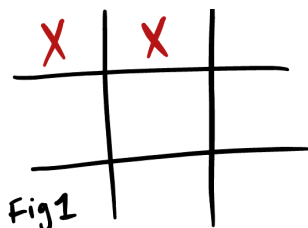


Quantum Games

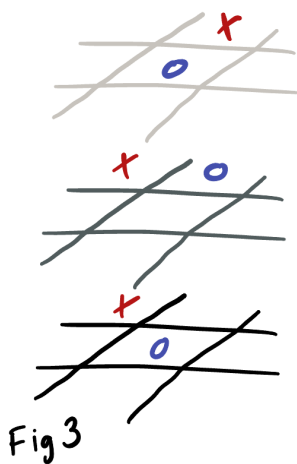
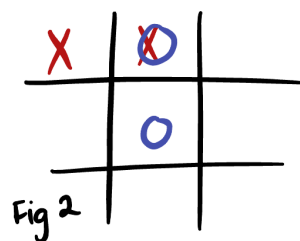
by Aspen Stuart-Cunningham

Imagine that you're at a tic tac toe tournament. You're in a high school gym on a Saturday afternoon, and the air smells exactly as if a gaggle of tic tac toe enthusiasts have been sitting at tiny tables and sweating over X's and O's all day. You sit at your tiny table, the classic four lined and nine squared board in front of you. Your last opponent of the day sidles up, scoots out his chair, and takes a seat. He is an older man, with circular glasses and a scruffy cat under his arm that he strokes every few seconds.



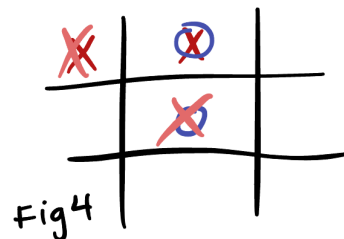
"Are you ready to play?" His eyes glitter with mischief as he makes his opening move. He places an X in the top left square. You raise your hand to place your O, but pause when you realize that he has drawn *another* X, in the top middle square (*Fig 1*). You frown and open your mouth to object, but something stops you - it is the look in his eyes. There is a challenge there; he has made a bid and now you must respond.

Slowly, cautiously, you also put down two marks: one O in the center square, and another in the top middle square, on top of his second X (*Fig 2*). He does not seem bothered by this - in fact, his lips turn up at the edges, as if he was testing you, and you have passed.

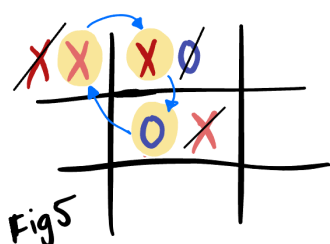


As you wait for the man to make his next move, you contemplate the board. You each have two marks on the board, from only one play. It is as if you are playing multiple games of tic tac toe at the same time; each one of your marks can make a single game of tic tac toe with each one of his marks. So, there are four possible games that could be going on right now - no, three, because the game with overlapping marks does not count (*Fig 3*). But you don't know which one to focus on. All of them, at the same time? You tilt your head, imagining the three game boards superposed on top of one another, moving through one another.

The man makes his second play. He places two more X's, one on top of his first X in the top left corner, and one on top of your O in the center square (*Fig 4*). You don't understand why he'd play his marks on top of where they already exist, but he seems to know what he is doing - a triumphant gleam glints in his eyes.

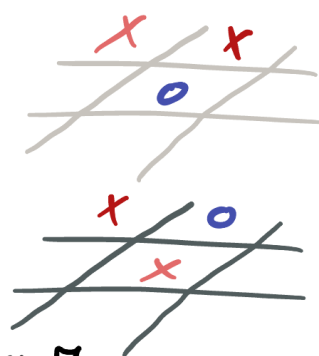
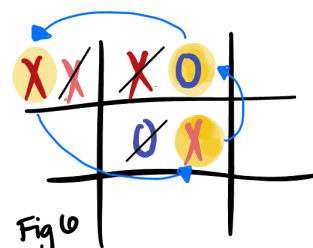


You stop to think about the board and realize that there's a cyclic connection between the marks. If only one mark from each turn can exist in each game, then that significantly reduces the number of simultaneous games that you're playing!



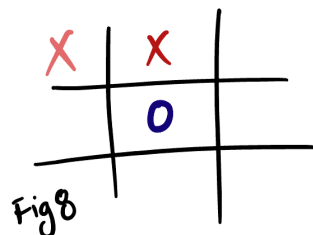
If you were to choose the game with the man's first X in the top center, it would force your O to only exist in the center square, therefore forcing his second X to only exist in the top left square, which cyclically would force his first X to exist only in the top middle (*Fig 5*).

