Accepting quantum reality requires believing the unbelievable

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Imagine pushing on a door. Instead of moving out of your way to allow you through, it swings right back into your face. Instantly, you should realize that quantum physics is in play.

OK, with the door, it's more likely that some jerk on the other side of the door is messing with you. But if you're doing experiments with mirrors and light beams, you can be darn sure that it's quantum weirdness in action.

In this case, the weirdness illustrates a peculiar difference between the old standard classical physics and the quantum mechanical math that rules the microworld. It shows that the difference is not just in the math, but in the foundations of reality.

Sometimes people try to pretend that quantum physics isn't really so radical. They're happy with using quantum physics for little things like atoms and classical physics for calculating the motion of rocks or spaceships or planets. Quantum physics doesn't really assault common sense because it's important only for things too small to see.

Actually, though, quantum physics rules all the world, big and small. It's just that classical physics seems to work for big things. Quantum math and classical math give pretty much the same answers on large scales, and the classical math is just easier. Only for small things does quantum math give different answers — in fact, the right answers — where classical math gets everything wrong.

Well, not everything. Sometimes classical math predicts exactly the same thing as quantum math. Consider an arrangement of mirrors and detectors (known as an interferometer) for playing around with the properties of light. Interferometers typically exploit light's wave properties to measure things, all in accord with the mathematics of classical physics. In quantum physics, though, light is typically regarded as a stream of particles (photons). Sophisticated interferometers can be devised to illustrate either light's wave or particle nature (although not both at once).

Interferometers can also illustrate some really weird features of quantum physics, as Yakir Aharonov of Tel Aviv University and collaborators point out in a new paper.

Helpfully, this interferometer looks a little bit like a baseball diamond, with mirrors at each of the bases (and home plate). The mirrors at first and third base are fully silvered — that is, they just reflect light. Second base and home plate have half-silvered mirrors (known as beam splitters) at which some of the light is reflected and some passes through.

Here's how the experiment works. The game begins when a player in the third base dugout (a pitcher with a laserlike arm) throws a baseball (or photon) toward the catcher, at home plate. He is a beam splitter, remember, so he can choose to throw the ball to either first base or third base. The first and third basemen are regular mirrors, angled so that both have no choice other than throwing the ball to second base.

The second baseman, a beam splitter, can then throw the ball either to the left fielder or right fielder. If left fielder gets the ball, the game is over. But if the ball goes to the right fielder, he fires it back to first base, hitting the first baseman in the head, who (yes, who is on first) falls toward the infield. In technical terms, the first base mirror gets a momentum kick.

Now, as Aharonov and colleagues analyze it, this all makes perfect sense — if you analyze the result using classical physics, when the baseball is simply a light wave. The light carries momentum proportional to its intensity; it is easy to calculate how much of a momentum kick the first-base mirror gets when the light hits it.

It is also easy (well, not too hard) to calculate the momentum kick using quantum physics and describing the light as a baseball-photon. You get exactly the same answer as when calculating using classical physics and waves. If you actually did the experiment, that's how much of a momentum kick the first base mirror gets.

But even though the math gives the same answer in each case, and it's the right answer, the underlying quantum physics is very different from the classical picture.

A subtlety overlooked in the original description is that it's not just the ball hitting the back of the first baseman's head that imparts a momentum kick. He also gets a kick when the catcher throws him the ball, nudging him away from the infield a little. But if the players (mirrors) are arranged just right, and the catcher is a bit more inclined to throw the ball to third base rather than first base, during the game the total impact of the right fielder's throw hitting the first baseman in the back will be greater than the impact of the throws from the catcher. The net result is a larger momentum kick toward the infield than away from it. That's just what the classical light wave picture illustrates: the intensity of the light from right field is greater than the intensity of the light from the catcher.

But with baseball photons, something fishy is going on. If you do the quantum analysis, (you don't need to, Aharonov and colleagues do it for you in their paper) you'll see that the momentum kicks from the catcher's photons add up to exactly the same amount of momentum from the right fielder. The net effect should be that the first baseman stays right on the base.

So why doesn't he? Because of the baseballs that ended up in left field. Those balls do not come back to hit the first baseman in the back of the head. But they are the reason he falls toward the infield.

It's because in quantum baseball, the catcher's throws don't really just go to third base or first base, they are in a sense going to both bases at once. So the first baseman gets a weird combination of momentum kicks and no momentum kicks that — the quantum math shows — add up to negative momentum on the first base mirror from baseballs thrown by the catcher.

"Astonishingly, although they collide with the mirror only from the inside of the interferometer, they do not push the mirror outwards; rather they somehow succeed to pull it in!" Aharonov and colleagues write in their paper (arxiv.org/abs/1305.0168).

So weird as it seems, photons hitting the first baseman coming from the catcher, which should push him away from the infield, actually kick him the other way; like that door hitting you in the face.

The point is that quantum and classical math don't just give numerically different answers to physics problems, they represent conceptually different physics. Quantum reality really is radically different from the classical conception of reality, and the reality we live in is quantum, not classical. And it matters, both for understanding nature and for exploiting it for human purposes.

"Allowing us to have a better intuition is essential for finding new and interesting quantum effects and may lead to new experiments and potential practical applications," Aharonov and collaborators write.

So beware of people who try to tell you that quantum physics is not as mysterious as it seems (or has been represented). They just don't grasp the truly radical view of reality that quantum physics has imposed on human understanding of the world. It's been a century now since the first glimpses of quantum weirdness came to light in Niels Bohr's mode of the atom. It may take another century for physicists to figure it all out sufficiently to persuade everybody to believe how unbelievable quantum physics really is.