If quantum mechanics requires that there is always an observer, who observes the universe?

Valia Allori

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More and more often we see headlines in popular articles declaring that quantum mechanics has proven that objective reality does not exist, and that instead it is the observers who create what they observe. So the Moon is not there if no one looks at it and trees falling in the forest make no noise. Certainly fascinating. But is it true?

In response, let me start with a long preamble on physics, philosophy, and quantum mechanics up to astrophysics and relativity.

When I took my high school graduation exam, around the time of the dinosaurs, as a final question I was asked what I wanted to do once I finished high school. Enthusiastically, I answered, "I still don't know whether to do physics or philosophy," certain that there was no need to provide further explanation to the committee. Instead, to my surprise, mixed with disappointment and perhaps even a little anger, my response elicited almost general hilarity. "You're a bit confused, I see!" said a member on the examination committee. In responding, I must have completely ignored my dear Italian and Latin teacher's warning ("Watch out, your opinions are all over your face!") because even before I opened my mouth, the smile had already frozen in everyone's face. In any case, I said, "Of course not, physics and philosophy are the same thing!" I will not recount here how my exam ended (not in a brawl, despite the premise). I will only say that no one convinced me otherwise, and so a few months later I enrolled in the Physics undergraduate program on the grounds that: "both philosophy and physics ask questions about the nature of the world, but only physics can give the answers" (I am quoting directly from one of the pages of my journal at the time).

In time I realized that the perplexity expressed (badly) by my examination committee about the relationship between physics and philosophy is widespread, and I understood that it depends largely on how these disciplines are taught, at least in Italy: philosophy is understood as the history of philosophical thought, while physics is too often seen either as abstract engineering or as applied mathematics. I cannot explain here why this is the situation, partly because the reasons are complex and I do not think I know and understand them all well. In any case, I have always remained convinced of what I thought as a high school student: physics is the philosophy of nature. Philosophy asks questions about the nature of things, but it is physics that gives us the information we need to answer them properly. How else can we find out what the world looks like except through scientific investigation? What alternatives are there? I could see none: surely, lying in the armchair scanning the ceiling and losing myself in my thoughts would not bring me great success, at least not in finding answers to a certain kind of question. Be that as it may, this is what I had convinced myself of at the end of high school, and what I am still convinced of now, probably because of my philosophy teacher and a certain chapter in my textbook, the "Abbagnano Fornero," in which the philosophy of the 1900s and quantum mechanics were discussed. And if I understood it, it was a given for me that the members of the committee understood it too. Anyway, here is an imaginary (but not so much) dialogue that exemplifies how physics answers philosophical questions. "What are the things around us made of?" Physics says that everything is made of matter, and in its history it has made several propositions about what, essentially, matter is. For example, according to Newton's classical mechanics, matter is made up of point particles, while we often hear that for quantum mechanics the situation is far more mysterious and inscrutable. "But where are things, where is matter?" They are in space, and again, different physical theories give different answers as to what space is. For example, according to Newton, space is an infinitely large box of three dimensions, while according to Einstein's general relativity, space is one with time and has a very counterintuitive structure. "Speaking of time: what is it?" And so on. It is physics that gives the answers, and so there were few alternatives: I had to enroll in the physics undergraduate program.

Well, everything went smoothly until my third year when I encountered, like everyone else, the course on Institutions of Theoretical Physics, in which the unsuspecting student (i.e., me) encounters the toughest obstacle to her career (after Calculus 1, of course, but for other reasons). It is the first course in which quantum mechanics is discussed, and it is unlike any other. The most shocking thing (to me) was that the professor was saying that quantum mechanics forced us to think that it was impossible to answer the questions I cared so much about. A chasm had just opened up under my feet: the most advanced physical theory we have proves that we cannot find an answer to questions about the world? But how was that possible? For a while I surrendered to the word of authority: if everyone thinks this, after so many years of study, and teaches it, it must be true. And so, since by that time physics had ceased to have any value other than to provide useful technologies, I changed my major from theoretical to nuclear medical physics. Later, however, within a few months of defending the dissertation, for various reasons I found myself rethinking these things and, in no hurry to have to prepare for the exam, I found alternative proposals to what I (we) had been fed and what we might call the "dogma of the impossibility of understanding." This led me to my doctorate in foundations of physics, to changing my research orientation more explicitly to philosophy, and ultimately to this article.