But, if you were to choose the game with the man's first X in the top left square, it would force his second X to exist only in the center, therefore forcing your O to exist only in the top center, and wrap back around to his first X existing only in the top left! (*Fig 6*).



So there are only two possible games left to play, and in either one, the man has two marks in a row (*Fig 7*). Now his understated smugness is starting to make sense. The man looks to you. "I've induced the collapse of the system, so you get to choose which game we're going to continue with before you play your next turn."

Now that there are only these two cyclic self-referential games left (*Fig 7*), you have to pick only one of them to continue playing. You consider the board(s). In the game with your O in the top center, the man is guaranteed to win as long as he makes all the right moves. But in the game with your O in the center, it might at least end in a draw. You tell the man you want to keep playing the game where your O is in the center square. He nods knowingly and slowly begins erasing the marks until there is only one mark in each square now (*Fig 8*). The simultaneous game play has collapsed down to a single game, and you've returned to the classic game of tic tac toe.



It clicks in your mind. Superposition and entangled marks, the collapse of superposed states - this was no normal game of tic tac toe. You've been playing *quantum* tic tac toe.

Quantum Tic Tac Toe is a real game that physics educators have developed to help teach quantum mechanics to their students. And it's not alone. In the past twenty years, physics educators have developed a handful of "quantum games" that they can play in the

classroom. You can learn how to play “Entangle Me!” a game where the “particle” students try to avoid being measured by the “scientist” students, or “Stranded,” an explorative puzzle-based virtual reality game. You could play “Hello Quantum,” or “Psi and Delta,” or “Quantum Flytrap.”

A quick search on the internet yields an endless supply of games that have been created to help teach quantum mechanics to high school and college students. A slightly more niche search through a research article database similarly yields dozens of papers on developing quantum games and how we can use them. When I think of “Quantum Physics”, my first thought isn’t usually “wow that sounds so fun and like a really good topic to make a game out of.” I mean, quantum physics *is* fun, in a nerdy kind of way, but it’s not my first thought when I’m planning game night. So why is creating games using quantum mechanics a big trend in physics right now?

Let’s take a look at why we’d use games in the classroom in the first place. Humans learn through failure – we try new things, we make mistakes, and we learn from them. When we’re being graded on our success though, it’s hard to let those essential mistakes happen. Games allow us to try new strategies, make wrong moves, and eventually learn how the game is played, without that fear of failure. Furthermore, when learning is framed in the playful context of a game, you’re a lot more likely to want to engage with the activity. I know I’d rather play quantum tic tac toe during class than solve differential equations! And a lot of the time, being able to act out a phenomenon or visualize it through a game helps me understand what is actually going on.

So this works for learning about really any topic – why read a textbook or listen to a lecture when you could just play a game instead? I know you remember how great a day it always was in elementary school when your math teacher would let you play on CoolMathGames instead of dividing fractions.

But quantum physics is special. While it might be entertaining and a nice treat to study kinematics or the carbon cycle through playing a game, you could probably understand these concepts equally well by going outside and throwing a ball off a cliff or watching a dead plant decay. You know, intuitively, that when you throw the ball, it is going to fly through the air and curve downward in a (parabolic) arc. You’ve played catch with your dad before, and so you know how gravity works. You also know, naturally, that when living things die, the stuff that they’re made of (carbon), returns to the earth, and is eventually reborn as new living things.

But you might not know what happens when you simultaneously send a single electron through two slits in a board. You don’t see this every day, so it is not intuitive. You might not know how two particles, separated by great distances, can know the exact state of the other particle instantaneously. It doesn’t make intuitive sense how information could travel through spacetime instantaneously - faster than the limited speed of light! I have just described two of the key phenomena that we see in quantum mechanics – the superposition of states (the electron going through both the left and right slit at the same

time), and entanglement (two particles being “entangled” so that they can inform you of the other).

Quantum physics is hard to observe, and so we just don't have a good intuition for what we'd expect to happen in a quantum system. Quantum effects only occur on very very small scales (like on the size scale of an atom), or in very special materials (like Bose-Einstein condensates). Furthermore, quantum physics does not follow all of the same rules that we see everyday. Particles can be in two states at once and they can “tunnel” to locations where we would never expect to see them. To make matters worse, quantum particles are happy to act wacky and quantum-y while we're not observing them, but as soon as we try to inspect them to see what's going on – they stop! This is maybe one of the coolest, and most confusing, things about quantum physics - it stops being quantum when you try to measure it.

