Essay, set subject: *Undecidability, uncomputability, and unpredictability*

To find the origin of these no go areas, quantum mechanics is the main question, as the rest is often limitations of the mathematical description. For the deep randomness in QM, missing concepts must be found, as in a new interpretation published in 2019.

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Abstract

With most forms of unpredictability, the limitations are not with the universe, but with the systems we use to describe it. Sometimes mathematics itself is limited, sometimes it's a lack of information, but either way, the description is incomplete. But then there are grey areas. Recent work shows that some chaotic systems, such as in the three-body problem, simply can't be computed, due to limitations set by the Planck length[1]. Is it the universe or the description that creates the limitation there? It can be shown that both are involved. But the main question is whether the universe is ever unpredictable in a way that is entirely unrelated to the description, and that can only be answered via quantum mechanics (QM). Here it is argued that three aspects of QM suggest there are missing concepts: the basic unpredictability, non-locality, and no consensus on how to interpret the theory. Some clues and ways to search for missing concepts are outlined, then a new interpretation for QM, in the hope that it sheds light on the unpredictability.

Author bio:

Jonathan Kerr is an independent researcher, published in peer reviewed journals, who worked mainly on the conceptual foundations of physics for twenty five years. A recent paper, *An interactions-based interpretation for quantum mechanics*, and the book 'The Unsolved Puzzle: Interactions, not measurements' were part of the subject of a 2019 documentary, *The Interactions Avenue*, in which he discusses the general avenue of thought on interactions, and a new interpretation for quantum mechanics, with some well-known physicists who also lean towards the interactions approach.

1. The edges of a system

We sometimes assume that mathematics is synonymous with what it describes. So if we find limitations to its descriptive ability, it can look like limitations to the world. But the questions about time, for instance, show that mathematics can be a 'shorthand version' of the world, and an incomplete description. The problems with time tend to disappear if one looks only at the mathematics, but not if one looks at the conceptual side.

There are many examples of this, so the questions about the scope of mathematics that started in the 1930s, with Gödel's incompleteness theorems, may be about reaching the edges of a good system. Perhaps mathematics is a skin that doesn't quite stretch over all that it tries to cover. If so, any general category for examples of that might be a catchall for mathematical quirks, with little connection between them, like 'irregular galaxies' as a classification.

Then there's also the kind of randomness that is not fundamental, but which arises from a lack of information. Chaos theory covers areas where a lot of information is needed. With too little, although we're used to a level of approximation, there are places where that won't do, and the description quickly becomes irrelevant.

But it seems that there are also more fundamental limitations involved, when trying to trace the path of a chaotic system. Recent work suggests that however much computing power one had, the limitation of the Planck length would make it impossible to compute certain chaotic paths, such as in the three-body problem[1]. This uncomputability might look like a fundamental aspect of the universe, and it may be one. But it only makes the universe essentially unpredictable if one assumes that our mathematical system is the best there is. We can't say for sure that there isn't a mathematical system, somewhere in a galaxy far away, or somewhere in our own future, that gets around the problem. So this is still potentially related to the description.

The randomness in QM seems to run even deeper than this. Perhaps there, the universe is being unpredictable without any 'ifs' or 'ands' or 'buts', in an uncompromising way. So if the question is about that, QM looks like it has the casting vote. Is it the thing, or its description, that breaks down? It seems that it's often the description, but is it ever the thing? To shed some light on that, I need to try to shed some light on QM.

2. Missing pieces of the puzzle

Three aspects of quantum mechanics suggest we don't have all the pieces of the puzzle in front of us. The basic unpredictability, non-locality, and no consensus on interpreting the theory: all suggest missing conceptual pieces. In physics we're sometimes held back by the hidden assumption that we have all the pieces of the jigsaw in front of us. It can seem that it's just a matter of arranging them correctly. (Recently people have been 'shuffling the principles' - making one thing emergent, such as causality, another thing fundamental, to see if a better picture appears.) But in QM, the lack of consensus looks exactly like a case of missing concepts. So does the physics.

But if this is so, however we arrange or rearrange our concepts, the present systems we have won't be able to encompass the theory to interpret it. For instance, in our present system, unpredictability tends to arise where there's an element of approximation. But to explain the randomness in QM - which looks like a different kind - and the apparent non-locality, we need more concepts. The view here is that the necessary concepts are mainly ones we knew about in another area, which have not been applied to QM.

