A Dialogue Concerning Fundamentality in Quantum Mechanics

Valia Allori
Philosophy Department
Northern Illinois University
vallori@niu.edu

Abstract

There is an ongoing debate over the metaphysics of quantum mechanics, in particular about the nature of fundamental objects in a quantum world. Here is an imaginary dialogue between Wendy, who believes that the wave function is fundamental, Patty, who believes that it is not the case, and Lauren, a smart journalist who tries to take home something from this discussion.

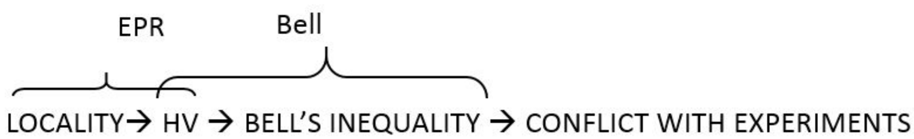
Lauren, Wendy and Patty meet at a party. Wendy and Patty do not know each other, but they both know Lauren: she is an old high-school friend of Wendy and she also met Patty in graduate school. Both Wendy and Patty work in the foundations of quantum mechanics, while Lauren is a journalist.

Lauren (to Wendy): Hello Wendy, my old mate! Long time, no see, eh? My cousin told me he read some article of yours on quantum mechanics and found it fascinating. **Wendy:** Hi! Yes, it has really been too much time. And I am glad your cousin liked my article!
L: Guess what? I need you to meet Patty: I met her in graduate school a couple of years ago and she's also working on quantum mechanics!
W: Oh, that would be nice!
(Lauren and Wendy move toward Patty)
L (to Patty): Hi Patty, nice to see you here!
Patty: Hi, Lauren! Nice to see a familiar face around here.
L: Yes, same here. Anyway, let me introduce you Wendy: we went to high school together and now she works on quantum mechanics. I thought it would be interesting for you guys to meet.
P (to L): Indeed! **(to W):** Hi, this is Patty. How do you do?
W (to P): Hello, I'm Wendy, how are you?
P (to W): I am great, thanks. Also, I'm glad I found someone with similar interests as me, or so I hope. Let's see… do you believe that quantum mechanics should be just a useful instrument to compute experiment results and advance our technology?
W: Absolutely not! I am a scientific realist: physical theories inform us about what is fundamental in the world, and quantum mechanics is no exception.
P: Oh, I am very glad to hear that! I am a scientific realist too. So, you agree that …
L: Wait a second, you are going too fast for me! Why would one think what you said, Patty?
P: Wendy can tell you as well: for a very long time, physicists were convinced that quantum mechanics forced us to instrumentalism.
L: But why is that?
W: It is a long and complicated story. In brief, quantum mechanics consists of an equation, the Schrödinger equation (named after one of the founding fathers) which governs the behavior of a mathematical object called the wave function. Nonetheless, a Schrödinger-evolving wave

