpretations’ of quantum theory seem to forget the existence of the Planck constant and offer no account of its physical meaning.

Here is a more detailed account of discreteness:

A physical system is characterized by an ensemble of variables. The space of the possible values of these variables is the *phase space* of the system. For a system with a single degree of freedom, the phase space is two dimensional. Classical physics assumes that the variables characterizing a system have always a precise value, determining a point in phase space. Concretely, we never determine a point in phase space with infinite precision—this would be meaningless—, we rather say that the system ‘is in a finite region  $R$  of phase space’, implying that determining the value of the variables will yield values in  $R$ . Classical mechanics assumes that the region  $R$  can be arbitrarily small.

Now, the volume  $\text{Vol}(R)$  of a region  $R$  of phase space has dimensions  $\text{Length}^2 \times \text{Mass}/\text{Time}$ , for each degree of freedom. This combination of dimensions,  $\text{Length}^2 \times \text{Mass}/\text{Time}$ , is called ‘action’ and is the dimension of the Planck constant. Therefore what the Planck constant fixes is the size of a (tiny) region in the space of the possible values that the variables of *any* system can take.

Now: *the* major physical characterization of quantum theory is that the volume of the region  $R$  where the system happens to be cannot be smaller than  $2\pi\hbar$ :

$$\text{Vol}(R) \geq 2\pi\hbar, \quad (2.1)$$

per each degree of freedom. This is the most general and most important physical fact at the core of quantum theory.

This implies that the number of possible values that *any* variable distinguishing points within the region  $R$  of phase space, and which can be determined without altering the fact that the system is in the region  $R$  itself, is at most

$$N \leq \frac{\text{Vol}(R)}{2\pi\hbar}, \quad (2.2)$$

which is a *finite* number. That is, this variable can take *discrete* values only. If it was not so, the value of the variable could distinguish arbitrary small regions of phase space, contradicting (2.1). In particular: any variable separating finite regions of phase space is necessarily discrete.

QM provides a precise way of coding the possible values that a physical quantity can take. Technically: variables of a system are represented by (self-adjoint) elements  $A$  of a ( $C^*$ ) algebra  $\mathcal{A}$ . The values that the variable  $a$  can take are the spectral values of the corresponding algebra element  $A \in \mathcal{A}$ .

## (b) Probability

Mechanics predicts the values of some variables, given some information on the values that another set of variables has taken. In QM, the available information is coded as a (normalized positive linear) functional  $\rho$  over  $\mathcal{A}$ . This is called a ‘state’. The theory states that the *statistical* mean value of a variable  $A$  is  $\rho(A)$ . Thus values of variables can be, in general, predicted only probabilistically.

In turn, the state  $\rho$  is computed from values that variables take. (Technically: using the notation  $\rho(A) = \text{Tr}[\rho A]$ , a variable  $b$  taking value in the interval  $I$  of its spectrum, determines the state  $\rho = cP_I^b$  where  $P_I^b$  is the projector associated with  $I$  in the spectral resolution of  $B$  and  $c$  is the normalization constant fixed by  $\rho(\mathbb{1}) = 1$ . If then a variable  $b'$  takes value in  $I'$ ,  $\rho$  changes to  $\rho' = cP_{I'}^{b'}P_I^bP_{I'}^{b'}$  and so on.)

The value of a quantity is sharp when the probability distribution is concentrated on it ( $\rho(A^2) = (\rho(A))^2$ ). For a non-commutative quantum algebra, there are no states where all variables are sharp. Therefore, the values of the variables can never determine a point in phase space sharply. This is the core of quantum theory, which is therefore determined by the non-commutativity of the algebra. The Planck constant  $\hbar$  is the dimensional constant on the right-hand side of

213 the commutator: it determines the amount of non-commutativity, hence discreteness, hence  
 214 impossibility of sharpness of all variables.

215 The non-commutativity between variables is Heisenberg breakthrough, understood and  
 216 formalized by Born and Jordan, who were the first to write the celebrated relation  $[q, p] = i\hbar$  and  
 217 to recognize this non-commutativity as the key of the new theory, in 1925.

