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PHILM0005 Philosophy of Physics

Everything is relative: Has Rovelli found the way out of the woods?

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Abstract

We shall explore the relational interpretation of quantum mechanics put forward by Rovelli in [28], paying particular attention to metaphysical and epistemological questions raised by this interpretation. We shall conclude that while relational quantum mechanics raises many deep questions that are at best only partially answered, it is a very promising interpretation of quantum mechanics and will hopefully inspire a fruitful research programme, both for physics and philosophy. For the sake of accessibility, we shall assume no particular knowledge of quantum mechanics on the part of the reader, with the exception of §4 and various footnotes.

1 Introduction

Quantum mechanics, since its very beginnings in the early 20th century, has puzzled some of the greatest minds that humanity has ever produced.[1] Its peculiar and counterintuitive phenomena seem to defy common sense. In this essay, we shall consider an attempt to explain quantum mechanics recently put forward by the physicist Carlo Rovelli in [28], which he calls *relational quantum mechanics* (RQM).

Rovelli's explanation rests on a fascinating idea, which can be summed up rhetorically by the old phrase

Everything is relative.

The idea is that there is no such thing as an absolute, observer-independent physical value, but rather only values relative to observers.[2] We shall explain this in much more detail in §2.2 and §2.3, but take as an example the miniature model of the Eiffel Tower that I have on my desk: according to RQM, it is not in its position absolutely, but rather is only in its position *relative to me* (or relative to my laptop or to my pen, etc.). This is a very confusing idea, since it goes against some of our most entrenched intuitions, but it is not as crazy as it first sounds and is very much worth

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[1] The historical development of quantum mechanics is a fascinating story that we unfortunately do not have space to discuss. I will simply say that it is one of the finest intellectual achievements of all time, involving many exceptionally gifted physicists and mathematicians, such as Bohr, Born, Dirac, Einstein, Heisenberg, Hilbert, von Neumann, Planck and Schrödinger, to name but a few.

[2] The term 'observer' is not meant to carry any connotations of consciousness. An observer is any system, such as a pen, a person, or a measuring device; our use of expression such as 'an observer sees X' is purely a linguistic turn employed for the sake of plain English. This somewhat misleading use of the word 'observer' is the result of its historical use; I have chosen to continue perpetuating this mild confusion simply for the sake of convention.

investigating. We shall not deal with the technical issues of RQM.[3] Instead we shall deal with the philosophical aspects of RQM, which have so far been discussed little in the literature;[4] we will focus in particular on metaphysical and epistemological questions arising from RQM, since I cannot find any discussion of these issues in the literature.[5] We shall conclude that while RQM raises many deep questions that are at best only partially answered, it is a very promising interpretation of quantum mechanics and will hopefully inspire a fruitful research programme, both for physics and philosophy. Indeed, to go with the metaphor of [29], RQM may be the way out of the woods in which physics currently finds itself lost.

The essay will consist of two halves. In the first half (§2) we will motivate and describe RQM. The second half (§3, §4) will then deal with questions arising from RQM. In §5 we shall draw our conclusions.

2 Relational quantum mechanics

In this section we shall outline RQM. In §2.1 we will motivate our discussion of RQM by describing what is perhaps the main problem in QM, the *measurement problem.* In §2.2 we shall then describe RQM and in §2.3 we shall discuss the consistency of RQM.

Before we move on to §2.1, I wish to emphasise an important distinction. *Quantum physics* is the study of microscopic particles, such as electrons and photons; it is a subfield of physics, in the same way that molecular biology is a subfield of biology. *Quantum mechanics* (QM)[6] is a mathematical model used to describe phenomena and make predictions in quantum physics, in the same way that the central dogma[7] is a framework in which to describe and make predictions in molecular biology. Just as the central dogma could turn out to be misleading or incorrect[8] and molecular biologists would have to come up with a new framework within which to work, QM could turn out to be an inaccurate mathematical model and quantum physicists would have to come up with a new, accurate model.

Now, the problem with QM is not its accuracy. In fact, we have quite the opposite: QM is considered to be one of the most accurate mathematical models of any phenomena ever devised. Put simply, the problem with QM is that it doesn't appear to make any sense. Let us illustrate this with what is perhaps the biggest problem in QM, the measurement problem.

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[3] For technical accounts of RQM, see [7], [15] and [28].

[4] There is some, although mostly brief, philosophical discussion of RQM in [7], [15], [22], [28], [29] and [33]. I believe there is also a discussion of RQM from a Kantian perspective in [4], but I have been unable to obtain a copy of the manuscript.

[5] This is perhaps an unfair characterisation of the literature, since, as we shall see in §3, the metaphysical and epistemological questions arising from RQM are similar to those arising from QM generally, as well as those from general relativity. However, no one (as far as I can tell) has looked specifically at the metaphysics or epistemology of RQM.

[6] Unless otherwise specified, 'QM' shall always refer to non-relativistic quantum mechanics; that is, the mathematical model of quantum physics that does not take into account relativistic effects due to high velocities relative to the speed of light.

[7] The *central dogma of molecular biology* states, roughly speaking, that information can only be transferred from DNA to protein, and not the other way around ([9], [10]).

[8] There is in fact increasing evidence that the central dogma is not the correct framework in which to study molecular biology: see [20].

