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Are Quanta Real?: A Galilean Dialogue

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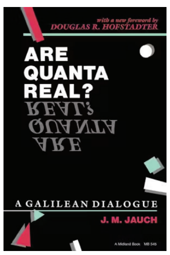

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PLATINUM OPEN ACCESS

The subtitle of the book is "A Galilean Dialogue" and is based on Galileo's "Dialogue Concerning the Two Chief World Systems," written circa 1632 AD. In it, three imaginary characters, *Simplicio, Sagredo,* and *Salvietti,* are having a profound conversation about the nature of reality and how it is perceived via experiments and meaningfully discussed via the theories of the day. Their dialogue was divided into four days; each day addressed a different area of concern: Was the sun or the earth at the center of the universe? This was Galileo's final book and was a scientific testament covering what later became classical physics (the only physics of his time). Jauch brings the characters forward in time to circa 1970.

Their up-to-date conversations take place again over four days, with each day becoming more and more difficult to comprehend than the previous day's contemplation. *Are Quanta Real?* explores the "new" physics known by 1970, namely quantum physics, and raises questions which were profound then and even today remain (for some scientists) not sufficiently well-answered—perhaps even mysterious.

To tell this story basing it on our present-day (circa 2024) understanding of quantum physics will require me to add another fictitious character—a time traveler from the present time—who goes back to the Fall of 1970 to the same villa situated on the shores of Lake Geneva, Switzerland and meets with the trio.

Call our time traveler (from our time around 2024), *fugitio,* who overhears their dialogue and adds his own futuristic (from their points of view) quantum-physical comments.

Day One

On day one, our trio explores the quantum physical question of realism brought into question by Niels Bohr's so-called Copenhagen interpretation: Accordingly, things "out there" only come into existence when (and only when) they are *observed*. Prior to their observations, these "things" only existed as ghost-like waves of possibility.

Thus, there seem to be hidden factors or variables that render our actual things apparently invisible until an observation. Our trio believes that before our observation or measurement, these things still existed "out there". Thus, Bohr's thesis leaves our trio all a bit confused since their commonsense view of the world and all its contents seemingly exist, regardless of whether any of them observe it.

Suddenly appears *Fugito* waving a flag of truce: Well, gentles all, we in the future, some fifty years hence, have added some light to this dark dilemma, for now, we have several new ideas which might help disperse the confusion, but I caution you all, for it also introduces some perhaps even stranger ideas.

The trio exclaims: "Speak, we can't wait to hear you!"

Fugito reports: Let me summarize your pondering: Albert Einstein, with whom you all are cognizant, had, during the quantum theory's inception, many discussions with Niels Bohr, Werner Heisenberg, and several other luminaries of this *new* physics, pointed out that we all previously believed that observed phenomena—attributes of real things brought forward by experiments—simply pre-existed "out there" regardless of what idea or theory we had about them. Einstein upset this point of view when he declared: "It is the theory that determines what we can observe." In other words, without any idea or concept of what is "out there"—we cannot really know what we are observing. We take it for granted that there must be real things or particles that exist and we expect our theory to tell us how these particles behave. But quantum theory doesn't describe that picture.

To this, they all reply nearly in unison, "Well then we need a better theory, one that can perhaps grapple with hidden controlling factors or variables that render the results of our observations."

Fugito responded: Albeit it turns out that our current theory of quantum physics does produce, in my time (2024), some new and very interesting proposals concerning reality especially those pesky hidden variables.

This left our trio hopeful but nervous and curious. So, they adjourned, planning to meet the next day.

Day Two

On day two, they again wonder whether the concept that there are real objects "out there" in the universe was true—an idea that seemed so successful in describing the everyday world they all perceived around themselves. Why, they ask, is it so elusive to describe real objects when they are very small—atomic-sized? Aren't large objects made up of smaller ones? Classical physics, as seen by Newton and others, seems to work very well when dealing with large objects. Even throwing Einstein's special theory of relativity into the pot, although a somewhat mysterious concept that changes our commonsense view of time and space, does seem to still grasp that objects are "real" and "out there."

Fugito: Yes, that raises a most profound question and observation. You all seem to think that we just need a new addition to our classical theory, one that contains such hidden variables—even Einstein thought the quantum theory was incomplete. You point out how difficult it is to make a consistent "hidden variable theory." How should such variables act? We all might agree that if "real" particles are really "out there" and are locally controlled by such variables, and if two such particles interact and then widely separate, their properties should be independent of each other.

An attempt towards such a classical hidden variable theory was given by David Bohm. He reinterpreted standard quantum physics such that the apparently ghost-like wave of possibility mentioned earlier was theorized to be a real wave and "out there" and, as such, was able to influence all real particles just as a magnetic field influences current-carrying wires and magnets. Later, Bohm's interpretation was revisited by physicist John Bell, in his famous no-go theorem (in essence, there cannot be hidden variables), who showed that such a "real" wave describing two quantum-entangled (meaning having interacted and thus influencing each other) and separated particles could not produce such independence. This meant a measurement made on one particle at one spacetime location could suddenly change the measurement result made on the other particle at a distant (spacelike—faster than light could travel from one to the other) spacetime location simultaneously. This is called *quantum entanglement* and resulted in 2022 three Nobel prizes to Alain Aspect, John F. Clauser, and Anton Zeilinger. Working independently, each of the three researchers forged new experiments demonstrating and investigating this seemingly magical connection.