3. Leaving room for unknowns

During the 20th century, the assumption of 'all the pieces in front of us' started to affect things. It had affected things in the 19th century as well, when some thought physics was more or less done and dusted. But by the 20th century, new decisions had to be made.

For instance, in our standard interpretation of special relativity (SR), *c* is seen as a speed limit for *everything*. Only light and matter have been shown to go by this universal limit, but particularly at the time of SR, light and matter were thought to be more or less all there is anyway.

Now if *c* had been simply called a speed limit for light and matter, that would have been in keeping with the scientific method. The scientific method is about testability. Instead, calling it a speed limit for everything, we added an untestable assumption into SR. We assumed that anything and everything we don't yet know about, which might perhaps be discovered in the next 10,000 years, will go by this speed limit. How do you test that? It can only be tested by falsifying it. It's arguable that we're not in a position to make an assumption of that kind.

And now, within just 100 years, we're already starting to falsify it. Strong experimental evidence has arrived that something exists that doesn't go by this 'universal' speed limit. The data can be interpreted in a number of ways, but the fact is, in 2015 loophole-free entanglement experiments were done by three separate teams[2],[3],[4]. And for many, the long awaited loophole-free tests effectively showed non-local connections at work, with experiment confirming theory.

So we need to leave room for unknowns, and for pieces of the puzzle we haven't found yet. To me, it has always seemed likely that we'll understand QM one day, but that for now there are missing concepts. We might need to brush up on the conceptual side of our thinking to find them, because the mathematics won't necessarily tell us what it's describing. Physics is full of equivalence: similar mathematics often describes a number of different conceptual pictures. So the picture underneath QM, if there is one, probably won't be reachable from the mathematics, and the conceptual foundations of QM may be the right place to look.

And this kind of approach is more of a starting point than it might seem. If one believes there are missing concepts, one can try to narrow things down. First, it would mean we need an analogy. Physics thrives on analogies - so does mathematics - and the universe is full of them. All this means is that a lot of things in the universe are like other things. But if one is looking for an analogy, then being an analogy, it would have to involve something we know about already. So it's possible to try searching with that in mind. I've talked about the conceptual side of physics[5], puzzle solving techniques and lateral thinking elsewhere, so I won't go further into these things here. Instead I'll just show some results of using them, though the interpretation that follows was arrived at in a far, far more roundabout way than it sounds like if you say that.

In the past, good physicists like Einstein and Wheeler have said that the final resolution will include a conceptual one. That would probably mean the final goal of physics is both a mathematical and a conceptual description. And in the present situation, along with others who think the same (such as David Deutsch[6]) my view is that to make significant progress now, conceptual progress is what's needed.

4. Genuine randomness

It's very possible that to explain the fundamental randomness of QM, a different kind of *entity* is needed. All we get is a set of probabilities, and experiment shows us afterwards that the odds were correct. The concepts and entities that we have are not geared up to explain that, and one reason is that it goes outside cause and effect. How can a random event have a cause? It might have a general one, about the setup in which it happens. But when you get down to it, cause and effect have been left behind. And although we do sometimes experiment with causality nowadays, our science is very much based on cause and effect, in all areas where we have a full understanding.

So to deal with the randomness, we might have to assume the existence of some new kind of entity. Occam's razor has taught us to be wary of assumptions: it's only a guiding principle, but we know that when comparing two explanations for the same thing, the one with fewer assumptions is likely to be the better one. But that's about two *complete* explanations. If instead you only have a set of incomplete explanations, and they don't hang together too well (as may be the case with humans and the universe), then rather than too many assumptions, you might be using too few. And too few might be just as bad as too many. More might be needed, and on top of the immediate benefits, new assumptions might allow others to be dropped, somewhere further down the line.

But if we bring in a new entity, it should help to explain both the genuine randomness, and the non-locality that we seem to find. So although it might be costly in assumptions, it should do a lot for the price. John Bell used to talk about ideas as being 'cheap' or 'expensive' in assumptions. A concept that's already on the map somewhere, in another area, would be the cheapest way to do it. Bertrand Russell's version of Occam's razor included the advice that this helps: *"Whenever possible, substitute constructions out of* *known entities for inferences to unknown entities."* The interpretation here seems to do something of that kind.

5. Superposition

Superposition wasn't included on the list of things that suggest missing concepts, as its interpretation is not so cut and dried. Some think there's no physical superposition, but a set of possibilities about knowledge of the system being examined. So although to me there are really four things that suggest missing concepts, not three, it made good sense to leave superposition out at first.