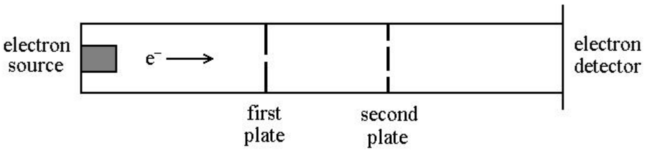

Figure 1: The apparatus. e^- is the symbol for an electron.

2.1 The measurement problem

We shall describe a specific example of the measurement problem, the famous *double-slit experiment*,[9] skirting over some technical details for the sake of clarity and accessibility.[10] Consider a piece of apparatus consisting of a tube, with an electron source at one end and an electron detector at the other. Inside the tube is a vacuum, so electrons pass along it freely, unobstructed by air particles. The electron detector consists of a black screen, upon which a small white mark appears when and where an electron hits it; the fact that it can tell you *where* the electron hit it is crucial. The electron source fires electrons along the tube one-by-one. In the tube we place two metal plates, the first with one thin slit and the second with two thin slits (see Figure 1). Electrons can only pass through the plates through the slits; that is, if we blocked the tube with a metal plate that had no slits and fired electrons down the tube, the electron detector would detect no electrons. (If there were no plates at all, then the electrons would scatter randomly over the detector screen.)

The experiment is carried out in two stages. First, we fire electrons along the tube and *do not* measure which slit in the second plate each electron passed through. In this case, we get an interference pattern (see Figures 2 and 3). This in itself is pretty amazing: an electron is meant to be a particle, but the interference pattern can only be explained if *each* electron behaves like a wave (see Figures 2), since we fire the electrons off *one-by-one*.[11] But things get even more interesting when we perform the second stage of the experiment: if we now place a measuring device by the second plate to see which slit each electron goes through (see Figure 4) and then repeat the experiment – first resetting the electron detector! – we no longer get an interference pattern (see Figure 5). This is really weird: the very act of measuring which slit each electron goes through affects the way in which the electrons land on the detector.

What on earth's going on here? Well, this is a (deep) open question; we shall discuss Rovelli's proposed answer in §2.2. However, QM, which we recall is just a mathematical *model* of quantum physics, can *describe* this behaviour – it just can't *explain* it. Without going into all the

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[9] Voted 'the most beautiful experiment' by readers of *Physics World*! ([8]).

[10] A more technical discussion can be found in [11], pp. 301–304. For a different example of the measurement problem, see [27].

[11] To help see how strange this is, imagine instead that we fired bullets along a tube at Kevlar plates. We would be very surprised to see the interfence pattern in Figure 3 on a screen we placed behind the tube.

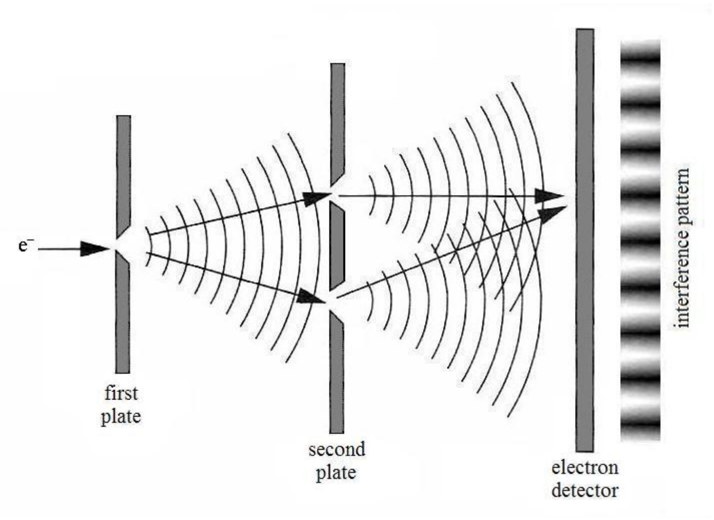

Figure 2: The first stage of the experiment.

Figure 3: The electron detector during the first stage of the experiment: the interference pattern becomes clearer as more electrons are fired. Number of electrons fired: (a) 11 (b) 200 (c) 6000 (d) 40,000 (e) 140,000.

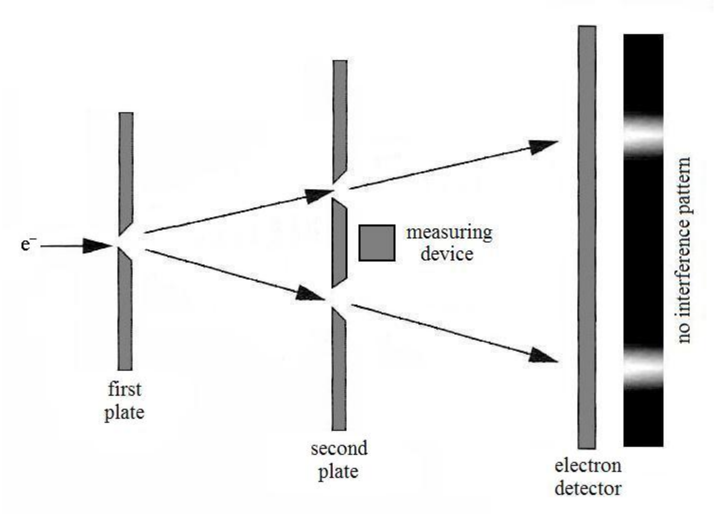

Figure 4: The second stage of the experiment.