218 The non-commutativity of the algebra of the variables (measured by  $\hbar$ ) is the mathematical  
 219 expression of the physical fact that variables cannot be simultaneously sharp, hence there is an  
 220 ( $\hbar$ -size) minimal volume attainable in phase space, hence predictions are probabilistic.

221 The fact that values of variables can be predicted only probabilistically raises the key  
 222 interpretational question of QM: when and how is a probabilistic prediction resolved into an  
 223 actual value?

224

225

### 226 (c) The relational aspect of quantum theory

227

228 When and how a probabilistic prediction about the value of a variable  $a$  of a physical system  $S$  is  
 229 resolved into an actual value?

230 The answer is: when  $S$  interacts with another physical system  $S'$ . Value actualization happens  
 231 at interactions because variables represent the ways systems affect one another. Any interaction  
 232 counts, irrespectively of size, number of degrees of freedom, presence of records, consciousness,  
 233 degree of classicality of  $S'$ , decoherence, or else, because none of these pertain to elementary  
 234 physics.

235 In the course of the interaction, the system  $S$  affects the system  $S'$ . If the effect of the interaction  
 236 on  $S'$  depends on the variable  $a$  of  $S$ , then the probabilistic spread of  $a$  is resolved into an actual  
 237 value, or, more generally, into an interval  $I$  of values in its spectrum.

238 Now we come to the crucial point. The actualization of the value of  $a$  is such only relative to the  
 239 system  $S'$ . The corresponding state  $\rho'$  determined by the actualization is therefore a state relative  
 240 to  $S'$ , in the sense that it predicts *only* the probability distribution of variables of  $S$  in subsequent  
 241 interactions with  $S'$ . *It has no bearing on subsequent interactions with other physical systems.*

242 This is the profoundly novel relational aspect of QM.

243 Why are we forced to this extreme conclusion? The argument, detailed in [12], can be  
 244 summarized as follows.

245 We must assume that variables do take value, because the description of the world we employ  
 246 is in terms of values of variables. However, the predictions of QM are incompatible with *all*  
 247 variables having simultaneously a determined value. A number of mathematical results, such as  
 248 the Kochen-Specker [24] theorem, confirm that if all variables could have a value simultaneously,  
 249 the predictions of QM would be violated. Therefore, something must determine *when* a variable  
 250 has a value.

251 The textbook answer is 'when we measure it'. This obviously makes no sense, because  
 252 the grammar of Nature certainly does not care whether you or I are 'measuring' anything.  
 253 Measurement is an interaction like any other. Variables take value at any interaction.

254 However, (this is the key point) if a system  $S$  interacts with a system  $S'$ , QM predicts that in,  
 255 a later interaction with a further system  $S''$ , a variable  $b$  of the  $S \cup S'$  system is *not* determined  
 256 by  $\rho'$ . Rather, it is determined by the joint dynamical evolution of the  $S \cup S'$  *quantum* system. In  
 257 physicists' parlance: quantum theory predicts interference effects between the different branches  
 258 corresponding to different values of the variable  $a$ , as if no actualization had happened.

259 We have thus to combine the presence of these interference effects (which pushes us to say that  
 260  $a$  had no value) with the fact that the variable  $a$  does take a value.<sup>1</sup>

261

262

263

264

265

<sup>1</sup>In Many World interpretations,  $a$  takes a value indexically relative to a world; in Bohm-like theories only an (abelian) subset of variables has value, not all of them; in Quantum Information interpretations,  $a$  takes a value only when the interaction is with the idealistic holder of the information; in Copenhagen-like interpretations, when the interaction is with the 'classical world'; in Physical Collapse theories, when some not yet directly observed random physical phenomenon happens...

The answer of relational QM is that the variable  $a$  of the system  $S$  actualized in the interaction with  $S'$  takes value *with respect to  $S'$* , but not *with respect to  $S''$* . This is the core idea underlying the 'relational' interpretation of QM.