But if I can show reason to think there's a physical superposition (location, location and location), that'll help. One argument against the view that the wave function is primarily epistemic, that is, involving knowledge or information, is that it seems to be both real and informational at the same time. But if it's *primarily informational*, what is this real part doing in there? The wave makes interference patterns, as real physical waves do.

Many see it as a mixture of the two. In the well-known poll on QM from 2011[7], 'real' got 24%, 'informational' got 27%, and a mixture of both got 33%. E T Jaynes also saw it as a mixture[8], and talked about the mathematics of quantum mechanics as: *"A peculiar mixture describing in part realities of Nature, in part incomplete human information about Nature - all scrambled up by Heisenberg and Bohr into an omelette that nobody has seen how to unscramble*".

But if it is a mixture, it's unlikely to be a 50-50 one. It will very probably have a primary nature, and a less important, side nature. And looking at that, 'primarily real' works far better than 'primarily informational'. If the wave is essentially real, there might also be some less important epistemic aspect. That looks possible, but the other way round, it's unconvincing. How can 'real' be a side aspect of something?

I say this in the hope that the idea of a real, physical superposition won't be dismissed. It seems that the interference patterns we find are created by a wave, and that the wave involves a physical superposition. So if one is looking for analogies to find some missing concepts, one can ask oneself what sounds like a stupid question: *"is there anything else we know of in nature that makes a physical superposition?"*

Before the 1980s, the correct answer might well have been "no". But with the advent of string theory, and other theories at the time, the axes of the dimensions started being taken far more literally than they had been before. And even though Kaluza-Klein theory goes back to the 1920s, many physicists before the '80s saw the dimensions as merely lines we drew in space to help with our mathematics, like a co-ordinate system. But if you take the axes of the dimensions literally, as they're widely taken now, they're in a physical superposition. That's because they're set at many different angles at once - to be more accurate, they're set at many different orientations in 3-space.

6. Dimensional quantum mechanics

Dimensional quantum mechanics (DQM)[9] is a spinoff from a wider background theory, which starts from a new description of the structure of space. The background theory has the mathematics, and predictions for experimental results, but it also led to a new interpretation for QM. To tackle the unpredictability within QM, there may be a need to tackle QM generally, so in the hope of shedding some light on either, a brief overview follows.

In DQM, if no positions for the axes have been specified, they're in all positions at once. Or alternatively, they have no positions. Either way, there's a set of possibilities about the situation, for what their orientation in space might be. So far, this is exactly as in the standard view of the dimensions. But in DQM their positions are important for matter, because matter arises as places where the dimensions are vibrating. So matter has to go where the dimensions go - but it's not always clear where they go.

The background arena of DQM looks superficially like a general picture from some string theories. There are three flat space dimensions, and a number of circular ones at the Planck scale. Space at a small scale looks like a fabric of parallel cylinders, which all point in the same direction, but that direction is often undecided. Light consists of waves that travel in a direction along the length (strictly the height) of the cylinders, while matter is waves that travel around their circumference. Both consist of waves in the fabric of the structure of the dimensions, which is ultimately a single structure.

This basic setup allows a new interpretation for QM. An electron near the nucleus of an atom, until a measurement is made, does not have any location in space. Instead, it has a set of possible locations. In DQM this set of possible locations corresponds to a set of possible positionings for the dimensional axis on which the electron lives. These can be taken to radiate outwards from any point in space, but in this instance it is relevant to take them to radiate outwards from the centre of the nucleus.

When a measurement is made, the interaction necessary for the measurement allows the electron to connect with an already existing network of entanglements that is in the laboratory, at a larger scale. (Decoherence has shown, via both theory and experiment, that something like this can happen, because interactions create entanglements.) The interaction allows the electron to relate itself to the lab frame, and 'get its bearings'. It reveals the relative orientation between the electron and a local, emergent positioning for the dimensions (as in Section 8). So the dimensional axis on which the electron lives is now allocated a radial orientation - in relation to the nucleus of the atom - and that corresponds to a specific location for the electron.

A quantum wave can be interpreted as follows: when light and matter move in 3-space, both travel along the length of the cylinders. The cylinders are aligned with the direction of motion. But if no positioning for the dimensions has been established locally, there are many possible orientations for the axes, so light or matter will travel along many paths at once, set at many different orientations. And that's what creates the wave. An emitted photon spreads out into a wave because it takes all these possible paths.