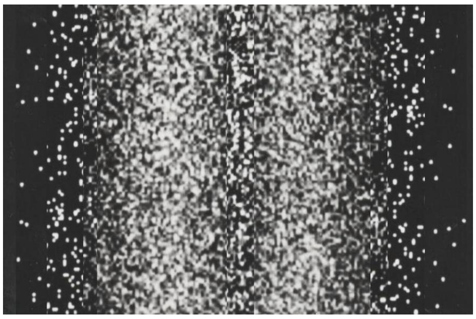

Figure 5: The electron detector after the second part of the experiment: there is no interference pattern.

technicalities, we shall outline how QM does this.[12]

Each electron fired has a *state*, which can be characterised as 'the exact condition of [the] system at a given moment of time' (p. 461 of [24]). In the above experiment, there are two possible *pure* states: going through the left slit or going through the right slit. Following convention, we shall denote these two pure states by $|\text{left}\rangle$ and $|\text{right}\rangle$ respectively. They are called *pure* because they can also be *mixed*: QM says that each electron, until it is measured, is in a *superposition* of these two pure states,[13] which in this case is

$$\tfrac{1}{\sqrt{2}}|\text{left}\rangle + \tfrac{1}{\sqrt{2}}|\text{right}\rangle; \tag{1}$$

we'll explain the $\frac{1}{\sqrt{2}}$ coefficients later on in this section. This is the puzzling thing about QM: particles can be in two apparently contradictory states at once. This is *not* just a state of ignorance: it is not the case that we do not *know* whether a given electron went through the left or the right slit, but rather that the electron, as it were, *actually went through both.* The evidence for this is Figure 3: if it were simply a state of ignorance, then at the end of the first stage of the experiment we would have the pattern in Figure 5, and not the pattern in Figure 3 that we actually get.

Now, the behaviour of each electron in the superposition (14) is described by the *Schrödinger equation* (SE), which I shall write down for any mathematically-minded readers:[14]

$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2m}\nabla^2\psi. \tag{2}$$

Crucially, SE describes *dynamic* – or *continuous* – motion; that is, the electron doesn't make any "sudden jumps". This is where the second stage of the experiment comes in. When we place a measuring device by the second plate to detect which slit each electron passes through, as in Figure 4, we no longer get an interference pattern, but rather the pattern we would expect from firing *particles* (and not waves) along the apparatus (see Figure 5). This is indeed very odd: why should simply measuring which slit each electron passes through affect the distribution of electrons on the detector? After all, placing a camera to see which slit in a Kevlar plate a bullet passes through wouldn't affect the bullet's trajectory. Well, we can answer this question, but the answer only raises another question. The crucial notion to grasp here is that all mesurements are physical interactions. For example, using a camera to see which slit a bullet passes through requires that photons bounce off the bullet into the camera's lens; in this case the photons' effect on the bullet is minimal, since the bullet, compared to the photons, is *very* big (hitting a cushion with the cue ball doesn't move the billiard table). However, in the case of our experiment, the measuring device

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[12] Nice introductions to the mathematical technicalities of QM can be found in [1] and [24].

[13] For those readers familiar with functional analysis: The state of a quantum system is described using a complex Hilbert space. The pure states are represented by rays, i.e. one-dimensional subspaces, and superpositions by linear combinations of these rays.

[14] We will not go into the mathematical details, but the Schrödinger equation describes wave-like behaviour, hence why electrons in superposition generate the interference pattern in Figure 3. Note that we can't explain this superposition by simply concluding that electrons are waves though, since the electrons also exhibit particle-like behaviour: for example, each electron lands *at a point* on the detector, and not spread out like a wave. This strange phenomenon of particles acting like waves is known as *wave–particle duality.*

detects which slit each electron passes through by bouncing photons off the electron, which *does* have a noticeable affect on the electron (hitting a red ball with the cue ball will certainly move the red ball).

Okay, so the very act of measuring which slit each electron passes through has a significant effect on the electrons. But then we have another question: if SE describes *continuous* motion, and QM is an accurate description of quantum physics, then why upon measurement does the electron "suddenly jump" from a superposition to a pure state? That is, why does SE 'collapse'? This is the measurement problem.[15]

For the sake of clarity, let's spell this out. QM says that the behaviour of quantum particles is governed by SE, which says that particles move continuously, behaving like a wave. So our electron will pass through the second plate like a wave, in a superposition of having passed through both slits, until, upon being measured, it will "jump" from the superposition to one of the pure states. That is, *after having passed through the plate*, the meauring device forces the electron to "choose" which slit it went through. The measurement problem is then the question: why does this happen, why does SE stop working at the point of measurement?

Now, as we said earlier, QM can describe quantum behaviour, it just can't explain it. So how does QM describe the collapse of SE? Well, built into the formalism of QM is the *Collapse Postulate*, which says that upon measurement, a quantum system will collapse into one of its pure states.[16] This collapse is not deterministic though: QM cannot predict with certainly which pure state the electron will collapse into. What QM can do, however – and it does so very accurately – is to give the *probability* of a quantum system collapsing from a superposition into a given pure state. These probabilities follow the *Born Rule*,[17] which we shall state (in a slightly simplified way) for the case of a superposition consisting of two pure states: if a quantum particle is in the superposition

$$a|A\rangle + b|B\rangle,$$

then the probability of observing $|A\rangle$ upon measurement is $|a|^2$ and the probability of observing $|B\rangle$ is $|b|^2$. So, in the case of the double-slit experiment, both the coefficients in the superposition (1) are $\frac{1}{\sqrt{2}}$, and thus there is a 50/50 chance of the electron passing through the left slit or the right slit (which is reflected by the experimental frequencies). The philosophical question is then: what do these probabilities mean physically? We shall only discuss this briefly in §4 and we shall see that RQM has only a partial answer.