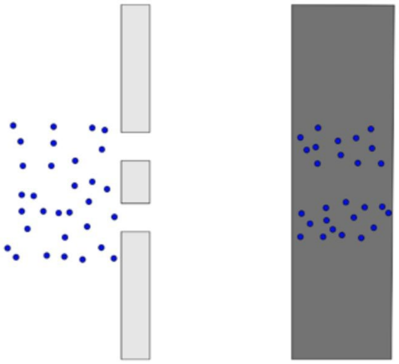

Figure1: the two-slit experiment for particles.

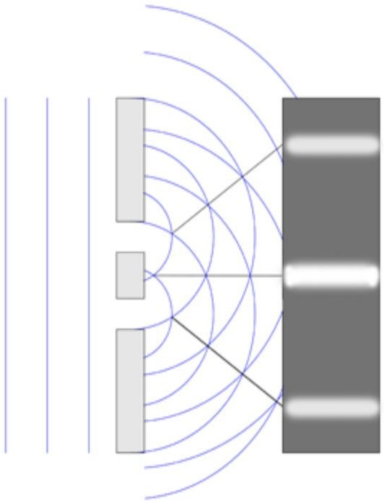

Figure 2: the two-slit experiment for waves.

The reason it is taught that quantum mechanics cannot help in understanding the world is that there seem to be experiments in which, the moment we try to describe what happens in them from the microscopic point of view, we find ourselves in contradiction. The most famous example of all is probably the two-slit experiment. Let us imagine a source that generates electrons. That is, some sort of electron cannon or gun that shoots, one at a time, these electrons toward a panel on which there are two slits (figures 1 and 2). If the electron ends up on the panel it is absorbed, while if it passes through one of the slits it is detected by a screen not far away, which, for example shows a blue dot. What should we expect if the electron gun fires, again one at a time, many electrons? What does the image made by the combination of the blue dots, corresponding to the electrons arrived on the screen, look like? Since electrons are thought to be particles, we should see on the screen an image with a high density of dots at the two slits: the electron passes either at one or the other slit, otherwise it is blocked by the panel, and then the blue dots will cluster at where the electrons passed through. Instead what is observed is an interference figure, made up of alternating high and low density areas of blue dots, and with the higher density area corresponding to the portion of the screen in between the two slits. Such a figure is typically generated by waves: the incident wave is "split" by the slits, which then generate two secondary waves that then interact, interfering with each other. How then to explain the interference figure, if you have particles? Have we make a mistake in considering electrons as particles? Are they waves instead? It is not so immediate to unravel the dilemma, because other experiments, such as those of the detectors used in modern accelerators, show that electrons leave continuous tracks, and therefore have trajectories, something that waves, being intrinsically delocalized, do not. So are electrons waves or particles? The answer you find in books is: they are both; sometimes they behave as waves, sometimes as particles. And if you try to find which way the electron went, for example by putting a detector on one of the two slits so that you can determine whether it went that way, you "force" it to become a particle, because the interference pattern disappears. The situation is crazy. In spite of this, one reads in books that there is a theorem, proved by the famous Hungarian physicist John von Neumann, one of the founding fathers of quantum mechanics, which showed that one cannot do better than this: no quantum theory can provide a more comprehensive description of reality than this.

But there is more: as a consequence of what we have just seen, we often also read that reality is created by the observer. In fact, quantum mechanics has two fundamental equations that describe the time evolution of an object called a wave function. The first, which goes by the name Schrödinger equation (after the Austrian physicist Erwin Schrödinger, who proposed it), is valid only as long as no measurement is made. This equation describes how a generic wave would also behave classically (with some essential differences, discussed below). In particular, as it must be for waves, any sum of solutions, also called superposition, is still a solution of the Schrödinger equation. It thus describes one possible way the world can be. In addition to Schrödinger's equation, however, we also need something else. In fact, let us take our electron gun, but this time it produces an electron whose wave function is the superposition of one electron directed to the right and one to the left. By means of a spherical screen that tells us where the electron ended up, since the wave function is in a superposition state, we should see a superposition of blue dots: one to the right and one to the left. But this is absurd, it is a logical contradiction: the electron cannot logically be "on the right" and "not on the right" at the same time! And indeed it is so, such macroscopic superpositions are never observed: the electron is detected either on the right or on the left (not on the right). This is explained by saying that every time a measurement is made, Schrödinger's equation ceases to apply and a second evolution equation, called von Neumann's "collapse" or "reduction" (which he realized was necessary) takes over. Such "collapse" randomly and instantaneously erases all but one of the superposition terms, namely, the one actually observed. The collapse ensures that the predictions of the theory agree with the experimental data through what is called Born's rule, which describes the probability of finding a given result following a given experiment.