function only tells us the *possible* results. To get actual ones the wave function needs to collapse, randomly, in one of the possible outcomes of the experiments. This is the so-called collapse postulate.
L: Are you saying that the theory has two temporal evolution, one that kicks in when someone makes an experiment?
W and P (together): Yes.
L: But aren't experiments physical interactions between objects?
W and P (together): Yes.
L: … and isn't there something missing that would determine when the second evolution would trump the other?
W: That's what many hoped, including Einstein. However, von Neumann, another influential figure of the time, *claimed* to have proved that quantum mechanics cannot be better than this.
P: If so, though, the situation is very grim, as Schrödinger's famous cat thought-experiment shows. It turns out in fact that: either the wave function provides the complete description, or it evolves according to the Schrödinger equations, or measurements have results. Imagine a cat in a box with a radioactive source connected to a vial of poison. If the atom decays, the vial releases the poison and the cat dies. The atom may or may not decay at a given moment and it is possible for the atom's state to be described by a sum of a wave function describing these two situations. The decayed wave function leads to a dead cat, the un-decayed one to an alive cat, and the sum leads to a state of superposition of a dead and an alive cat. However, since the cat is either dead or alive, the wave function has to collapse in one of the two states. These unacceptable superposition of states (corresponding to an absence of measurement results) is a consequence of assuming that the wave function is complete, and that it evolves according to the Schrödinger equation, which both seem undeniable. So, people concluded that quantum mechanics and scientific realism are incompatible.
W: However, in the 1950s the situation changed. People started questioning each premise: Bohm's theory denies that the wave function provides the complete description of the system, …
P:… the GRW theory denies that the wave function evolves according to Schrödinger's equation, and Everett's theory denies that measurements have unique outcomes.
L: Wow, you are completing each-other sentences! However, I have hardly understood a thing. What are these new theories?
P: All right, sorry. We got excited about our work. Anyway in Bohm's theory, proposed by David Bohm, the wave function does not provide the complete description of a system. So, even if the cat's wave function is in a living-dead superposition, the particles of the cat are either in the 'dead' or in the 'living' part of the wave function. No more mysteries.
L: So, let me see whether I understand: according to this theory, particles *and* waves are fundamental?
W: Well, one could say that…
P: No, *I would not* say that!
L: Here we go: we thought we had agreement, eh? Before entering into this, please explain me the other theories you mentioned.
W: We have the so-called GRW theory, from Ghirardi, Rimini and Weber who first proposed this theory. The idea is that the wave function does not evolve according to the Schrödinger evolution at all times. The wave function collapses into random places, with a very high frequency for macroscopic objects. In this way, while at the microscopic level atoms can be in superposition, this is not the case for macroscopic objects like cats.

L: OK, I have so many questions, but I am more interested in hearing more about the third alternative.
P: The third alternative was developed by Hugh Everett. The idea is that superpositions are real: all possible measurements results are realized, 'somewhere'. This is why this view is called the many-worlds theory: the cat is dead in the world we experience, say, and she is alive in another world, which our counterpart experience.
L: Wow, it looks like a science fiction story.
W: Yes, the world is not one, but a collection of infinitely many words identical to one another except that for one term of the superposition of the wave function.
P: I hardly agree with that! The mystery of quantum mechanics is nonlocality, certainly not the existence of many worlds!
L: OK, let's get some fight going! What are you talking about, Patty?
P: Quantum theory is nonlocal: that is, what happens here can affect instantly what happens in an arbitrarily distant region of space. How that can happen, is mysterious, since it seems to be incompatible with the theory of relativity, according to which signals can travel at a finite velocity, and thus influences should take time to travel to any places.
W: I would be less dramatic. After all, while Bohm's theory is nonlocal, it is unclear whether the other interpretations are as well.
P: No, no! They are all nonlocal! This is, unquestioningly, what John Bell has proven!
W: Well, Patty, you are being a little dogmatic here, don't you think? People have argued …
L: Ehm, guys, do you mind filling me in?
P: Oh, I am so sorry, again! Everything stared with a paper by Einstein, Podolsky and Rosen known as EPR [8]. Einstein and two other colleagues developed an argument to show that quantum mechanics is incomplete. Imagine two particles in a singlet state….
L: A *singlet* states?! As opposed to what, an *engaget* states? **(L starts giggling)**
W: You do have a point here my friend! **(Laughing)**
P: Roughly, this is a state that describes two particles as having opposite spin (which is sort of a quantum property), and it is the opposite of a 'single' state: it is a 'together-for-life' state, and entangled state. If these particles travel in opposite directions, and their spins are detected, the results show perfect correlations: when one measure the first spin being one way, the other is found to have opposite spin. What is the origin of these correlations? If quantum mechanics is correct, there is no fact of the matter about which spin each particle possess since they are described by an entangled wave function. So, the correlations could only be explained by a non-local interaction: one particle, once measured, communicates the result to its 'twin' particle, which thus fulfils the correlation. Einstein thought this was absurd, and concluded that the spin values after the measurement are the discovery of the values of the spin the particles had all along. Therefore, since quantum mechanics does not specify what these values are, quantum mechanics is incomplete: these 'hidden variables' need to be added to the wave function.
L: But haven't you guys said that German guy proved this is impossible?
P: von Neumann? He's Hungarian and Wendy said he *claimed* he proved it, and it's right. Some promptly pointed out the poof was mistaken [9], but people did not pay attention.
W: Yes, let me continue: Bell, one of the people that discovered the mistake, wanted to see the consequences of a completion of quantum mechanics as suggested by EPR [5]. He found that, assuming such completion, one should find certain measurable correlations among given experimental results. This mathematically translates into an inequality, dubbed Bell's inequality, which can be checked experimentally. The bizarre thing is that when these experiments were