So we now know how QM describes the measurement problem. But how are we to solve it? Well, in the next section we shall outline RQM, Rovelli's proposed solution. Before we move on,

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[15] Note that we have only demonstrated one particular example of the measurement problem. In general, the problem refers to the collapse of SE of a quantum system when it interacts with a macroscopic object.

[16] For those readers familiar with functional analysis: The collapse is described by the application of a projection operator on the superposition; the pure states – which are rays, not just vectors – correspond to the eigenvalues of the operators (and hence pure states are often called *eigenstates*).

[17] The rule is named after Max Born, who first proposed the probabilistic interpretation of collapse in [5]. See pp. 353–354 of [24].

however, we should mention that there have been many previous attempts to solve the measurement problem. One idea is that every measurement leads to the creation of 'many worlds', with different worlds corresponding to different outcomes.[18] Another suggests that QM is in fact an incomplete description of quantum physics, and that there are 'hidden variables' that describe quantum particles deterministically.[19] There are many others. We shall not discuss any of these other proposed solutions in any detail in this essay; instead I will simply say that while each of them has been subjected to a great deal of analysis, none of them has achieved universal acceptance amongst physicists or philosophers.

2.2 An outline of RQM

Rovelli motivates RQM with his 'Main Observation':

> 'In quantum mechanics different observers may give different accounts of the same sequence of events.' (p. 4 of [28])

We shall use a different example from that employed by Rovelli in [28] to illustrate the Main Observation, namely the double-slit experiment, but the consequences will be the same.[20] Before we get into the explanation, we need to go over a little more of the formalism of QM. We already know the two possible pure states of an electron: $|\text{left}\rangle$ and $|\text{right}\rangle$. We now need to consider the possible pure states of the *electron detector*. The electron detector dsiplays '`left`' if it sees the electron pass through the left slit and '`right`' if it sees the electron pass through the right slit. That is, the state of the electron detector is correlated with the state of the electron: if the electron passes through the left slit then the detector is in the state $|\texttt{left}\rangle$, and if the electron passes through the left slit then the electron detector is in the state $|\texttt{right}\rangle$.

We can now proceed. First consider the measurement from the perpective of the measuring device, which we shall denote M. Upon measuring the electron, M observes the electron to be in the state $|\text{left}\rangle$ or $|\text{right}\rangle$; without loss of generality, suppose it observes $|\text{left}\rangle$.

Now consider the measurement from the point of view of a third observer, which we shall call P. P knows that a measurement will be performed, but P does not know the outcome of the measurement.[21] P views the apparatus as a whole; that is, P views the combined system of the electron and the measuring device, which we shall denote $\mathrm{e}^- + M$. After time t, since P does know the outcome of the measurement, it views $\mathrm{e}^- + M$ as being in the superposition

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[18] See §5 of [3] for a succinct summary of this interpretation of QM.

[19] See §23.3 and §24.3 of [11] for a description of this view.

[20] Rovelli uses what is in effect a version of the *Wigner's friend* thought experiment; see [2] and [28].

[21] More precisely: P has interacted with the apparatus enough to know that an electron will be fired at time t (remember that all measurements are physical interactions), but P stops interacting with the apparatus before time t.

$$\tfrac{1}{\sqrt{2}}|\text{left}\rangle \otimes |\texttt{left}\rangle + \tfrac{1}{\sqrt{2}}|\text{right}\rangle \otimes |\texttt{right}\rangle.^{22,23} \tag{3}$$

So what's happened exactly? Well, after time t, M thinks the electron passed through the left slit, while P thinks the electron (in correlation with the detector) is still in a superposition of having passed through both slits. M and P have given different, yet *correct*, descriptions of the same event – and this is all described in QM, the mathematical model, and not in any interpretation of it. The Main Observation is thus quite correct.[24]

We now come to the crucial step. Rather than trying to explain away the Main Observation by appending many worlds or hidden variables to the formalism of QM, Rovelli takes the formalism at face value and simply concludes that quantum states are observer-dependent.[25] So, in RQM, it is wrong to say that the electron passed through the left slit *absolutely*: one must specify the observer. In the case above, the electron passed through the left slit *relative to M*, which we denote by $|\text{left}\rangle_M$.[26] Relative to P, the electron (in correlation with the detector) is in a superposition, which we denote by

$$\left(\tfrac{1}{\sqrt{2}}|\text{left}\rangle \otimes |\texttt{left}\rangle + \tfrac{1}{\sqrt{2}}|\text{right}\rangle \otimes |\texttt{right}\rangle\right)_P.$$