If we stop and think for a moment, we quickly see that not all mysteries have disappeared, far from it: what does it mean that the act of making a measurement changes the equation of evolution? Isn't making a measurement a physical process like any other? Perhaps what makes the difference is not the measurement but the presence of a measurer? That is, perhaps what happens is that it is I, as a conscious being, who in looking at the superposition produced by the Schrödinger equation, "reduces" it to one of its terms? So perhaps it is my consciousness that changes the microscopic reality just because I look at it? If this were not an article but a speech, and if you could see my face as I say this, you would all understand immediately what I think of this option: it is not acceptable. If only because it assumes that the theory itself is incomplete: we need something external, non-material, non-physical, that is, consciousness, to collapse the wave function. But where is consciousness? How does it interact with matter? What are its laws of evolution? In any case, although assuming that the collapse is due to consciousness is possible (which means little or nothing, however, since almost anything is possible except logical contradictions), before accepting such an option, methodologically speaking, one should at the very least make sure that there are no simpler, less radical alternatives. Typically it is replied by appealing to von Neumann's theorem: "according to the theory the observer creates reality by looking at it; it will be strange we cannot do better; therefore, put your heart at rest and get back to work." Indeed, this is what has historically happened: everyone has thrown in the towel and agreed to "shut up and calculate," to use a quote from American physicist David Mermin.

This attitude created problems for essentially no one except astrophysicists, who find themselves in the awkward position of having no observer to appeal to in order to collapse the wave function: who observes the universe? Moreover, in astrophysics it is crucial to consider, in addition to quantum mechanics, the other important theory developed in the last century. I am thinking of general relativity developed by Einstein, which describes the structure of space-time and eliminates Newton's force of gravity: space-time "simulates" the gravitational force through its curvature under the weight of matter. Since its effects are especially important in the presence of very massive entities, such as celestial objects, general relativity cannot be ignored in astrophysics. One of the fundamental postulates of relativity prescribes that there is a velocity, that of light, beyond which nothing can go, not even the interaction between objects: if I feel the earth shaking under my feet, what happens is that the vibrations generated by an earthquake tremor that occurred a few seconds ago in some nearby region have finally reached me. This is one of the reasons why Einstein believed that quantum mechanics was incomplete. I remember that all physical systems are described by a wave function and that wave functions can stand in superposition of states. In the case of systems composed of more than one element, such as a system composed of two particles, the wave function can also be "entangled": the two particles are not each described by a single wave function but have a wave function in common. Now consider two particles traveling in opposite directions that are entangled. What can be shown is that if I measure one of the two particles, then instantaneously collapse its state, since the two are in an entangled state then I also collapse the state of the other particle, regardless of how far away it is. In other words, my influence on one particle (the measurement I made on it, "collapsing" it) also instantaneously affected that other one, which might be on Alpha Centauri. This means that the collapse acts at speeds greater than the speed of light, contradicting relativity.

Beginning in the 1960s, some astrophysicists working in so-called quantum gravity, which seeks to unify the two theories, including the American Bryce de Witt began to become interested in alternative possibilities to collapse, not so much because of the tension with relativity but more because, more simply, it is not possible in this context to appeal to an observer who "collapses" everything, as mentioned earlier. They realized (or rediscovered) the existence of a few "valiant" people who had resisted the dogma since the 1920s, and who had proposed alternative theories to von Neumann's collapse. Primarily, the theory proposed by American student Hugh Everett III in his doctoral thesis was rediscovered and publicized, presumably because it requires no modification of the quantum formalism. Everett's idea is that there is no collapse and that the wave function always evolves according to the Schrödinger equation, provided, however, that one interprets the wave function properly. According to Everett's version preferred by de Witt, which goes by the name of many-worlds theory, the individual terms of the superposition of the wave function should be interpreted as belonging to different worlds, which do not interact with each other and are therefore by definition unobservable. Thus, one equation, linear and deterministic, no privileged observer, no instantaneous collapse. Good, but not great: according to this theory there are infinite unobservable worlds that keep forming every time there is an overlap. Every time we observe something that is in superposition, we split into infinite copies, each in a different universe that we will never encounter. Is this really believable? This sounds like science fiction, not science. Is there really nothing less convoluted?

