# Science AMA Series: I'm Adam Becker, astrophysicist and author of WHAT IS REAL?, the story of the unfinished quest for the meaning of quantum physics. AMA!

Adam-Becker [1] and r/Science AMAs[1]

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## Abstract

Hi, I'm Adam Becker, PhD, an astrophysicist and science writer. My new book, What Is Real? The Unfinished Quest for the Meaning of Quantum Physics, is about the scientists who bucked the establishment and looked for a better way to understand what quantum mechanics is telling us about the nature of reality. It's a history of quantum foundations from the initial development of quantum mechanics to the present, focusing on some people who don't often get the spotlight in most books on quantum history: David Bohm, Hugh Everett III, John Bell, and the people who came after them (e.g. Clauser, Shimony, Zeh, Aspect). I'm happy to talk about all of their work: the physics, the history, the philosophy, and more. FWIW, I don't subscribe to any particular interpretation, but I'm not a fan of the "Copenhagen interpretation" (which isn't even a single coherent position anyhow). Please don't shy away if you disagree. Feel free to throw whatever you've got at me, and let's have a fun, engaging, and respectful conversation on one of the most contentious subjects in physics. Or just ask whatever else you want to ask—after all, this is AMA. Edit, 2PM Eastern: Gotta step away for a bit. I'll be back in an hour or so to answer more questions. Edit, 6:25PM Eastern: Looks like I've answered all of your questions so far, but I'd be happy to answer more. I'll check back in another couple of hours. Edit, 11:15PM Eastern: OK, I'm out for the night, but I'll check in again tomorrow morning for any final questions.

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**ADAM-BECKER** R/SCIENCE

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Did you have any particularly interesting people or interesting places you went for the interviews during the writing of this book?

jmdugan

I took a tour of CERN, which was pretty cool! (John Bell spent most of his career at CERN, and Wolfgang Pauli's papers are kept there too.) And while I was in Geneva, I interviewed the retired CERN physicist Mary Bell, John Bell's widow. I also spoke with some big-name physicists who I had looked up to for a long time, like Yakir Aharonov, Alain Aspect, Roger Penrose, and Dieter Zeh (among many others). I really enjoyed speaking with Penrose and Zeh in particular; they both took a lot of time out of their day to talk with me. Penrose set aside a couple of hours while he was visiting a museum with his wife and son; Zeh invited me into his home for half a day to talk. Those interviews might have been the most fun of the lot. But it's hard to single out anyone — I interviewed over forty people for the book, and nearly all of them were very kind to me and very generous with their time.

You say:

the scientists who bucked the establishment and looked for a better way to understand what quantum mechanics is telling us about the nature of reality

But isn't "looking for a better way to understand what quantum mechanics is telling us about the nature of reality" exactly what nearly every physicist working in that field is doing? How is that bucking the establishment? Trying to come to better grips with quantum mechanics seems to be exactly what anyone studying quantum mechanics is aiming for.

arcosapphire

It's certainly true that most physicists who work on anything quantum are probing the connection between quantum physics and reality, in that they're testing the limits of quantum physics, verifying its predictions, and seeing if they can move beyond it to another theory. But for much of the 20th century, most physicists were surprisingly incurious about what quantum physics has to say on the subject of what's actually happening in reality. The theory certainly works very well when it comes to making predictions about the outcomes of experiments, but the traditional answer to questions like "what's the electron doing when we don't look" or "what's happening to this molecule when it's in a superposition" has been "don't ask that kind of question" or something to that effect. And this is a profoundly unsatisfying answer. Quantum physics can't simply be a theory that predicts the outcomes of lab experiments without also being a theory that has some connection to the world around us. There must be some set of facts about nature that quantum physics has successfully latched onto, otherwise the theory wouldn't work so well. Yet figuring out what it is about nature that makes quantum physics true —that is, figuring out what quantum physics is telling us about the world around us—has been a question that most physicists have dismissed, historically speaking. That's the status quo that Bell, Everett, Bohm, and others were fighting against when they did their work in this area.