This leads to an explanation for the most basic form of quantisation (the energy levels within an atom are explained in a separate way). A quantum wave is made up of many versions of the same particle, each travelling along a path at a different orientation. It's known that the energy in a quantum wave can only be divided into fixed, equal units. In a given wave, they can go no smaller than a certain quantity. But smaller units of energy can still be found, if one looks in a different wave. So there's no universal quantum of energy - instead its value is related to other aspects of the wave.

DQM explains this via the idea that each wave is based on a specific particle, seen many times. But they're not multiple images, they're 'multiple versions' of it. So a given wave may have a different quantum of energy from another wave, because the particle on which it is based has a different energy. So the fact that the energy in a quantum wave can only be divided up into fixed, equal units, is a result of the wave consisting of many different versions of the same particle.

To explain the wave-particle duality, there's a general need to show why it affects both light and matter. Light and matter have major differences, so whatever the cause of the dual nature they both have, it should be explained as arising at some deeper lever than the level at which these differences between them appear.

In DQM, the structure of the dimensions is the bedrock from which everything arises, as everything consists of vibrations in its fabric. The ether that was falsified by experiment 130 years ago was seen as a different kind of medium, behaving like matter. The fabirc of the dimensions provides a very different transmitting medium, and one that we don't have to invent 'out of thin air' - it's thought to exist anyway, for separate reasons.

And if the dimensions themselves have a dual nature, it arises at a level deep enough to affect both light and matter, so it can provide a viable explanation for the wave-particle duality. According to DQM, the structure of the dimensions has a dual nature, involving two states: without defined positions, which leads to the wave state; and with defined positions, which leads to the particle state.

7. Some background to DQM

Before going any further, I need to fill in some background. In the 1990s, mainly because of decoherence, a new idea appeared. It was that the cause of state reduction, rather than being measurements, is interactions. To make a measurement, you have to cause a collision between matter and matter, or light and matter. And decoherence had already shown that the so-called collapse of the wave function takes a finite, derivable period of time. And we had found out that in that short period of time, there's a rapid series of interactions between the matter and its environment, creating entanglements. So when matter interacts with other surrounding matter, the superposition is reduced. The new clue, and arguably one of the best clues we've ever found, was: when matter becomes entangled with its environment, it becomes more clearly defined.

Interactions had been found to cause sudden changes, and they make state reduction happen with or without a measurement. But when we make a measurement, we have to create an interaction, so it starts to look like the interaction, not the measurement, is what's doing it. (The idea of 'interaction-free measurement' seems an interpretation-dependent idea, and R M Angelo has strongly argued the same point[10].)

This new approach could completely remove some of the harder to pin down aspects of quantum mechanics - mind, consciousness, the observer. But it was not discussed much outside decoherence, because no-one could say why interactions should do that. Still, some interpretations for QM since the 1990s, without giving much of a cause, have had interactions setting off state reduction, sometimes indirectly. One of these is relational quantum mechanics (RQM)[11]. In a relational theory, things look essentially different from different viewpoints, or reference frames. In some ways DQM is closely related to RQM, and adds an extra layer of interpretation underneath it.

I won't go into the questions involved, but both RQM and DQM looked more viable after the Frauchiger-Renner paper of 2018[12], which, loosely speaking, showed that different things are seen from different viewpoints. Experimental confirmation of a similar setup was published in 2019[13], which supported all relational interpretations generally. The experimenters said in their abstract: "*This result lends considerable strength to interpretations of quantum theory already set in an observer-dependent framework and demands for revision of those which are not.*"

A 2019 documentary[14] included discussion about 'interactions not measurements' as a general approach, and a conversation with Carlo Rovelli about DQM. Some years earlier, Rovelli had written that he thought when two particles interact, there is an 'exchange of relational information'. Reading this in 2014 led to some of the conceptual picture of DQM, which was very much unfinished at the time. According to DQM, this 'exchange of relational information' means an exchange of orientation information.

According to RQM, matter's observed properties vary with the viewpoint, or frame. In DQM, matter's small-scale orientation, relative to the system from which it is observed, can affect a range of things about it, including its observed properties. So the viewpoint differences in RQM are related to the relative orientation between two systems.

8. How the dimensions get defined positions

Returning to the dual nature of the dimensions, I've said that the wave state arises from the dimensions having no fixed positions, while the particle state arises when they have fixed positions locally. This is related to the scale question in QM, of why the large-scale world behaves differently from the small-scale world. In the earlier 20th century, it was thought that there are two sets of rules for two different scales. More recently, people tend to think that the world is quantum at all scales. To me it seemed likely, to allow this to be true, that something emergent must be going on at a larger scale.