You can imagine my great surprise when I discovered that there is a theory without collapse, without observer, without many worlds, and it has been in existence since 1923 when the Frenchman Louis de Broglie, also a Ph.D. student, laid the foundation, and that in 1951 it was rediscovered and completed by the American physicist David Bohm. The theory is very simple: there are point particles whose motion is governed by a law, called the driving equation, in which the wave function described by the Schrödinger equation appears. This law has highly nonclassical trajectories as its solution, so much so that it explains the two-slit experiment without mysteries (Figure 3). In fact, while classically one expects to see objects going straight if there is nothing to disturb them, this is not true in the case of the theory in question: the particles have tortuous trajectories that are truly strange by classical standards, but which have also recently been observed experimentally (figure 4). What more could one ask for?

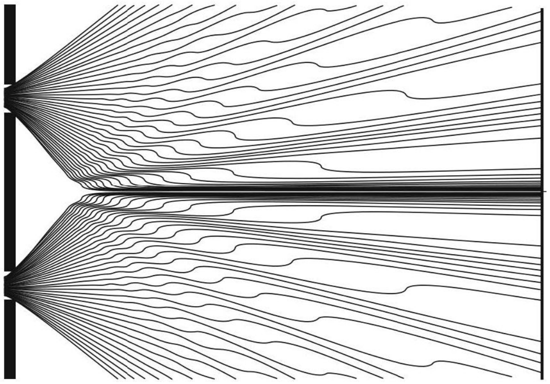

Figure 3: Theoretical trajectories of particles as the exit the two-slit apparatus (figure 3 in Philippidis, C., C. Dewdney, and B.J. Hiley, 1979, "Quantum Interference and the Quantum Potential", Il Nuovo Cimento B, 52(1): 15–28).

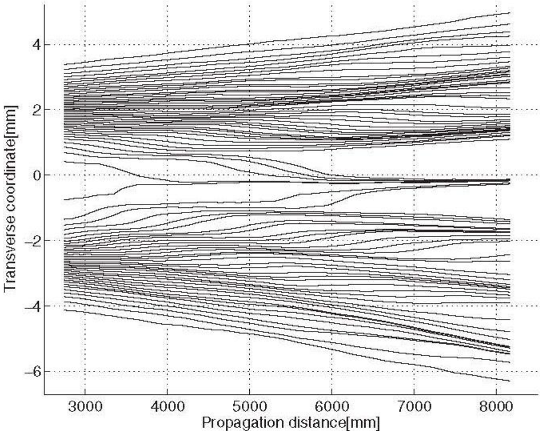

Figure 4: Measured trajectories using the weak measurement techniques (from Kocsis, S., B. Braverman, S. Ravets, M.J. Stevens, K.L. Shalm, and A.M. Steinberg, 2011, "Observing the average trajectories of single photons in a two-slit interferometer", Science 332, 1170-1173).

This theory is called pilot wave theory because the wave function is still present in the formalism of the theory. Other names for this theory are de Broglie-Bohm theory or Bohmian mechanics. A thousand questions arise, the first of which might be, "but if it was so simple, why is pilot wave theory not taught in physics courses instead of quantum mechanics? There must be something wrong with it, necessarily. Yes, there must be: didn't you say earlier that von Neumann proved a theorem that states that doing better than quantum mechanics is impossible? So this theory can't be right."