So how are we supposed to learn about quantum mechanics if we can't see any examples of it, our intuition about how it's supposed to work is totally wrong, and the math that we need to describe it is very difficult? (Quantum physicists have even invented their own mathematical notation, called “bra-ket” notation, to be able to describe quantum states). The answer, it seems, lies in quantum games.

It's okay if you didn't totally understand those last few paragraphs. I tried to explain the basics of quantum mechanics, but it's confusing – that's the whole point. Reading about quantum mechanics, or hearing someone lecture about it, or even learning all the necessary math and then deriving it from first principles, just isn't going to be as helpful as playing games that help it *become* intuitive. In each of these quantum games, the rules of the game mimic how a quantum system might act, instead of how a classical system might act.

The quantum tic tac toe game from the beginning of this article tries to make the idea of “superposition” intuitive. In quantum tic tac toe, almost everything about the game is the same, except for the fact that we can now have superposition - your X or O can exist in two places at once. This makes it so that it seems like there are multiple games happening at once. Eventually, the players have to “measure” what state the system is “actually” in, and the superposition collapses into a single game for the duration of the play. The idea is that, if you played this game enough times, you'd gain intuition for how quantum states can exist in superposition, and this essential quantum nature wouldn't seem so foreign.

This is only one of the quantum games that exist out there – there are many more that can teach you about other phenomena in quantum mechanics, like the uncertainty principle, spin, and interference. Check out the Appendix for a list of quantum games you can play!

As a self-proclaimed nerd and physics enthusiast, I love that all of these games exist and that I could play them if I wanted to really get a grasp on quantum behaviors. But probably not everyone thinks the same way. So why is it important that these resources exist so that anyone can learn about quantum physics? Well, while it's unlikely that we're going to start

seeing quantum mechanics in our everyday lives¹, quantum physics is becoming more prevalent in the technologies that we *do* use every day. We are beginning to use quantum computers for our computing (you can play with a real quantum computer on the [IBM website](#)), and our information security is slowly becoming dependent on the advanced cryptography that quantum computers allow us to use. Maybe you won't have to ever use quantum mechanics yourself, but the systems and technologies that you rely on will – so wouldn't it be good to understand them?

And isn't it just a little cool that we - anyone, of any age, anywhere - will be able to understand what happens between the minute pieces of an atom, in the particle accelerators and in the basement labs of physics researchers? Understanding quantum physics is a step towards understanding how the whole universe works. Understanding why balls fall and why plants decay. I know that I want to understand how those things work.

So hey, maybe next time you're at a tic tac toe tournament (yes, they do exist, and yes, you should go), you'll catch me there playing a round of superposed games with old Erwin and his cat.

Appendix of Quantum Games

[Quantum Tic Tac Toe](#)

[Entangle me! A game to demonstrate the principles of quantum mechanics](#)

[Encrypt me! A game-based approach to Bell inequalities and quantum cryptography](#)

[Quantum Moves](#)

[Quantum Physics Puzzle Game](#)

[qCraft and Quantum Chess](#)

[Particle in a Box and Psi and Delta](#)

[Virtual Lab by Quantum Flytrap](#)

[Quantum Odyssey - Quarks Interactive](#)

[QPlayLearn](#)

[IF Quantum Game Jam 2021 - IF2021](#)

[A simple game simulating quantum measurements of qubits](#)

¹ It's probably a good thing that quantum effects won't show up in everyday life – it would be very inconvenient if my laptop started tunneling to the other side of the room every time I tried to type anything!

References

[Allan Goff](#) , "Quantum tic-tac-toe: A teaching metaphor for superposition in quantum mechanics", *American Journal of Physics* 74, 962-973 (2006)
<https://doi.org/10.1119/1.2213635>

[Andrea López-Incera](#), [Wolfgang Dür](#) , "Entangle me! A game to demonstrate the principles of quantum mechanics", *American Journal of Physics* 87, 95-101 (2019)
<https://doi.org/10.1119/1.5086275>

ML Chiofalo, C Foti, M Michelini, L Santi, A Stefanel, "Games for Teaching/Learning Quantum Mechanics: A Pilot Study with High-School Students" *Education Sciences* 12, 446 (2022) <https://doi.org/10.3390/educsci12070446>

Ross Hoehn, Nick Mack, Sabre Kais, "Using Quantum Games To Teach Quantum Mechanics, Part 1", *Journal of Chemical Education* 91, 417-422 (2014)
<https://doi.org/10.1021/ed400385k>