Relationality is no surprise in physics. In classical mechanics, the velocity of an object has no meaning by itself: it is only defined with respect to another object. The colour of a quark in strong-interaction theory has no meaning by itself: only the relative colour of two quarks has meaning. In electromagnetism, the potential at a point has no meaning, unless another point is taken as reference; that is, only relative potentials have meanings. In general relativity, the location of something is only defined with respect to the gravitational field, or with respect to other physical entities; and so on. But quantum theory takes this ubiquitous relationalism, to a new level: the actual value of *all* physical quantities of *any* system is only meaningful in relation to another system. Value actualization is a relational notion like velocity.

### 3. What is the quantum state?

The above discussion shows that the quantum state  $\rho$  does not pertain solely to the system  $S$ . It pertains also to the system  $S'$ , because it depends on variables' values, which pertain only to  $S'$ . The idea that states in QM are relative states, namely states of a physical system relative to a second physical system is Everett's lasting contribution to the understanding of quantum theory [25].

A moment of reflection shows that the quantum states used in real laboratories where scientists use QM concretely is obviously *always* a *relative* state. Even a radical believer in a universal quantum state would concede that the  $\psi$  that physicists use in their laboratories to describe a quantum system is not the hypothetical universal wave function: it is the relative state, in the sense of Everett, that describes the properties of the system, relative to the apparatus it is interacting with.

What precisely is the quantum state of  $S$  relative to  $S'$ ? What is  $\psi$  (or  $\rho$ )? The discussion above clarifies this delicate point: it is a theoretical device we use for bookkeeping information about the values of variables of  $S$  actualized in interactions with  $S'$ , values which can in principle be used for predicting other (for instance future, or past) values that variables may take in other interactions with  $S'$ .

Charging  $\psi$  with ontological weight is therefore like charging with ontological weight a distribution function of statistical physics, or the information I have about current political events: a mistake that generates mysterious 'collapses' anytime there is an interaction. More specifically, in the semiclassical approximation  $\psi \sim e^{iS}$  where  $S$  is a Hamilton–Jacobi function. This shows that the physical nature of  $\psi$  is the same as the physical nature of a Hamilton–Jacobi function. Nobody in their right mind would charge  $S$  with ontological weight, in the context of classical mechanics:  $S$  is a calculational device used to predict an outcome on the basis of an input. It 'jumps' at each update of the calculation.

QM is thus not a theory of the dynamics of a mysterious  $\psi$  entity, from which mysteriously the world of our experience emerges. It is a theory of the possible values that conventional physical variables take at interactions, and the transition probabilities that determine which values are likely to be realized, given that others are [26].

The fact that the quantum state is a bookkeeping device that cannot be charged with ontological weight is emphasized by the following observation [16]. Say I know that at time  $t$  a particle interacts with a  $x$ -oriented Stern–Gerlach device. Then I can predict that (if nothing else happens in between) the particle has probability  $\frac{1}{2}$  to be up (or down) spinning, when interacting with a  $z$ -oriented Stern–Gerlach device at time  $t'$ . Key point: this is true irrespectively of which between  $t$  and  $t'$  comes earlier. Quantum probabilistic predictions are the same both forth and back in time. So: what is the state of the particle in the time interval between  $t$  and  $t'$ ? Answer: it depends only on what I know: if I know the past (respectively, future) value, I use the state to bookkeep the future (respectively, past) value. The state is a coding of the value of the  $x$  spin that allows me to predict the  $z$  spin, not something that the particle 'has'. We can be realist about the



319 two values of the spin, not about the  $\psi$  in between, because  $\psi$  depends on a time orientation,  
 320 while the relevant physics does not.

321 A coherent ontology for QM is thus sparser than the classical one, not heavier.

322 A good name for the actualization of the value of a variable in an interaction is ‘quantum  
 323 event’. The proper ontology for QM is a sparse ontology of (relational) quantum events happening  
 324 at interactions between physical systems.