In fact, the further surprise, almost as incredible, is that von Neumann got it wrong: his theorem starts from untrue assumptions, so it proves nothing. Finding this information is not easy, but it is just so: in 1932 German mathematician Grete Hermann discovered it right away but was inexplicably ignored, and in 1964 Northern Irish physicist John Stuart Bell proved it again. As to why the pilot wave theory is so little known, even though it is so natural, I could go on and on. Let me just say that Bell's demonstration against von Neumann is neither widely known nor well understood. Moreover, and more importantly, pilot wave theory is often presented in misleading contexts. Many hear it mentioned as yet another frill to be added, we are not sure why, to quantum mechanics. But in fact, as I hope has become clear in this presentation, pilot wave theory is just a different theory from quantum mechanics, talking about different things, with different equations, and providing different explanations. In this article, I have tried to explain why one needs a theory other than quantum mechanics. In short, quantum mechanics viewed without wave function collapse provides, unjustifiably, a contradictory description of reality: it predicts that a particle can be "here" and "not here" at the same time. To eliminate the logical contradictions, collapse is introduced, which, however, again unjustifiably requires the observer to create the reality he observes. The question then arises as to whether the situation can be improved. Once one realizes that von Neumann's theorem imposes no limitations in this regard, and that better theories exist, one arrives quite naturally at the pilot wave theory. Of course, one can imagine a virtually infinite number of other new theories that are more satisfactory than quantum mechanics. But why go beyond the pilot wave theory, which is the simplest, both mathematically and conceptually, for no reason? In fact, we have already seen Everett's theory, which requires accepting the existence of infinite copies of unobservable worlds, one for each possible solution of the Schrödinger equation. Another possible alternative to quantum mechanics that I have not yet discussed is the theory of spontaneous collapse, proposed by the Italian physicists GianCarlo Ghirardi, Tullio Weber and Alberto Rimini in 1986, and then called GRW theory, from the initials of their names. In this theory, the Schrödinger equation and collapse are replaced by a single nonlinear, stochastic equation. In that theory the superpositions collapse on their own, because the equation is no longer linear. Moreover, while in the pilot wave theory matter is made up of particles, in the spontaneous collapse theory the nature of things appears to be wave-like, described by the wave function. This, however, is implausible: in fact, as pointed out immediately by de Broglie, Schrödinger and Einstein (they said this in the context of quantum mechanics, where one could say the same thing, not in that of spontaneous collapse theory, which did not yet exist in their time), mathematically the wave function does not oscillate in physical (three-dimensional) space but is defined in an abstract very high-dimensional space. So it does not seem sensible to regard it as a material, or "true" wave (this is the difference I was referring to earlier, speaking of the wave function as a wave).

This is why, although one often reads things that may suggest otherwise, in my opinion it is a mistake to think that in the context of pilot wave theory the wave function represents a real wave that "pushes" particles around. More pragmatically, instead, it should be thought of in this theory as a useful ingredient describing the interaction between particles, just as the potential was used in the classical context. Beyond that, returning to spontaneous collapse theory, the challenge is to see if there is a way to think of the wave function as something that represents a real wave, despite being mathematically abstract. Or, in the case of a negative answer, it is to determine what matter represents in such a theory, if not the wave function. In general, then, physicists and philosophers have set to work to find answers. If, however, we move outside the specific, and thus look at things from above, with perspective, justifying these efforts becomes difficult. In fact, as anticipated, there is already a theory such as the pilot wave theory that is simpler mathematically (it is deterministic and linear; this one, on the other hand, is stochastic and nonlinear) and that has no conceptual problems: it does not have the open problem of figuring out what matter is made of, as is the case with spontaneous collapse, because it is clear from the outset that the pilot wave theory is a particle theory. So why look elsewhere, if there is no advantage, neither in understanding nor in mathematical utility (in fact, things get worse)? Actually an advantage in spontaneous collapse theory I thought I saw, however slowly (and unfortunately) my enthusiasm for it is fading. I will try briefly to explain why, before concluding.

The real novelty of pilot wave theory is that the interaction between particles is nonlocal: the interaction between (a certain type of) particles can be instantaneous. Actually this should not be surprising because such instantaneousness had already been noticed by Einstein, as mentioned earlier, in the case of quantum mechanics. Only Einstein thought that this feature, in tension with relativity, was "the fault" of collapse, and that a better theory would not have it. Instead it was shown by the experiments of French physicist Alain Aspect's group in 1981, based on an inequality proposed in 1967 by Bell and for which he was awarded the 2022 Nobel Prize in Physics, that all theories that reproduce experimental data must be nonlocal. So the explicit non-locality of the pilot wave theory is not a defect, since it is a feature that all theories must have. The remaining problem, however, is enormous. The main reason why Einstein did not want nonlocality is because it is in tension with relativity, as mentioned many times before. So how can this tension be overcome if reality is in fact nonlocal? Is there perhaps another spirit of relativity that can be respected by a future relativistic quantum theory? A thousand questions, few answers, only one certainty: the non-locality of the world.