This is the main argument for RQM, but before we move on we need to qualify precisely what we meant by 'Rovelli takes the formalism at face value'. Rovelli takes QM to be a complete description of the quantum world (p. 7 of [28]). He backs this up by the wealth of accurate predictions made by QM and suggests that much of the unease surrounding QM comes from the assumption that QM is incomplete (p. 7 of [28]). He also accepts that all systems are equivalent (p. 4 of [28]); that is, the only difference between a 'system' and an 'observer' is a linguistic one – physically they are no different as quantum entities. This may seem like a reasonable thing to suppose, since quantum physics is meant to be fundamental (and so why would an observer be governed by a different set of rules than the system being observed?), but some interpretations make a distinction between observers and systems.[27]

Let us now explain how Rovelli actually derives the formalism of QM (so far we have only demonstrated how Rovelli justifies the underlying idea of observer-dependence). We shall do this

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[22] The symbol $\otimes$ represents the *tensor product* of the two Hilbert spaces representing e^- and M; what this means physically is correlation. That is, $e^- + M$ being in the state $|\text{left}\rangle \otimes |\texttt{left}\rangle$ means that e^- being in the state $|\text{left}\rangle$ is correlated with M being in the state $|\texttt{left}\rangle$; similarly for $|\text{right}\rangle \otimes |\texttt{right}\rangle$.

[23] A technical note: We are implicitly using the linearity of QM here (see §II.A of [28]).

[24] We do not have space to consider possible objections to this line of reasoning. Fortunately, however, Rovelli has already dealt with them: see §II.B of [28].

[25] See [30] for Rovelli's view of scientific progression, which appears to implicitly motivate this step.

[26] Do not confuse this notation with the common use of subscripts to denote the *system*, rather than the observer observing the system as we are doing.

[27] I am referring to the *Copenhagen interpretation* of QM, which was the consensus amongst most physicists from around the 1930s to around the 1960s. Under the Copenhagen view, intuitive notions of causation break down at the quantum level and the collapse of the Schrödinger equation is somehow due to the difference between the observer and the system. In my opinion, it is more of a non-interpretation than an interpretation, since it doesn't try to explain collapse, but rather just accepts it as being a bit strange. See §20 of [11] for a more detailed (and more balanced) exposition, and see [14] for a polemic on the Copenhagen view.

only heuristically, since the details are highly technical.[28] The language in which Rovelli derives the formalism of QM is information. We shall not discuss the philosophical pros and cons of quantum information, since that would be a whole other essay; we shall simply explain how Rovelli uses it. The important points to note are that: (a) the notion of information that Rovelli uses is a very abstract one that does not require consciousness or meaning (§II.E of [28]);[29] and (b) Rovelli does not complete the derivation of QM.

In RQM, a quantum system is characterised by a set of yes/no questions that can be asked of it. For example, in the case of an electron in the double-slit experiment, one of the questions would be 'Did the electron go through the left slit?'[30] When system B, say a measuring device, interacts with a system A, B gains information about A by acquiring answers to one or more of the questions associated with A. These answers are relative to B.

Rovelli then attempts to derive the formalism of QM from two simple information-theoretic postulates. We shall not discuss them due to their technical nature, other than to say that they reflect experimental practice and Rovelli's justification for observer-dependence, as discussed earlier.[31] The important point for our essay here is that Rovelli does not complete the derivation: to obtain the full formalism of QM, Rovelli – by his own admission – has to introduce a third, ad hoc postulate (p. 14 of [28]). This is by no means fatal for RQM, since the derivation might be completed,[32] but it is certainly an aspect of RQM that will require further work before RQM can be held up as the correct interpretation of QM.

At this point, perhaps some discussion of what we mean by 'derivation' is in order. As we stated earlier, the mathematical model QM has been around for a long time. The puzzle has been to explain it. So far, most attempts to do this have either simply appended an interpretation to the formalism (e.g. many worlds) or have tried to alter the formalism (e.g. hidden variables). Such attempts have (so far) been unsuccessful.[33] What Rovelli is trying is different. He is attempting to put forward 'simple physical assertions' (p. 2 of [28]) from which the formalism of QM can be derived. He admits, as we said earlier, that he has not yet done this, but the strategy is still a good one. As Rovelli points out himself, Einstein's genius in 1905 was not to come up with the mathematical formalism of special relativity, but rather to realise that it could be derived from just two simple postulates (p. 2 of [28]).

So far we have described how Rovelli justifies and derives RQM, but we haven't yet addressed

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[28] The technical details can be found in Rovelli's original paper [28]. Further technical dicussion can be found in [15], [17], [18] and [19], [18] being slightly tangential.

[29] Rovelli employs the notion of information put forward by Shannon in [32].

[30] As van Fraassen points out on p. 399 of [15], this is actually an absolute of RQM: that A is characterised by this set of questions is not relative to anything else. We shall discuss this in §3.1.

[31] For the precise statements of these postulates, see [28].

[32] There seem to be two possible ways in which this could be done: (a) Rovelli's original two postulates may in fact be enough and Rovelli simply hasn't seen their full potential; or (b) the two postulates aren't enough, but another postulate (or postulates) may be discovered which are deemed to be correct and are enough to fully derive QM.

[33] This comment will no doubt be met with disapproval by many philosophers and physics alike. My (less than analytic) response is simply that the debate between Everettians and Bohmians reminds me of two poker players vying with only a pair and a ten-high.

what we set out to solve: the measurement problem. The crucial idea is that a given system cannot measure itself. (This is in fact a theorem of QM, as proved by Breuer in [6].) The apparent collapse of the Schrödinger equation is then due to lack of total information on the part of the observer. The Schrödinger equation – like everything else in RQM – is relative to the observer (§IV of [28]). When a measurement takes place, SE relative to the observer does not include the observer in its dynamics; thus, the Schrödinger equation does not fully describe the interaction between the system and the observer, which causes the (apparent) collapse of the equation from the point of view of the observer. However, a second observer viewing the combined system of the first observer and the system would not see any collapse – this is what we essentially showed when justifying the Main Observation.