In DQM the laboratory at a large scale has a pre-existing network of entanglements. This arises because the matter in the laboratory has interacted with other matter there. A framework builds up, and it includes an implied positioning for the dimensions. In DQM, this is loosely called a 'local framework', because its range is often local only. But being constructed out of entanglements, it can cover any distance. This framework arises from a set of spatial relationships between bits of matter, and is emergent.

So the matter in the lab has already 'latched onto' a local positioning for the dimensions. But at the quantum scale, there can be bits of matter floating around that have not yet connected with this framework. So as a result they're disorientated, and certain things about them exist as a set of possibilities. When a measurement is made, the interaction necessary for the measurement connects the matter to this framework, it then 'gets its bearings' in relation to the lab, and finds out its relative orientation to the lab. It then becomes more clearly defined, taking on definite properties, as a particular version of it has been picked out.

It's worth mentioning that we know of two ways that entanglements get started, and they have something in common. Both involve physical contact between particles. Two particles that started out together can be entangled. And in decoherence, interactions create entanglements. So particles that have touched retain a lasting relationship. This supports DQM, and also the general interactions approach.

9. Bohm's variant on EPR

DQM in its present form doesn't state any classification for the interpretation. But it has some aspects of a non-local hidden variables theory (very different from the pilot wave interpretation), although it lacks key defining features that hidden variables theories are expected to have. It is in some ways nearer to objective collapse theories, but again the similarities are limited. The phrase 'quantum realism' has more than one meaning[5], and although DQM does not have local realism, looking at the question of whether DQM has any kind of realism, only some of these apply. The problem is shown in a recent study on the word 'realism', which concluded that it should be banned[15].

There's a point that can be made about a middle step that was taken, between EPR and Bell's theorem. David Bohm's variant[16] on EPR came around halfway between them in time as well, in 1951. I won't go far into the details, but some still see it as presenting a particular problem. It can be set out as a task for Alice and Bob: each is sent one of a pair of entangled particles. If both make a measurement along the same axis, there is a

100% likelihood that they will find a correlation. But if Alice chooses to measure along a different axis, what Bob can measure will be different, and there are questions about if and how the spin orientation Bob can measure becomes an 'element of reality'.

DQM potentially throws a unique factor into the mix of this question. In DQM, making a measurement on a particle along a particular axis establishes the orientation of one of the dimensional axes along that axis. An entangled pair is a small local framework, and the two particles are on the same dimensional cylinder, whether the pair has related itself to any larger framework, such as a laboratory. The two frameworks are like two islands - they start off unconnected. A measurement sets an orientation for the cylinder, relative to the laboratory, so connecting them. The DQM picture fits the setup and the possible outcomes, and shows a new way to interpret the results.

Other properties of matter will also appear when the spatial orientation is decided via an interaction. But spin orientation is property that in the context of DQM, shows the picture at work in a very direct way. It is known that matter's orientation in space can appear 'as if out of nowhere' due to a measurement (or an interaction). This fact gives support to an absolutely central premiss of DQM: that what is really being decided at the point of a measurement is the spatial orientation.

10. Fundamental unpredictability?

I've tried to show that a lot of unpredictability or uncomputability is about limitations to our attempts to describe the universe. To me, it seems possible that it's all like that, and that in the case of quantum mechanics, DQM will eventually lead to a fuller non-local hidden variables theory, perhaps with very small-scale events affecting things.

But the randomness in QM looks like something else. It looks like a very fundamental unpredictability, made possible by an entirely new *entity*, the dimensions, entering into the conceptual picture. In Section 4, I argued that a new kind of entity was needed to explain some aspects of QM, which can't be explained using our standard vocabulary of concepts.

The dimensions provide a kind of 'buffer' between ourselves and matter, if matter arises as vibrations in their fabric. The weird behaviour of matter in QM can then be explained by the weird behaviour of the dimensions. And although that approach involves a very familiar concept, it's an entirely new entity in the context of QM.

It's possible that this is enough to explain the deep randomness. But so far, this principle has done better in another area. Adding in this 'new entity' explains non-locality well in DQM. The dimensions are already thought to have certain properties, in the way they're 'connected up', that could make non-local connections possible. But this only becomes relevant if matter is places where the dimensions are vibrating. And that concept is from DQM, so elsewhere, these properties of the dimensions might seem irrelevant.

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