This immediately suggests that relativity is only approximately true. The first postulate of relativity asserts that the speed of light is the same in all reference systems, from which it follows that the simultaneity of two events can only be defined non-objectively: two events occurring at the same instant for someone could be one before the other for someone else. A nonlocal interaction is incompatible with this, because it must be possible to say that the interaction was instantaneous, that is, it happened at the same time in an absolute way. So one might assume that there is a preferred reference system, often called the "foliation" of spacetime (which, however, cannot be identified experimentally). This is the path taken by researchers who are developing pilot wave theories in the relativistic domain. But there is also another path, which some prefer because it seems not to require changing relativity that much. Indeed, if one thinks of relativity as a theory of the structure of spacetime, to postulate a privileged foliation is to modify that structure quite substantially. So the question that some people asked was whether it was possible to find a theory (not local, because this must be, following Bell's inequality and Aspect's experiments) that contained only relativity-compatible spacetime structures, that is, without any foliation. And what they found was that theories built on the idea of spontaneous collapse could be fit for purpose. This observation is what justified my initial enthusiasm for this research program. In analyzing their work, however, I realized the enormous cost that such theories have, which makes me doubt whether the game is worth the candle. In fact I think it can be shown conclusively that what makes these relativistic theories without privileged foliation is the fact that they are stochastic, and that in such theories the notion of cause and effect is completely symmetric. But this borders on the absurd: the egg broke because you threw it on the floor, but you also threw it on the floor because it broke. In such a theory, what is the point of talking about the locality or nonlocality of the interaction between two objects, if the notion of interaction seems to be losing its meaning? In other words, it had been thought to study these stochastic theories because they are perhaps more compatible with relativity than the pilot wave theory, and these theories seem to succeed in terms of the kind of spacetime structure they possess. But there is another fundamental element of relativity, namely, the idea of locality of interaction, which is based on the idea that the interaction between two objects propagates at finite speed. We know thanks to Bell and Aspect that nature is nonlocal, but these theories, in which interaction cannot be said to have started here and arrived there, precisely because in them the notion of cause and effect dissolves, seem to threaten the very idea of interaction. What purpose, then, do these theories serve? What do they explain? In what sense are they better than the pilot wave theory? These theories were supposed to explain what it means to have a nonlocal interaction in a purely relativistic space. But in fact it seems to me that they simply explain it by watering down the meaning of "interaction" so much that much of its explanatory sense is lost. In the case of the pilot wave, on the other hand, it is clear what it means for particles to interact in a nonlocal way, so much so that it is clear that this requires assuming that there is an unobservable privileged system: interacting with one component of an entangled pair causes both components to change, instantaneously and independently of their relative positions, and for this reason we need an absolute notion of time. Having a privileged foliation to make nonlocal interaction possible may not be the best (but why not, then?), however, it is at least understandable.

In any case, at this point, I have no definite answers; I only have questions. But off the top of my head, if it were really necessary to abandon the very idea of interaction in order to save relativistic spacetime structure, that would mean for me to say goodbye to the possibility of understanding the microscopic world (again!). Consequently, as I probably would have done as a young girl, I feel like saying that I would rather sacrifice relativity for a deterministic quantum theory. Which is not to diminish Einstein's greatness-after all, even classical mechanics is not strictly true, but no one thinks that Newton was not a giant of physics!

In the end, you be the judge. As far as I am concerned, either I have not grown up at all, and so I still cling to my childhood dreams of figuring things out with Lego, in terms of particles fitting together and interacting with each other. Or I am already too old to be able to understand phenomena using new categories of thought or sophisticated concepts yet to be invented that would allow me to understand reality without a clear sense of cause and effect. Given, however, that the first option is far from impossible since I am still allowed with pilot wave theory, I see no need to embark on the necessary undertaking to develop the second.

Biography:

Valia Allori was born in Milan, Italy, where she studied Physics at the State University. After receiving her Ph.D. in Physics from the University of Genoa, she moved to the U.S., first to complete a doctorate in Philosophy at Rutgers University in New Jersey, and then as a Professor at Northern Illinois University. She works on the foundations of physics, particularly quantum mechanics. In 2018 he won the Carl and Lily Pforzheimer Foundation Fellowship at the National Humanities Center, North Carolina, since 2019 he has been a Fellow of the John Bell Institute for the Foundations of Physics, Croatia, and since 2021 he has been a member of the FQXi, Foundational Questions Institute.