This led our trio to question whether classical physics could ever be the ground for the ultimate theory sought for. So, the three adjourned to look forward to the next day.

Day Three

Our still somewhat befuddled trio began to wonder if any theory would suffice being that experimental results were so uncertain, as if God were throwing dice, producing results that were seemingly chancy, yet at times quite close to what was predicted. "Could the future vision given to us by you, *Fugito*, be of any help?"

Fugito replied: When we consider joint measurements (of two or more variables) based within quantum physics, something called *contextuality* of our observations comes into question, and with it, so does *classicality*—the notion that underlying the world are objects that behave just like large objects of our everyday world behave. We have already discussed classicality (that there are real particles) during the previous two days. The new notion of contextuality probably first came into quantum physics in 1968, so you may have already read about it. In brief, any observed result will depend on the context with which it was observed—the other variables that are also observed before, at the same time, or after.

Two physicists, Simon Bernhard Kochen and Ernst Paul Specker (KS), came up with a rather perhaps complex but nevertheless surprising proof, a mathematical inequality, dealing with such apparent classical hidden variables, specifically what we assume to be real and "out there," even if we don't actually look to see them, turns out to be an illusion. KS concluded that classical hidden variables cannot represent "elements of physical reality."

Later, Israeli physicist Asher Peres showed using a simple exercise that what we call "the result of a measurement of a variable **A**" cannot depend only on **A** provided that other allowed variables, such as, e.g., **B**, are also measured. Thus, the result for **A** depends on the choice of other quantum measurements like **B** that may possibly be performed—at any time—in the so-called context of **A**'s measurement.

Simplicio then replied, "That would mean if I flipped two coins and one came up heads while the other came up tails, the observation of the first coin's result would depend on whether or not the second coin came up heads or tails no matter when I flip the second coin?" *Fugito* replied, yes, that is correct, even though the coins may be spatially completely out of range of each other.

Day Four

Fugito decided to continue his commentary the next day while the trio was perhaps waking up while still reflecting about contextuality. He went on: Yes, some new ideas may be helpful in this regard, but they may require you to give up some precious ideas about the nature of time. For example, consider a paper by Yakir Aharonov, Eliahu Cohen, Doron Grossman, and Avshalom C. Elitzur (ACDE), written circa 2015, entitled *Can a Future Choice Affect a Past Measurement's Outcome*? Here, the idea of two kinds of measurement is introduced: weak and strong measurement. Whether a measurement is weak (WM) or strong (SM) depends on the measuring instrument. SMs are produced when the measuring instrument is sharply tuned, while WMs are produced when the instrument is not sharply tuned. Surprisingly, WMs are able to yield significant results *when they are made before* an SM. One such result produced the outcome that the WM made at the earlier time was actually determined by the SM made at the later time. The reciprocal, however, does not hold for a combination of measurements of which the latter one is weak and the first one strong. *The latter SM affects the former WM, never vice versa*. Therefore, when a weak measurement precedes a strong one, the only possible direction for the causal effect seems to be from the future to the past.

Surprisingly, even though the experimenter did not recognize that this WM result would be determined by what would be done in the future, the relationship between the later SM and the earlier WM result was indeed as predicted. The most reasonable resolution seems to be that the experimenter's choice has been encrypted within the WM's outcomes, even before the experimenter knew what their choice would be.

Our trio was quite upset that such results could be the truth. *Fugito* continued: Finally, this work of ACDE sheds new light on the age-old question of free will. One would tend to believe that the anticipation of the choice of a measurement by a human being to be made much later renders that choice fully deterministic and only bound by earlier causes. The profound result of ACDE, however, shows that this is not the case. The choice anticipated by the WM outcomes can become known only after that choice is actually made. This inaccessibility, which prevents causal paradoxes like "killing one's grandfather," secures human choice full freedom from both past and future constraints. The earlier choice is fully deterministic, seemingly but erroneously bound by even earlier causes. The choice anticipated by the weak outcomes can become known only after that later SM choice is actually made, even though what earlier choice is made depends on what will be chosen later. But our earlier experimenter seemingly doesn't know what will be observed later. He will think his earlier choice is freely made—even though it will be determined by what he will choose to do in the future. This inaccessibility thus secures human choice and full freedom from both past and future constraints, even though they are connected.

Simplicio said: I am totally at sea with this extension of quantum physics theory. I am still wondering about how we are able to measure anything at all. I go back to the old dichotomy: are things waves or particles? Could this be resolved by what you have told us so far?

What shall we do when the theory gives two contradicting points of view? This dichotomy led us to the idea that whatever was accurately revealed in a measurement always contained a hidden complementary reality. (Observe the momentum of a particle and its position cannot be seen with any accuracy and vice versa.)

Fugito responds: That old conundrum still remains, but it is now pictured quite differently. Quantum physics has not only re-pictured matter, it has also made us rethink what is meant by space and time. Our everyday view has it that things or particles exist as separate things appearing at unique times, always such that what occurs now can only have an influence on what happens later but never before. Quantum physics has now changed that. Measurements of things occurring now must depend on what else is being observed now or, before, or even after. So, the old picture of wave or particle duality is replaced by a whole new ballgame. Not only does matter take on a new meaning but so do time and space. Perhaps what is still missing is the role human minds play in the arena we call the universe.