325

### 326 (a) Information

327

328 Equation (2.1) can be expressed by saying that

329

(P1) *The amount of information that can be extracted from a finite region of phase space is finite.*

330

331 ‘Information’ means here nothing else than ‘number of possible distinct alternatives’.

332

333 The step from  $\rho$  to  $\rho'$  determined by an actualization modifies the predictions of the theory. In  
 334 particular, the value of  $a$ , previously spread, is then predicted to be sharper. This can be expressed  
 335 in information theoretical theorems by saying that

336

(P2) *An interaction allows new information about a system to be acquired.*

337

338 There is an apparent tension between the two statements (P1) and (P2). If there is a finite  
 339 amount of information, how can we keep gathering novel information? The tension is only  
 340 apparent, because here ‘information’ quantifies the data relevant for predicting the value of  
 341 variables. In the course of an interaction, part of the previously relevant information becomes  
 342 irrelevant. In this way, information is acquired, but the total amount of information available  
 343 remains finite.<sup>2</sup>

344

345 It is the combination of (P1) and (P2) that largely characterizes quantum theory (for the case  
 346 of qubit-systems, see [27]). These two statements were proposed as the basic ‘postulates’ of QM  
 347 in [12]. The apparent contradiction between the two capturing the counterintuitive character of  
 348 QM in the same sense in which the apparent contradiction between the two Einstein’s postulate  
 349 for Special Relativity captures the counterintuitive character of relativistic space–time geometry.  
 350 Very similar ideas were independently introduced by Zeilinger and Brukner [28,29].

351

352 An attempt to reconstruct the full formalism of quantum theory starting from these two  
 353 information-theoretic postulated was initiated in [12] (see also [30]). Recently, a remarkable  
 354 reconstruction theorem along these lines has been successfully completed for the case of finite-  
 355 dimensional systems in [27,31], shedding considerable new light on the structure of the theory  
 356 and its physical roots.

357

358 The role of information at the basis of quantum theory is a controversial topic. The  
 359 term ‘information’ is ambiguous, with a wide spectrum of meanings ranging from epistemic  
 360 states of conscious observers all the way to simply counting alternatives, à la Shannon. As  
 361 pointed out, for instance, by Dorato, even in its weakest sense information cannot be taken  
 362 as a primary notion from which all others can be derived, because it is always information  
 363 about something. Nevertheless, information can be a powerful organizational principle in  
 364 the sense of Einstein’s distinction between ‘principle theories’ (like thermodynamics) versus  
 365 ‘constructive theories’ (like electromagnetism) [32]. The role of the general theory of mechanics  
 366 is not to list the ingredients of the world—this is done by the individual mechanical theories,  
 367 like the Standard Model of particle physics, general relativity, of the harmonic oscillator.  
 368 The role of the general theory of mechanics (like classical mechanics or QM) is to provide  
 a general framework within which specific constructive theories are realized. From this

369

370 <sup>2</sup>Here is a simple example: if a spin- $\frac{1}{2}$  particle passes through a z-oriented Stern–Gerlach apparatus and takes the ‘up’ path,  
 371 we have one bit of information about the orientation of its angular momentum  $\vec{L}$ . If it then crosses an x-oriented apparatus,  
 we gain one bit of information (about  $L_x$ ) and we lose one bit of information (about  $L_z$ ).

372 perspective, the notion of information as a number of possible alternatives may play a very  
373 useful role.

374 It is in this sense that the two postulates can be understood. They are limitations on the  
375 structure of the values that variables can take. The list of relevant variables, which define a  
376 physical system, and their algebraic relations, are provided by specific quantum theories.

377 There are several objections that come naturally to mind when one first encounters relational  
378 QM, which seem to render it inconsistent. These have been long discussed and have all been  
379 convincingly answered; see in particular the detailed arguments in van Fraassen [17] and Dorato  
380 [20] and the original paper [12]; I will not rediscuss them here. Relational QM is a consistent  
381 interpretation of quantum theory.