Who is this book written for?

Why did you write it for them?

jmdugan

This book is written for anyone interested in quantum physics or the history and philosophy of science, even if they don't have any sort of background in physics or history or philosophy. It's also aimed at professional physicists who may not be aware of the history of their field, or may be misinformed about it (there are a lot of myths floating around about the history of quantum physics).

I wrote this book because I think this story — the story of how the standard answer to legitimately thorny questions about quantum physics became "shut up and calculate" — is a fascinating story, one that deserves to be more widely known. It sheds some interesting light on the interplay between science, philosophy, politics, and interpersonal conflicts. And I've never been satisfied with simply dismissing the puzzles at the heart of quantum physics, and this story makes it clear why we can't just dismiss those questions.

If you could make a change to how QM is taught in undergrad physics, or to graduate students, what would it be?

jmdugan

I think there should be more time given to talking about the quantum measurement problem, and the different solutions that have been proposed (i.e. the different available interpretations). And I think some of the best philosophical work on the subject should be brought into the classroom too. I don't think this would require a radical change; simply devoting one or two weeks (2-6 lectures) to these topics during a semester-long course on the subject would be sufficient.

There's also a certain impatience and disdain for quantum foundations among some physicists, and I'd love to see that fully dissipate, but that's a cultural problem that can't be fully solved by a mere curriculum change. I'm hopeful that my book will go some way toward addressing that problem, but even in a best-case scenario it couldn't solve that problem entirely — it's just too entrenched.

Hi! Speaking of interpretations of quantum mechanics, one of them in particular has become the center of an interesting case of cultural osmosis regarding science: Everett's many-worlds interpretation. It probably became popular because of its intuitive formulation and its many possible interesting consequences when applied to fiction and real life alike.

As someone who is not involved in the scientific community (yet!), I wanted to ask: what is the general opinion of professionals about Everett's interpretation? Does anyone still take it seriously, or has it fallen out of favor nowadays? What do you think of it?

Thanks in advance!

Edit: unnecessary paragraph

MindfulDelight

The many-worlds interpretation certainly has a fair amount of support among professional physicists, though I don't think it's got a majority or even a plurality (it's hard to say exactly how much support any single interpretation of quantum mechanics has, since there's never been a good unbiased survey done on the subject). Plenty of smart physicists believe this is the right way to think about quantum physics, and plenty of other smart physicists believe it's wrong, or just silly. I think it's a viable option — I don't think it's silly — but I'm not convinced it's correct. But I'm also not convinced it's incorrect, and I wouldn't be hugely surprised if it turned out to be the right answer.

In movies such as Interstellar you see time dialation as a result to gravity. Is this accurate? Can large gravitational objects affect how we experience time relative to the rest of the universe?

The_impericalist

Yes. This is a direct result of Einstein's general relativity, and it's been verified with outrageous accuracy in experiments using atomic clocks. In fact, GPS wouldn't work without taking this effect into account. More here: https://en.wikipedia.org/wiki/Gravitational_time_dilation

don't subscribe to any particular interpretation, but I'm not a fan of the "Copenhagen interpretation"

Can you explain more why are you not a fan of the "Copenhagen interpretation"? I'm guessing this is in the book?

jmdugan

The Copenhagen interpretation isn’t really a single thing — it’s a collection of vague and mutually-contradictory positions about what quantum physics means. And none of those positions actually answer the questions at the heart of the theory.