Okay, so far so good: RQM is justified by the formalism and can (almost) be derived from simple postulates. But then an obvious question comes to mind: if physical values are observer-dependent, what is to stop different observers contradicting each other? This is the topic of the next subsection.

2.3 Consistency

In this section we shall address the key notion of consistency. We shall demonstrate that RQM, despite any prima facie concerns, is in fact coherent.[34]

Let us set up what appears to be a potential inconsistency in RQM. Suppose we place *two* measuring devices by the second plate to measure which slit the electron passes through; call them M_1 and M_2. Since which slit the electron passes through is relative to the measuring device, it seems possible that M_1 could see the electron go through the left slit, while M_2 could see it go through the right slit; because of its somewhat contradictory nature, we shall call this eventuality BAD. We will first show that BAD cannot occur and then show that, without further any qualification, the very statement of BAD is in fact '*meaningless*' (p. 204 of [29]; Rovelli's emphasis).

A consistency theorem of QM, due to von Neumann ([26]), states that BAD cannot actually occur; that is, the theorem implies that should the two measuring devices communicate their observations, each will see the other's observation to be consistent with their own. In a phrase: any observer will see a consistent picture of the world.[35] So far so good: BAD can't happen. This, however, isn't the whole story.

At the start of this essay, I said that RQM could be summed up by the phrase 'everything is relative'. BAD is no exception: *knowledge of what an observer sees is relative to another observer.* This concept is crucial. Let us illustrate it with a light-hearted example. Imagine two people, Albert and Isaac, are looking at a playing card. Each can see what the card is and that the other can see the card, but neither can see *what* the other can see of the card; that is, Albert knows that

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[34] The notion of consistency is both crucial to RQM and deeply confusing. Should the reader quite reasonably require more than my exposition to understand this key concept, I would recommend [7], [28] and especially §4.4 of [33].

[35] Rovelli in fact takes this theorem as 'a strong indication of the relational nature of the world' (p. 6 of [22].

Isaac can see the card, but he does not know what Isaac sees the card to be (and vice versa). Now, that Albert sees A♠ is *relative to an observer*: to say 'Albert sees A♠' without any reference to an observer is meaningless in RQM. So, I would be wrong to say 'Albert sees A♠ and Isaac sees Q♡' without saying who sees this. However, if I do say who sees this, von Neumann's consistency theorem implies that it is impossible that this third observer could see such a contradictory state of affairs. So, returning to BAD, we see that its statement is in fact meaningless, since it makes no reference to a third observer describing the situation. Moreover, if we respond by restating BAD in terms of a third observer (or claim that the original statement was implicitly from the point of view of a third observer), Rovelli can reply by pointing out that von Neumann's theorem tells us that it is impossible that this observer could see M_1 measure left and M_2 measure right.[36]

A few remarks about what is absolute and what is not are in order. The most thorough analysis of this aspect of RQM is by van Fraassen in [15]; we shall follow his exposition. Van Fraassen identifies four absolutes in RQM (pp. 399–400 of [15]); that is, four things that are not dependent on an observer.[37] We shall cover only three of them:[38]

(i) Each system is characterised by a set of yes/no questions.

(ii) '[A]n observer who has been in measurement interaction with a system has a record of the questions that have been asked and the sequence of outcomes thus obtained. That the observer has this *is not relative* to another observer.' (p. 399 of [15]; his emphasis)

(iii) Each question of a system has a probability associated with each answer.

We shall discuss (i) in §3.1 and (iii) in §4. What I want to discuss here is (ii), since it is crucial to the notion of consistency – and because I believe van Fraassen's description is perhaps slightly misleading (hence why I quoted (ii) verbatim). What is absolute in RQM is correlation (pp. 9, 16 of [28]): that a question has been asked is absolute, but the answer obtained is relative.[39] So, in our explanation of the Main Observation in §2.2, that the states of M and e^- relative to P are correlated is absolute, but the actual values of these states is relative to P. That is, before interacting with $\mathrm{e}^- + M$, P can predict with certainty that the state of $\mathrm{e}^- + M$ is $|\text{left}\rangle \otimes |\texttt{left}\rangle$ or $|\text{right}\rangle \otimes |\texttt{right}\rangle$ (and not $|\text{right}\rangle \otimes |\texttt{left}\rangle$ or $|\text{left}\rangle \otimes |\texttt{right}\rangle$), but if P does interact with $\mathrm{e}^- + M$ then the state that it observes is relative to itself.

This is no doubt extremely confusing. Rovelli sums up the situation as follows:

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[36] As Brown points out in §6 of [7], this resolution of BAD via the realisation that all descriptions are relative is reminiscent of the apparent paradoxes of special relativity, which were resolved when the notion of absolute time was rejected.

[37] Alas our catch-phrase 'Everything is relative' doesn't quite hold universally.

[38] The fourth absolute regards the notion of irrelevant information, which comes from one of the information-theoretic postulates used by Rovelli to derive RQM (which we did not discuss).