performed the results turned out to be incompatible with what Bell found [4] **(both P and W nod in agreement)**.
L: So, let me get this straight: he proved that hidden variables are experimentally impossible?
W: Yes! **P (at the same time):** No!
L starts laughing loudly, and after a second W and P start laughing too.
W: OK, let be more precise: he proved that local hidden variable theories are impossible. Indeed, Bohm's theory, in which the hidden variables are the particle positions, is nonlocal.
P: OK, at least you are not saying that Bell proved hidden variables are impossible and thus Bohm's theory has to have something wrong in it. However, I think what you said is very misleading, since it suggests that there are two options: either quantum theory is local and there are no hidden variables, or quantum mechanics is nonlocal and there are hidden variables. If this were the case, everyone would go with the first option and ditch hidden variables, including Bohm's theory. However, one cannot uphold to locality, *ever*. People think they can avoid nonlocality because they forget that Bell starts from the EPR argument as a premise. EPR assume locality and derive hidden variables to explain the perfect correlations. As I have just told you, Bell starts from this and proves this leads to a conflict with experiments. Notice that 'this' in the previous sentence is actually the assumption of locality, not of hidden variables: hidden variables are derived from locality. One therefore has not the option of keeping locality and thrashing hidden variables, because locality *implies* hidden variables in the EPR argument. What Bell has shown (even according to him!) is that quantum theory is nonlocal, rather than having put an end to the hidden variable program. Here's a way to summarize the situation (**P grabs a paper towel and start scribbling**):



So, you see: the only assumption to be rejected here is the first: locality [18].
W: You are making thing way too simple: you are forgetting that one has to assume that, after the measurement is performed, there is something like a measurement outcome. However, this is not true for the many-worlds view, by definition. So, there is a sense in which the many-worlds theory may be able to avoid nonlocality.
P: Yes, maybe. However, it is not clear how to do that, given that the wave function is a nonlocal object…
L: Please, my head is going to explode! Will you please slow down? I am not sure I follow: you, Patty, say that Bell showed that there are spooky actions at a distance, and you, Wendy, say that this is true for hidden variable theories, while in the many-worlds interpretation this may not be the only conclusion. Is that right?
W: Yes, it is roughly like that. But let me add something more interesting. In our discussion we kept talking about quantum mechanics but we never discussed how this theory is supposed to represent reality. We both started out claiming to be scientific realists, but scientific realists *about what*? I think that for a scientific realist the best way of thinking about quantum mechanics is thinking that tables and chairs are made of wave functions [1]: after all, the fundamental equation of the theory is Schrödinger's equation, which is an equation for the wave function. What else would one want the wave function to do, if not represent material things? In classical mechanics the fundamental equation is Newton's equation, and this is an equation for point-like entities. Don't we conclude from this that matter is made of particles? So, we do the same here.