The most important of these questions is known as the “measurement problem,” which is basically a question about when the Schrödinger equation (the central equation of quantum mechanics) applies. The usual answer is to say that the Schrödinger equation applies whenever a measurement isn’t being made, and when a measurement does happen, then the Schrödinger equation is temporarily suspended and something else called the Born rule is used instead. The details of the Schrödinger equation and the Born rule don't matter here: what matters is that they're not the same, and we need to know when to use one and when to use the other. Simply saying "we use the Born rule when we make a measurement" isn't good enough, because the idea of "measurement" is really vague, and it's not obvious why it should be any different from any other physical interaction. What constitutes a measurement? Does a measurement have to involve a person? Most physicists would say no — it's just about when something big interacts with something small. But in that case, there are measurement-like interactions happening all the time, so when would the Schrödinger equation apply at all? It's certainly true as a practical matter that we treat big objects as if they don't obey the Schrödinger equation, and as if they're endowed with the power to suspend the Schrödinger equation for small objects. But in principle, most physicists (myself included) don't believe that there's any sort of size limit to quantum physics, which means that the Schrödinger equation also applies to large objects. In that case, measurement can't mean "big thing interacts with small thing," because big things obey the Schrödinger equation too. (Some people say decoherence completely solves this problem, but that's simply a mistake.) So what's a measurement? And why does measurement behave so differently from any other process in nature — why does it have the power to suspend the Schrödinger equation and invoke the Born rule instead?

The Copenhagen interpretation gives a jumble of contradictory answers to these questions. One version of Copenhagen says that big objects really are different, they really don't obey the Schrödinger equation, and measurement happens when anything sufficiently big interacts with anything sufficiently small. Almost nobody believes that anymore; it's not supported by experimental evidence. Another version of Copenhagen says that measurement really is different from any other process — but conveniently avoids the questions "what's a measurement?" and "measurement of what?" Another, related version says that nothing is real until it's measured, and that the process of measurement brings things into reality. But again, the notion of "measurement" is never defined, nor is it clear how measuring devices (whatever they are) can maintain their reality independently of being measured. Another version says that these questions don't need answers because the answer is right there in the mathematics; that's patently false, as the mathematics say nothing about when to apply the Schrödinger equation and when to ignore it and use the Born rule instead. And another version says that these questions are unscientific, that quantum mechanics is merely an instrument for predicting experimental outcomes. According to this version, asking what happens when we're not making measurements is meaningless, because things that happen when we're not looking are unobservable in principle, and unobservable things lack meaning. This is based on shoddy and outdated philosophy of language and philosophy of science. Scientific theories are about the world, not about the mere outcomes of experiments. If quantum physics really had no relationship at all to anything in the world — if there were really nothing at all in the world that was even approximately like the mathematical structures found in the theory — it would be a miracle that quantum physics worked so well.

Finally, there's a version of Copenhagen that says there is something out in the world, but that it's so foreign to our experience that we have no hope of understanding it, and the best we can do is to come up with this set of weird rules, based on the notion of "measurement", that will predict the outcomes of experiments. But this is doubly problematic. First of all, the problem with the rules isn't that they're weird, it's that they're contradictory. Without a good notion of "measurement," we can't use quantum physics at all. The practical version of the term that we use for everyday work in quantum physics — "big thing interacts with small thing" — is based on a version of quantum physics that almost nobody believes in (namely the idea that there's a limit to the size of thing that you can describe using quantum physics). So we can't just say "measurement" and leave it at that.

The second problem with this version is that there are alternatives to the Copenhagen interpretation, alternatives that actually do describe a (deeply weird and counterintuitive) world. These alternatives — many-worlds, pilot-waves, and more — are all quite strange, but that's fine. It's a strange world out there. And they also give precise and realistic answers to the questions raised by the measurement problem. Given that these alternatives exist, the Copenhagen interpretation should be relegated to the history books.

TL;DR: Given the incoherence of the Copenhagen interpretation, its inability to resolve the measurement problem, and the existence of multiple superior alternatives, I see no reason to entertain it. And yes, I go into more detail about this in my book.

In terms of "bucking the establishment", I think this is a direction a lot of young researchers are facing now, in many areas.

Of the people you researched for this book, who do you think had the most difficulty or success with "bucking the establishment", and how did their actions result in how we view QM today?

jmdugan

Hard to say who had the *most* difficulty or success bucking the establishment, but I'd probably have to say that Bohm had the most difficulty, and Bell had the most success.