[39] This is precisely the difference between RQM and Mermin's *Ithaca interpretation* of QM (IIQM) in [23]: while in RQM only the asking of a question is absolute, in IIQM the answer obtained is also absolute. Criticism of IIQM can be found in [7].

> '[R]eality admits one description per (observing) system, each being internally consistent. ... In turn, any given system can be observed by another system.' (p. 7 of [33])

The best analogy I can think of is the first- and third-person in language. Imagine a description in a novel written in the first-person. The 'I' in the novel, whom we shall denote I, says things such as 'the table is to my left' (this novel won't make the *New York Times* bestseller list). From the point-of-view of I, this third-person statement is absolute. But now imagine a metanovel, written from the perspective of I'. I' can see I, and so I' says 'the position of the table is correlated with I'. From the point-of-view of I', this third-person statement about correlation is absolute, but the actual position of the table is relative to I.[40]

So, in fact all of our discussion so far has implicitly been from the point of view of a 'metaobserver'. For example, our explanation of the Main Observation was implicitly from the point of view of a third observer watching P watch M watching e^-. Importantly, however, in RQM there is no global observer who can see everything. Such an observer would be observable itself, and moreover would not be able to see itself, and so would lead to contradiction in RQM.[41]

Let's take stock. So far we have seen the need for an explanation of QM and we have described Rovelli's proposed answer. We have also seen that RQM is coherent. We shall now move on to the second half of the essay and discuss questions arising from RQM.

3 Metaphysical and epistemological questions

In this section we shall consider a metaphysical and an epistemological question arising from RQM. I do not claim to ask all metaphysical and epistemological questions resulting from RQM and nor do I claim to fully answer the questions that I do raise: I simply wish to highlight some metaphysical and epistemological issues arising from RQM and paint broad pictures of possible solutions.

From this point on in the essay, unless otherwise specified, we shall work under the broad realist (and physicalist) assumption that RQM is the correct picture of the fundamental level of the universe. This is of course a strong assumption and we shall discuss it in §4.

3.1 A metaphysical question

So far we have been talking about different observers seeing different things about the same system; for example, we have simply been talking about 'the electron' in our running example of the double-slit experiment. The question is then: what is the electron? Is its existence/identity relative or absolute?[42] That is, if the identity of an object is observer-dependent, then what exactly is an

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[40] The Zen of RQM: If a tree falls and it in no way interacts with you, then, in your first-person description of the world, it *doesn't* make a sound; in fact, if it doesn't interact with you, then it is meaningless to even talk about the tree. The question of one hand clapping is still open though.

[41] This goes against Everett's idea of a global wave equation.

[42] I am conflating identity and existence here, which are of course two related but different things. However, for the purposes of our present discussion, this distinction is unimportant and we shall use the terms interchangeably.

object?[43]

First suppose that the identity of a system is absolute; that is, an object's existence does not depend on an observer. The question is now how, under RQM, this could be possible. One response would be that the system is in fact the set of questions that can be asked of it: the system isn't *characterised* by the set of questions, the system *is* the set of questions. After all, as we noted earlier (in footnote 30), the fact that each system is characterised by a set of questions that can be asked of it is not relative to any observer, and so equating the system with its set of questions would give us (some sort of) absolute identity of the system. This does seem like a viable suggestion, but one that certainly requires development: how are we to reconcile fundamental notions in physics, such as space, time, energy, mass and fields, with an information-theoretic approach to quantum physics? I will not attempt to answer these questions here (I'll leave that to future Nobel Laureates).

What could another approach be? The only other picture I can think of is that there is an underlying absolute reality, in which systems exist and different observers see differently.[44] While this may seem like a possible solution, it seems to go against the very idea of RQM that everything is relative. Also, we then have the question of what constitutes this underlying absolute reality. After all, if RQM is correct then we cannot observe it, since all observation is relative, so could we ever begin to understand its nature? Any such attempt would be pure metaphysics: experimental physics wouldn't be able to help. Whether or not this is a problem depends on how one thinks metaphysics should relate to physics, but it seems a bit too speculative for my taste.

Now suppose the identity of a system is relative; that is, the very existence of a system is observer-dependent. This certainly seems to be more within the spirit of RQM. However this perhaps leads us to a problem of trans-observer identity. Returning to the example of my miniature Eiffel Tower model, I know that it exists relative to me, and (by von Neumann's consistency theorem) that if I ask Sabrina sat next to me if it is there she will say 'yes', but how am I to know that it actually exists in Sabrina's description of the world? I think Rovelli would view this as a category mistake, since he says that different observers' accounts 'should not be juxtaposed' (p. 7 of [33]), but it seems puzzling how there could be any descriptions of the world if even the existence of objects is observer-dependent – what are the observers observing if the observer is ontologically primary to the object? Alas I have no coherent thoughts on this matter, so we shall move on to the next section.

3.2 An epistemological question

The epistemological question that I wish to address in this section is this: if everything is relative, how do we (appear to) perceive and have knowledge of macroscopic objects, such as pens, cats, and people? That is, how do quantum systems combine to form perceivable objects? I propose that we

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[43] As we alluded to in footnote 5, this issue is similar to the philosophical problem facing general relativity regarding the nature of relative spacetime. We shall briefly discuss links between general relativity and RQM in §4.