382 However, like all other consistent interpretations, it comes at a price.  
383

## 384 4. Philosophical implications

### 385 (a) Every interpretation has a cost

386 Every interpretation of quantum theory comes with a 'cost'.

387 Examples from some interpretations popular nowadays are the following. The cost of  
388 the Many World interpretations is the hugely inflated ontology of a continuous family of  
389 equally existing 'worlds', of which we basically know nothing, and an awkward difficulty  
390 of rigorously recovering the actual values of the variables in terms of which we describe  
391 the world, from the pure- $\psi$  picture taken as fundamental. The cost of the Physical Collapse  
392 interpretations, such as the Ghirardi–Weber–Rimini theory, is to be based on physics which  
393 is so far unobserved and that many physicists view as not very plausible. The cost of the  
394 Bohmian interpretations is to postulate the existence of stuff which is unobservable *in principle*  
395 and which, in the view of most physicists, violates too badly what we have learned about  
396 Nature in the last century. The cost of Quantum Informational interpretations (partially inspired  
397 by relational QM [33]) is to be tied to a basically idealistic stance where the holder of the  
398 information is treated as an unphysical entity, *a priori* differently from all other physical systems,  
399 which cannot be in superpositions. The so-called Copenhagen Interpretations, which are held  
400 by the majority of real physicists concretely working with QM, postulate the existence of  
401 a generally ill-explained 'classical world', whose interactions collapse quantum states. And  
402 so on. . . .

403 Do not take these criticisms badly: they are not meant to dismiss these interpretations; they are  
404 simply the reasons commonly expressed for which each interpretation does not sound plausible  
405 to others: the point I am making is that there is no interpretation of QM that is not burdened by  
406 a heavy cost of some sort, which appears too heavy a price to pay to those who do not share  
407 the passion for that particular interpretation. Many discussions about quantum theory are just  
408 finger-pointing to one another's cost.

409 The evaluation of these costs depends on wider philosophical perspectives that we explicitly  
410 or implicitly hold. Attachment to full fledged strong realism leads away from Quantum  
411 Informational interpretations and towards Bohm or Many Worlds. Sympathy for empiricism or  
412 idealism leads in opposite directions, towards Copenhagen or Quantum Information. And so on;  
413 the picture could be fine-grained.

414 The beauty of the problem of the interpretation of QM is precisely the fact that the spectacular  
415 and unmatched empirical success of the theory forces us to give up at least some cherished  
416 philosophical assumption. Which one is convenient to give up is the open question.

417 The relational interpretation does not escape this dire situation. As seen from the reactions in  
418 the philosophical literature, relational QM is compatible with diverse philosophical perspectives.  
419 But not all. How strong is the philosophical 'cost' of relational QM?

420 Its main cost is a challenge to a strong version of realism, which is implied by its radical  
421 relational stance.  
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423  
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## (b) Realism

425 'Realism' is a term used with different meanings. Its weak meaning is the assumption that there is  
426 a world outside our mind, which exists independently from our perceptions, beliefs or thoughts.

427 Relational QM is compatible with realism in this weak sense. 'Out there' there are plenty of  
428 physical systems interacting among themselves and about which we can get reliable knowledge  
429 by interacting with them; there are plenty of variables taking values, and so on. There is nothing  
430 similar to 'mind' required to make sense of the theory. What is meant by a variable taking value  
431 'with respect to a system  $S'$ ' is not  $S'$  to be a conscious subject of perceptions—it just the same as  
432 when we say that the velocity of the Earth is  $40 \text{ km s}^{-1}$  'with respect to the sun': no implication  
433 of the sun being a sentient being 'perceiving' the Earth. In this respect, quantum theory is no  
434 more and no less compatible with realism (or other metaphysics) than classical mechanics. I  
435 myself think that we, conscious critters, are physical systems like any other. Relational QM is  
436 anti-realist about the wave function, but is realist about quantum events, systems, interactions. ...  
437 It maintains that 'space is blue and birds fly through it', and space and birds can be constituted  
438 by molecules, particles, fields or whatever. What it denies is the utility—even the coherence—of  
439 thinking that all this is made up by some underlying  $\psi$  entity.