P: Well, well, here's where we disagree: I see!
W: Yes? Great! And here's another reason to think of the wave function in this way: the theory is still local, despite of what Bell proved.
L (intrigued): OK, that's interesting. Patty, before jumping in the discussion to say that Wendy's mistaken, please let me ask Wendy why she thinks this theory is local.
W: The basic idea is this. According to some, including me, the best way of thinking of the wave function is as a field. There are other fields in physics, like the electric and magnetic fields: they assign to every point in space a value that indicates the strength of the field. However, in this case the field strength is assigned to every point in *configuration space*. Since configuration space is the space of the positions of all particles in the universe, this is a major difference. In fact, configuration space has many more dimensions that the regular three we experience. Indeed, since one can estimate there are 10^{80} particles in the universe and each of them has three spatial coordinates, the dimension of configuration space is roughly $3 \cdot 10^{80}$**.** You, Patty, will presumably think that this is already too much to accept, but let me finish: if we assume that material things are not in three-dimensional space but in configuration space, then the Schrödinger equation in this space *is* local. Think about it: nonlocality is the existence of instantaneous interactions between objects in three-dimensional space. If instead you go to configuration space, these are merely local interactions: the wave function, as a function of a configuration space point, will not be instantaneously influenced by other configuration space points [16]. So, no nonlocality!
L: Wow, that is so much to take on! Let me see if I get at least some of it: the idea is that we do not live in a three-dimensional world, right? And while one might think it is crazy, the advantage is that nonlocal interactions do not exist anymore, isn't it?
W: Yes, that's right.
P: Now, let me respond to that. I could point out that this view is crazy [12], but you already did it for me, suggesting that it is the price to pay to preserve locality. However, remember what the reason is to keep locality: to make quantum mechanics and relativity compatible. Now look at what you got: locality in *configuration* space, not in three-dimensional space. Does this make the theory compatible with relativity? No! In fact there is a sense in which the wave function is explicitly in conflict with relativity: to specify the configuration is to specify the positions of particles at the same time. This implies that there is an absolute sense of simultaneity, which is denied by relativity [20] **L:** Wait, what? Why is that?
P: Because it is one of the consequence of the postulates of the theory, namely that all physical laws are of the same form in all inertial frames and that the speed of light is constant, that there is no unique sense of simultaneity of two events. Therefore, if a theory talks about absolute simultaneity then the theory is in conflict with relativity.
W: You are not being fair, Patty. In fact, in my view there are no particles on the fundamental level, only the wave function. Thus, assigning a configuration at one time does not amount of assigning the position of all particles at that time: instead it means assigning a point in our newly discovered physical space, namely configuration space. So, I do not see an explicit conflict with relativity here.
P: Fair enough, that may be so. Be that as it may, this model is too simplistic: why think of the wave function in the position representation? After all, as far as the results are concerned, it would be also OK to use the wave function in the momentum representation [21].
L: OK, here we are again: what are you talking about?