[44] I think Schopenhauer might have liked this idea.

can use Wallace's idea in [34] of applying Dennett's notion of a *real pattern* in [12] as a potential answer.

Wallace's idea is that macro-objects are not directly represented in the formalism of QM, but are rather real patterns. We do not have space to describe the notion in detail, but for our purposes a real pattern is an object of our perception whose study at the level of that pattern is much more parsimonious than at the fundamental level.[45] This is perhaps best illustrated with an example; we shall go with Wallace's tiger. A tiger can be studied at various different levels: the atomic level, the molecular level, the cellular level, the physiological level, the tiger level, and so on. Considering the tiger at subsequently higher levels will yield successively better descriptions and predictions of the tiger's behaviour. For example, if I were to be trapped in a cage with a tiger (I would have no trouble in a lion's den), I would be wise to consider the tiger at the level of being a tiger, rather than at the level of protons, neutrons and electrons.

Now, this proposed solution does not answer the more metaphysical question of *why* quantum systems should combine to form complex macrosystems such as tigers and human brains – why is there increased explanatory power at higher levels? I don't have an answer to this question, but I don't believe that it is a problem for RQM specifically, but is rather a problem for reductionism in general: should everthing be reducible to physics (and in turn QM/QP)? This is a long-debated issue and we will not discuss it here. What I want to emphasise is that this epistemological question of macrosystems is not a problem specific to RQM, but rather for QM in general. After all, I got the idea of applying the notion of a real pattern to RQM from Wallace, who applies it to the many-worlds interpretation in [34], an interpretation incompatible with RQM (p. 5 of [28]).

Let us now move on to more general questions facing RQM.

4 Further questions

In this section we shall cover some further questions arising from RQM. Our discussion will be brief: I simply wish to illustrate the wealth of questions implied by RQM – and hence show how fruitful a research programme RQM may inspire. For the sake of brevity, in this section we will assume some knowledge of physics on the part of the reader, as well as various current issues in the philosophy of science.

Let us start with some technical points. We have so far not mentioned locality (the notion that nothing can happen instantaneously at a distance). RQM appears to be able to offer a solution to the apparent EPR paradox,[46] since one can view the measurements of the spatially separated measuring devices as descriptions from different observers. However, there is disagreement about precisely how this solution should go ([21], [33]), so further work is required before RQM can claim

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[45] There are different ways of cashing out this parsimony, such as increased predictive power and computational economy; we do not have room to discuss them.

[46] The EPR paradox was an apparent demonstration of the incompleteness of QM put forward by Einstein, Podolsky and Rosen in [13]. The parodox turned out to be related to issues of locality.

to have solved the EPR paradox. There is also the issue of information theory. Some work has been done on the technical aspects of the derivation of RQM ([15], [17], [18], [19]), but the project is by no means complete. There are also philosophical debates to be had: what does it mean for information to be the fundamental currency of physics?

There are of course big conceptual issues at stake as well. Relational notions are crucial to general relativity; the concepts in RQM are very reminiscent of these notions (as we noted in footnote 43). Could RQM be the necessary conceptual leap needed to break the current impasse in physics over how to unify general relativity and quantum theory? Rovelli thinks it might be (see [29]).

Another conceptual issue that we haven't discussed is the nature of probability. As van Fraassen points out, the probabilities associated with Born's Rule are absolutes of RQM. While we could say, as Rovelli does, that measurements are 'intrinsically probabilistic' (p. 8 of [28]), this doesn't (conceptually) explain why these probabilities should be fundamental.

There are some further philosophical issues that can be re-evaluated in light of RQM. The realism–antirealism debate in relation to RQM has received no treatment in the literature. Is the notion of observer-dependence actually a fundamental aspect of reality or is it simply a good conceptual framework in which to make accurate predictions and to progress in physics? Our discussion in §3.1 assumed the former – was this a mistake? Furthermore, one may wonder how RQM might affect the current debate over structural realism. While RQM marks a big conceptual shift, the formalism of QM remains the same under this new interpretation, which would fit in with the general idea of structural realism.

Lastly, there has been a lot of recent literature regarding the Principle of Identity of Indiscernibles (PII), in particular with regard to quantum particles (e.g. [16], [25], and [31]). The issues at play are subtle (hence the debate), but PII can be roughly characterised as the principle that no two distinct objects have exactly the same properties. Our discussion in §3.1 regarding the nature of objects in RQM will no doubt have some bearing on PII, since we can no longer talk of objects having certain properties absolutely (or perhaps not even talk of *objects* absolutely).

This section has skimmed over many issues in little depth. However, the sheer quantity of questions raised illustrates how big an impact RQM may have on current thinking, both in physics and philosophy. Let us now finish our discussion by drawing our conclusions.

5 Conclusion

In this essay we outlined the main concepts of RQM, used it to solve the measurement problem and saw that it is a coherent theory (despite prima facie concerns). We then addressed various questions arising from RQM, focusing in particular on a metaphysical and an epistemological question. What we saw was that while many – if not all – of these questions are currently unanswered (or only partially answered), RQM's fundamental notion of observer-dependence opens up many new interesting avenues of thought and sheds new light on old issues. It is my hope that these new ideas will drive a fruitful research programme in both physics and philosophy. Indeed, as I hinted at in the previous section, perhaps the rejection of absolute physical value is the conceptual leap we need to drive physics forward. Only time will tell.

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