David Bohm really got the shaft, both personally and professionally. For the "crime" of briefly being a member of the Communist Party during his student days, he ended up arrested, blacklisted, and ultimately was forced into exile. He spent four years trapped in Brazil, and he never lived in the US (his native country) again. And while all of this was going down, he found the time to independently develop an entirely new way of looking at quantum physics. (It later turned out that Louis de Broglie had developed some of the same ideas 25 years earlier, but Bohm hadn't known that — and he finished the job that de Broglie had started.) But his ideas were first ridiculed, then ignored and forgotten. There's been a resurgence of interest in the last 10-20 years, but Bohm didn't live to see that; he died in 1992 in the UK, still in exile.

John Bell, on the other hand, enjoyed a lot of professional success — he spent most of his career working at CERN, which is a pretty ideal place to do physics, and he did a lot of very important work in quantum field theory that paved the way to at least one Nobel Prize. And at the same time, driven by his dissatisfaction with the Copenhagen interpretation, Bell built on Bohm's work to prove something truly remarkable: Bell's theorem, among the most profound scientific discoveries ever made. The theorem requires more space to fully explain than I can take here (I've written an interactive essay explaining it if you're interested), and it's commonly misunderstood. But Bell's work almost single-handedly revived interest in the measurement problem and quantum foundations at a time when these subjects had basically been left for dead by most physicists.

I noticed you interviewed Sean Carroll u/seanmcarroll who has argued/claimed that the Core Theory implies causal closure and completeness regarding everyday phenomena. This implies no strongly emergent causation and no extra-causal 'free will', assuming such are everyday phenomena.

Could you opine on this, or comment on any ways in which your picture of "What is Real" might differ from this version of the core theory? Can quantum physics as you understand it tell us something broad like this about everyday macro stuff? What if anything can the Core Theory tell us about broader questions about how the world works?

For info on Core Theory see here.

Mauss22

I don't think that Sean is wrong in any particularly important way. He's right that the physics of everyday life are completely understood, and that there isn't room in there for anything like a soul or extra-causal "free will" (though I find the arguments for compatibilism compelling, so I don't really see a contradiction between this kind of determinism and free will).

As for what the Core Theory tells us about what is real: at a fundamental level, not a whole lot. As Sean is quick to point out, this is an effective theory: it only applies in certain situations. Those are the situations we encounter in everyday life, and the Core Theory certainly tells us that there are structures in the world that correspond to the things we see in the everyday world around us. But we don't know what fundamental theory underlies the Core Theory, because we don't have a theory of quantum gravity, nor do we know how to interpret this theory that we don't have. And we don't even know for sure how to interpret some of the theories we do have, like quantum mechanics and quantum field theory. So that means we don't know what's really going on in nature at the fundamental level, even though we have a good approximate idea of what's going on in the everyday world.

So, who was more "correct", Bohr or Einstein?

In a related topic, did you cover in the book, or do you know anyone now in physics doing serious research/good work on the interpretations connected to superdeterminism?

jmdugan

In the Bohr-Einstein debates, Einstein was more correct (though not entirely correct). The story of those debates is usually told as if Einstein's major problem with QM was the fundamental randomness that appears to be in the theory — "God doesn't play dice" and all that — but that wasn't really Einstein's main concern. He was more concerned with two other things: realism and locality. Einstein didn't like that Bohr's way of thinking about quantum physics seemed to deny the idea of a real external world, and that physics was about studying that world. And Einstein was also (correctly) troubled by the apparent non-locality (i.e. faster-than-light influences) that showed up in the theory. He repeatedly tried to explain these issues to Bohr, and Bohr repeatedly missed the point. This culminated with the famous EPR paper, where Einstein and two of his colleagues tried to point out yet again that quantum physics seemed to involve faster-than-light influences. Bohr replied with something that was, uh, let’s say *less than clear*. In fact, Bohr’s reply was so unclear that he actually apologized for the lack of clarity about 15 years later in another essay! But after that apology, remarkably, Bohr didn’t go on to clarify what he had meant. It wasn’t until Bell’s work in 1964, after both Einstein and Bohr were dead, that it became clear that Einstein was closer to the truth, and that there really was a problem with non-locality in quantum physics.