440 But there is a stronger meaning of 'realism': to assume that it is in principle possible to list all  
441 the features of the world, all the values of all variables describing it at some fundamental level,  
442 at each moment of continuous time, as is the case in classical mechanics. This is not possible in  
443 relational QM. Interpretations of QM that adhere to strong realism, like Many Worlds, or Bohm,  
444 or other hidden variables theories, circumvent the Kochen–Specker theorem, which states that  
445 in general there is no consistent assignment of a definite values to all variables, by restricting  
446 the set of elementary variables describing the world (to the quantum state itself, or to Bohmian  
447 trajectories, or else). Relational QM assumes seriously the Kochen–Specker theorem: variables  
448 take value only at interactions. The stronger version of the realist credo is therefore in tension  
449 with QM, and this is at the core of relational QM. It is not even realized in the relatively weaker  
450 sense of considering a juxtaposition of all possible values relative to all possible systems. The  
451 reason is that the very fact that a quantity has value with respect to some system is itself relative  
452 to that system [12].

453 This weak realism of relational QM is in fact quite common in physics laboratories. Most  
454 physicists would declare themselves 'realists', but not realists about  $\psi$ . As one of the two (very  
455 good) referees of this paper put it: 'In physicists' circles, Schrödinger's  $\psi$  is mostly regarded as a  
456 mere instrument'. Relational QM is a way to make this position coherent.

457 There are three specific challenges to strong realism that are implicit in relational QM.

458 The first is its sparse ontology. The question of 'what happens between quantum events' is  
459 meaningless in the theory. The happening of the world is a very fine-grained but discrete swarming  
460 of quantum events, not the permanence of entities that have well-defined properties at each  
461 moment of a continuous time.

462 This is the way the relational interpretation circumvents results like the Pusey–Barrett–  
463 Rudolph theorem [34]. Such theorems *assume* that at every moment of time all properties are  
464 well-defined. (For a review, see [35]) They essentially say that if there is a hidden variable theory,  
465 the hidden variables must contain at least the entire information which is in the quantum state.  
466 But the assumption is explicitly denied in relational QM: properties do not exist at all times: they  
467 are properties of events and the events happen at interactions.

468 In the same vein, in [36] Laudisa criticizes relational QM because it does not provide a 'deeper  
469 justification' for the 'state reduction process'. This is like criticizing classical mechanics because  
470 it does not provide a 'deeper justification' for why a system follows its equations of motion.  
471 It is a stance based on a very strong realist (in the narrow sense specified above) philosophical  
472 assumption. In the history of physics much progress has happened by realizing that some naively  
473 realist expectation was ill-founded, and therefore by dropping these kind of questions: How are  
474 the spheres governing the orbits of planet arranged? What is the mechanical underpinning of  
475 the electric and magnetic fields? Into where is the universe expanding? To some extent, one can  
476  
477

say that modern science itself was born in Newton's celebrated 'hypotheses non fingo', which is precisely the recognition that questions of this sort can be misleading. When everybody else was trying to find dynamical laws accounting for atoms, Heisenberg's breakthrough was to realize that the known laws were already good enough, but the ontology was sparser and the question of the actual continuous orbit of the electron was ill-posed. I think that we should not keep asking what amounts to this same question over and over again: trying to fill in the sparse ontology of Nature with our classical intuition about continuity. On this, see the enlightening discussion given by Dorato in [37].

The second element of relational QM that challenges a strong version of realism is that values taken with respect to different systems can be compared [12] (hence there no solipsism), but the comparison amounts to a physical interaction, and its sharpness is therefore limited by  $\hbar$ . Therefore, we cannot escape from the limitation to partial views: there is no coherent global view available. Matthew Brown has discussed this point in [22].