W: She is referring to the fact that there are two equivalent ways of deriving the predictions of quantum theory, one with the wave function written as a function of position and the other in terms of momentum, which is proportional to velocity. So she is saying that I'm not justified in picking the position over the momentum representation. However, I think I am for the simple reason that momentum is not as fundamental as position: momentum is defined in terms of velocity which in turn is defined as the rate of change of position.
P: Yes, but then it's you who forgets that there are no particles in your theory, and therefore no positions, at the fundamental level. Anyway, your approach does not work if you go to quantum field theories, since there are creations and destructions of particles. How can that make sense for you, given that it would imply that the fundamental space we live in changes dimension all the time [21]?
W: You are assuming that I have to stick with configuration space in this new framework, but why should I? Here we have a different theory, and since my motivation is to keep locality, then I will look for an ontology of quantum field theory which preserves that.
P: Whatever. What about this: in quantum field theories the wave function is constructed from field operators in space-time, and …
L (appalled): …field operators? As in power plant workers? What are you talking about?! **(W and P start laughing)**
P: Ah, I never thought of that! No, this is just some mathematical jumbo-jumbo to describe the formalism of the theory. What matters in what I said is that they are constructed, not fundamental, and that the entities they are built upon are in space-time, rather than configuration space [13].
W: Fine, now it's my time to say: 'whatever'. Who cares about how wave function *can* be constructed? One could think of a way of building them from marshmallows, for what I care. Even classical physics can be constructed in all a variety of ways, each of which implies different things about the nature of the fundamental entities. Think about Hamiltonian mechanics: it is equivalent to the Newtonian formulation, but we do not use to infer what's fundamental...
L (frustrated): I will not even try to ask what Hamiltonian mechanics is…
W: It does not matter: the point is that there are always different ways of re-constructing a theory, and one will use criteria to pick which of them provides the guide to the nature of things. In this case, one can reconstruct wave functions in ways other than from space-time entities, and there is no a priori reason to think that the later derivation is the 'right' one [17].
P: So, how do you pick the preferred picture?
W: I pick the one that allows for locality. Then, I see what the consequences of this choice are.
L: OK, now stop. It's my turn. Please let me ask you, Wendy, why you insist so much on locality. I myself would say that's because it is intuitive to think that there is no instantaneous action at a distance. However, why should we care about intuitions at all? Intuitions are guide as long as they do not fall short, and in the past they fell short many times. Moreover, it seems to me, trying to keep locality leads us to abandon other intuitions, like that the world is three-dimensional, which is perhaps more basic. See, suppose I ask my grandmother which, among space being three-dimensional and there being no action at a distance, she takes to be most indubitable intuition: I bet she would go for the former. So, I am not happy with the result we got. However, I have no idea of whether there is an alternative here…
P: Let me help you with that: there is one alternative, and in fact this is the view I like the most. Remember classical mechanics? The fundamental things there were particles, in a three-

dimensional world. Then quantum theory arrived, and all hell broke loose. However, I think there is in principle no reason to abandon the idea that the world is three-dimensional and matter lives in it. Indeed, this is what happens in Bohm's theory, if we think of it as describing particles moving around governed by the so-called guidance equation, defined by the wave function. This is why I said at one point that I would not think of it as a theory in which there are particles and waves. In this reading, the wave function is not describing material entities. This is not the right kind of entity to do so since, as Wendy has pointed out, it is in configuration space. I do not what to enter in the debate on what the wave function is: one can have different views on that. What matters to me now is to emphasize that it is not a material thing. If you accept that, you have a theory that preserves your least-dubitable intuition, namely that the world is three-dimensional [3].

L: Ah, that's interesting! Let me think about this. If I understand, though, this theory will be nonlocal.

P and W (at the same time): Yes.

L: Therefore, it will have a problem with relativity.

W: Yes! **P (at the same time):** No!

L: Please, Patty, tell me why not.

P: Because one can construct relativistic models that work!

W: Well, my friend, you are forgetting to mention that you need a preferred foliation [6]. That is, a preferred reference system with respect to which one can define absolute simultaneity. And this hardly qualifies as a relativistic theory.

P: You are referring to some earlier work. However, people have been able to show that such a foliation is determined by the wave function. In this way, it is not arbitrary, but follows naturally from the theory [7].

L: OK, I understand better. However, by maintain the three-dimensional intuition we complicate things in other ways. In fact, we have the equation for particles, in addition to the Schrödinger equation. Also, there is an important sense in which the wave function *is* fundamental, given it is in the theory. Since it is in the theory, does not that mean that it is also in the world?

W: Yes, I agree with that. Let me also add this…

P: No please, wait: one at the time. Right, one need to add an equation. But be careful: add to what? To the Schrödinger equation. But so does Wendy: if she believes that the world is made of wave functions, then she needs to explain why we think we live in a three-dimensional world. She needs to specify some rule to make the connection between stuff in configuration space and stuff in 'regular' space. It is important to realize that she needs to add not one rule, but an infinite amount: one for space, and so many others for every object and every property we seem to observe. For instance, one rule will be one that allows us to say that space is three-dimensional, then another to say that here there is a table, another that this table is white, another that over there one finds a cat, another one that the cat is black, and so on [2]. This is not much of a simplification, isn't it?