Also, it’s quite astonishing that most presentations of the Bohr-Einstein debates suggest that Bohr was more right than Einstein, or even that Bohr was completely right. This is simply a mistake. Bohr was at best confused and obfuscated, and at worst he was just hopelessly wrong. There was even an embarrassing episode where Bohr tried to show a flaw in a thought experiment that Einstein had devised by invoking Einstein's own general relativity. But Bohr had completely misunderstood that thought experiment — Einstein was concerned with locality, but Bohr thought that his problem was with something completely different, the energy-time uncertainty relation. And not only did Bohr misunderstand Einstein, but he then tried to defend the consistency of quantum physics by invoking a completely different theory, general relativity, which we still don't know how to reconcile with quantum physics. This should have been a massive embarrassment for Bohr, but instead it's usually presented as a failure for Einstein (even Wikipedia makes this mistake).

Bohr’s writing is much more opaque than Einstein’s. Weirdly, this might have worked to Bohr’s benefit: people saw profundity in the tortuous prose of Bohr, whereas in Einstein’s writing they saw oversimplification. And Bell fell victim to this as well: he made it very clear in his writing that his sympathies were with Einstein’s views, and that Bohr’s position was unclear at best and wrong at worst. Yet despite Bell’s lucid writing, people regularly misunderstood the meaning of his results, and took his work to be a vindication for Bohr, a fact that Bell himself lamented in his later papers.

Does under-determination pose a unique problem for quantum physics and fundamental sciences?

Higher level, course-grained sciences are often under-determined. These ambiguities can be resolved by turning to lower-levels of description. For example, a number of psychological explanations might generate equivalent predictions, but make different assumptions about underlying mechanisms--which can be tested. But if lower-level descriptions depend on the higher-level evidence, then they may not resolve such issues. From my general understanding, fundamental theories often do not generate or depend on novel evidence. If this is the case, then the problems with interpreting QM seem unique when compared to other sciences.

If this is a problem, how might it be overcome?

Mauss22

As a historical matter, it's not true that new fundamental theories don't generate new predictions or depend on new evidence. Quantum mechanics itself is an example here: it was motivated by an enormous body of experimental work from about 1890-1930. There are many more examples: general relativity explained existing anomalies in data and predicted novel effects that were later confirmed (e.g. bending of starlight during a solar eclipse, gravitational time dilation); electroweak theory predicted the existence of the W and Z bosons. So in this sense, I don't think that the underdetermination of theory by data presents an entirely different problem for fundamental theories. It's basically the same as it is everywhere else — except, as you say, you can't appeal to a lower level of explanation. But we still manage to develop theories based on the data at hand and the theories that came before. And as with any other theory, the way we interpret our theories will be influenced by future discoveries. Similarly, I don't think we'll know which interpretation of quantum physics is correct until we have a theory that goes beyond it.

Hi. I learned in physics class that electrons can only exist in discrete energy states that we call orbitals. So electrons are quantized. But if they are made of energy, and since Einstein's equation ($E=mc^2$) would tell us that a body's rest mass times $c^2$ equals it's energy, couldn't we say that mass itself is also quantized? If that is true, would it be possible for less dense matter in bigger wavelengths to be around us, undetected by most physics?

Tura63

Mass and energy are both quantized, that's true! But mass and energy always come with a gravitational pull, and we're pretty good at detecting matter, so if there's some low-density matter around, we'd probably see its gravitational effects here on Earth or elsewhere in our solar system. That being said, there's extremely solid cosmological and astrophysical evidence for unseen matter, known as "dark matter," and that stuff is probably around us in very low densities all of the time, even though we haven't seen it directly. So there's a sense in which you're right!