The third, emphasized by Dorato, is the related 'anti-monistic' stance implicit in relational QM. As the state of a system is a bookkeeping device of interactions with *something else*, it follows immediately that there is no meaning in 'the quantum state of the full universe'. There is no something else to the universe. Everett's relative states are the only quantum states we can meaningfully talk about. Every quantum state is an Everett's quantum state. A reason for rejecting relational QM, therefore, comes if we assume that the monistic idea of the 'state of the whole' must makessense and must be coherently given in principle.<sup>3</sup>

This relational stance of relational QM requires a philosophical perspective where relations play a central role. This is why Candiottto [21] suggests to frame relational QM in the general context of Ontic Structural Realism. This is certainly an intriguing possibility. My sympathy for a natural philosophical home for relational QM is an anti-foundationalist perspective where we give up the notion of primary substance-carrying attributes, and recognize the mutual dependence of the concepts we use to describe the world. Other perspectives are possible, as we have seen in the strictly empiricist and neo-Kantian readings by van Fraassen and Bitbol, but strong realism in the strict sense of substance and attributes that are always uniquely determined is not.

### (c) How to go ahead?

There are three developments that could move us forwards

The first is novel empirical information. Some interpretations of quantum theory lead to empirically distinguishable versions of the theory. Empirical corroboration of their predictions would change the picture; repeated failure to detect discrepancy from standard QM weakens their credibility. This is the way progress happens in experimental physics. So far, QM has been unquestionably winning for nearly a century, beyond all expectations.

The second is theoretical fertility. If, for instance, quantum gravity turned out to be more easily comprehensible in one framework than in another, then this framework would gain credibility. This is the way progress happens in theoretical physics.

My focus on relational QM, indeed, is also motivated by my work in quantum gravity [38,39]. In quantum gravity, where we do not have a background space-time where to locate things, relational QM works very neatly because the quantum relationalism combines in a surprisingly natural manner with the relationalism of general relativity. Locality is what makes this work. Here is how [40]: the quantum mechanical notion of 'physical system' is identified with the general relativistic notion of 'space-time region'. The quantum mechanical notion of 'interaction' between systems is identified with the general relativistic notion of 'adjacency' between space-time regions. Locality assures that interaction requires (and defines) adjacency. Thus quantum states are associated to three-dimensional surfaces bounding space-time regions and quantum mechanical transition amplitudes are associated to 'processes' identified with

<sup>3</sup>This does not prevent conventional quantum cosmology to be studied, because physical cosmology is not the science of everything: it is the science of the largest scale degrees of freedom.

the space–time regions themselves. In other words, variables actualize at three dimensional boundaries, with respect to (arbitrary) space–time partitions. The theory can then be used locally, without necessarily assuming anything about the global aspects of the universe.

The third manner in which progress can happen is how it does in philosophy: ideas are debated, absorbed, prove powerful or weak, and slowly are retained or discarded. I am personally actually confident that this can happen for quantum theory.

The key to this, in my opinion, is to fully accept this interference between the progress of fundamental physics and some major philosophical issues, like the question of realism, the nature of entities and relations, and the question of idealism. Accepting the reciprocal interference means in particular to reverse the way general philosophical stances colour our preferences for interpretation. That is, rather than letting our philosophical orientation determine our reading of QM, be ready to let the discoveries of fundamental physics influence our philosophical orientations.

It wouldn't certainly be the first time that philosophy is heavily affected by science. I believe that we should not try to understand the world rigidly in terms of our conceptual structure. Rather we should humbly allow our conceptual structure to be moulded by empirical discoveries. This, I think, is how knowledge develops best.

Relational QM is a radical attempt to directly cash out the initial breakthrough that originated the theory: the world is described by variables that can take values and obey the equations of classical mechanics, *but* products of these variables have a tiny non-commutativity that generically prevents sharp value assignment, leading to discreteness, probability and to the relational character of the value assignment.

The founders of the theory expressed this relational character in the 'observer–measurement' language. This language seems to require that special systems (the observer, the classical world, macroscopic objects. . .) escape the quantum limitations. But neither of this, and in particular no 'subjective states of conscious observers', is needed in the interpretation of QM. As soon as we relinquish this exception, and realize that *any* physical system can play the role of a Copenhagen's 'observer', we fall into relational QM. Relational QM is Copenhagen QM made democratic by bringing all systems onto the same footing.

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