W: That's not necessarily the case! One could start with a rule about the particle three-dimensional locations in terms of the wave function's distribution in configuration space and then be reductionist about the macroscopic objects and their properties.

P: As I suspect you already know, this is not sufficient: there is nothing that suggests the configuration space coordinates are grouped into triplets. Because of this, points in configurations space may correspond to particle positions in dimensions other than three. In other words, one would have to recover three-space first [12].

W: Yes, but one can do this: while there is nothing in the wave function at one time, if one looks at its temporal evolution one can explain why the world looks to us as three-dimensional. It is because the way we write the temporal evolution, namely the dynamics, that the world seems three-dimensional [1].
P: I do not find this convincing at all: does the world appear three-dimensional because of how we write the equation, or do we write the equation as we do because the world is three-dimensional?
W: Fine, but one could find other ways to recover the apparent three-dimensionality. For instance, one can use symmetries: there are certain invariances of the wave function that can be explained only assuming that the world appears three-dimensional. Having a given symmetry amounts to say that there is no difference in the behavior we observe in the original system and in the system transformed according to the symmetry. For instance, this glass of wine can be translated over here and it will not change the fact that it is empty. In quantum mechanics, one symmetry is permutation symmetry: it makes no difference for our observations if we consider one electron on the left and another electron on the right, or the other way round. In looking at a three-dimensional reading of configuration space, one explicitly sees that the original and the swapped wave functions are the same. Instead, this is not the case in the two-dimensional picture, in which the original and swapped wave functions are not symmetric [15].
P: Nice try. However, I still have problems with it. Do the two wave functions being indistinguishable explain that the world appears three-dimensional? Or does the three-dimensionality of the world explain the symmetries of the wave function? Be that as it may, here's another issue: where is your *evidence* to believe in your theory? We receive confirmation that a theory is correct in terms of three-dimensional locations of pointers and the like. However, if your theory is correct, no such locations exist! So, how can you count this as evidence [11]?
W: It is evidence because I am not denying that three-dimensional objects are real, I am just denying that they are *fundamental*. Rather, they are derivative: as one can recover three-dimensional space, one can also recover three-dimensional things and their properties from the wave function [14]. But let's get back to your account: if you can explain all experimental results without the particles, what is the point of adding them [10]?
P: Well, my point is that you cannot, can you? At least, no such story has been told so far. Moreover, even if we had such a story, why would I go for it?
L: Because it's simpler?
P: But is it? It may be more parsimonious because you have one object and one equation, but to go from this to our experience you need a lot of work, as we just saw, because of the radical departure of the image science gives us of reality and the image of our everyday life. In my approach instead the discrepancy is minimal: stuff moves around in three-dimensional space, both according to science and according to my grandma! It's because of this that the explanation is simpler, not because how many things you have in your ontology [3].
W: But your approach is nonlocal!
L: Here we go again… let me get another drink for everyone…

But as Lauren turns around she notices that they are the only ones left in the room and that the bar has closed. The bartender looks at them for a while with half a smile, and finally addresses them.

Bartender: Hi! I planned to let you know we were going to close soon, but you were so into your discussion that I did not want to disturb you.
(All three apologize at the same time) L: Oh my! **W:** I am so sorry! **P:** We did not realize…
B: No worries. I actually did not mind: I like when someone is passionate about their ideas.
L: and they certainly are! Anyway, before we all go help closing the bar, can we at least agree on something?
W and P (together): What?
L: … that in order to discover what's fundamental you need to look at fundamental physics?
W and P (together): We can certainly agree on that!

They all take their empty glasses and, together with the bartender, start cleaning up the mess the others have made behind their back.

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