Wizards of Wright

Lesson: Quantum Computing – Superposition

To get started, we must take you to our secret laboratory. Don't worry! You won't be alone.

Chapter 1: Enter the Secret Laboratory

A helicopter sets down and you step out onto a windy concrete pad somewhere in the Rocky Mountains. The wind is whipping, and you are freezing cold.

As the helicopter lifts off, blowing snow in every direction, you spot a steel trap door in the helipad and yank it open.

You climb down a side ladder to the warmth below. Overhead, the trap door slams shut.

You've reached your destination: The Quantum Computing Laboratory.

You look around at a wide central hall lined with science exhibits. On one side, a corridor leads away, lined with doors marked by unfamiliar scientific symbols.

The hall seems empty, without a human in sight. The only other living thing in the room is a cat, sleeping in the corner. Its coat is a strange, fluorescent blue.

You wait, but nobody comes to meet you.
Whoa! The cat's coat just turned orange! What's going on?

You lean over the cat, and you say, “If cats could talk, you might tell me where I’m supposed to go.”

The cat—she’s blue again—stares at you, blinks her eyes, and says …

Chapter 2: The Hall of Wonders

“So, you’re the new recruit! You must have a powerful interest in quantum computing.

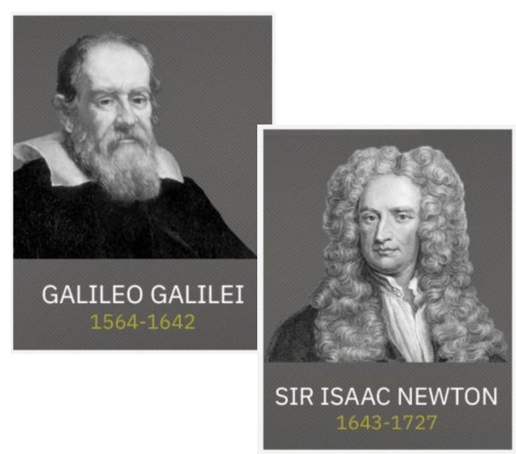
My name is Schrodinger. The humans who work here named me after a physicist who invented a thought experiment about me.

What’s a thought experiment?
That’s an investigation you run in your own mind.

It saves a fortune in lab equipment if you need something like a subatomic wrench or a jar of space vacuum.
We’ll run an experiment, similar to the one that I’m named after, in a little while.

Welcome to the Quantum Computing Labs. This big room ...? We call it the Hall of Wonders.”

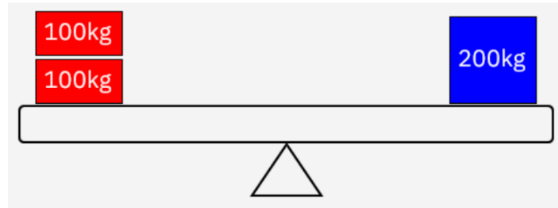
Chapter 3: The Strange World of Quantum Physics



Like most people, we have an intuitive understanding of *“classical” physics*. It’s the way that great scientists of the past, like Galileo and Newton, described the physical universe.

They established the idea that things like gravity, light, mass, and temperature can be measured and predicted with 100% accuracy.

That means, for example, that in classical physics, if you weigh exactly two 100-kilogram weights together, the result is exactly 200 kilograms. No more, no less, no kind of, not maybe.



Classical physics depends on **three absolute assumptions** that tie matter and energy together.

1. Matter is made of particles. (Particles are tiny, unbreakable bits of matter that group together to form solids, liquids, and gasses.)
2. Waves are made of vibrations.
3. **Matter and waves are different!** (Although they both have energy, particles and waves are **different** from each other.)

For generations, these assumptions were “the truth.” After all, they feel like how our world works. You hold a handful of sand, and you can feel gravity pulling its particles downward.
You hit a gong and you can hear the sound waves radiating off it.
Those sound waves don’t have weight, and the sand particles don’t radiate waves.

But… early in the 20th century, quantum theory overturned classical physics with predictions that sound crazy. We call them “counter-intuitive” because they feel wrong. They don’t feel like how our world works.

Physicists have found strong evidence—supported by math and by rigorous experiments—that waves and particles are somehow the same thing.

What’s more, it appears that reality is not exactly, well, exact! At least, not at the atomic level. Things like mass and energy exist as probabilities rather than 100% guaranteed truths.

This makes quantum theory sound like something out of Alice in Wonderland.

But quantum theory works! It has passed every test for over a century, making it the most successful set of ideas about physics that humans have ever come up with.

*Today, scientists are developing **a new kind of computer** that uses quantum theory to perform calculations that were once considered impossible to complete.*

Chapter 4: Three Questions About Quantum Computing

In a moment, Schrodinger will take us into the Superposition Laboratory. There you'll perform your own thought experiments! You won't need to do much math. But you'll think about revolutionary ideas like an elementary particle being in two contradictory states—at the same time!

On future tours we can visit a couple of more laboratories and perform even more experiments.

Let's halt our tour of the Hall of Wonders so I can ask you three questions. I'm expecting you to not know enough about quantum science yet, so please guess when making an answer.

Here's a tip: if you make each guess based on your understanding of classical physics, you'll get the answer wrong. Whatever answer you choose, you'll get a taste of the mysteries—and the opportunities—of quantum computing.

Here's the first question. Make your first guess!

1. *Scientists are exploring quantum computers because on conventional computers some problems…*

    A. *are too difficult to solve.*
    B. *take too long to solve.*
    C. *are impossible to program.*

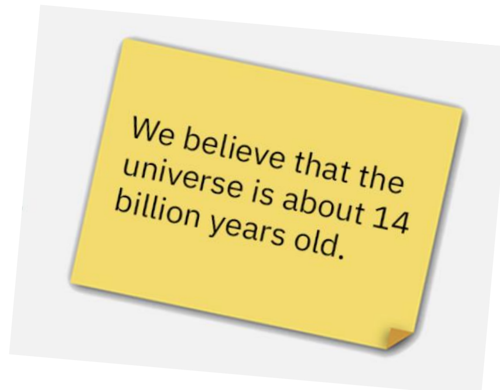
The best answer is… ______________________________. I'll tell you a story that explains why.

Now imagine that, to save the world, you need to decrypt a secret message by factoring a number that's … oh … 10,000 digits long. (This is a real scale for a decryption problem.)

The message is so important that your government has given you access to the fastest supercomputer in the world!

You write a brilliant program that breaks the message's number into prime factors, then tests each group of factors until it finds the combination that can unlock the secret code. (This is how a conventional computer would try to solve the problem.)

Now you run the program and wait.



You go out for lunch.
You return to find that the computer is still processing the program.
You come back the next morning and find the same thing.

Eventually your program solves the problem ... in a longer time than the age of the universe!

Problems whose calculations take impossibly long, turn up in fields ranging from the development of new medicines to artificial intelligence.

You're thinking, "Naww! Computers get faster chips every year, so it won't be long before…"
Stop right there. No super-advanced computer chips of the future will ever solve this problem in a reasonable length of time. To learn why not, try guessing the answer to my second question.

2. *Some computations take too long on a conventional computer because…*

   A. *computers programs can't do the math.*
   B. *the universe has put a permanent speed limit on computer chips.*
   C. *computer memories can't store enough variables.*

The best answer is… ____________________________.
No amount of advanced engineering will change that. Not ever. Here's why.

Conventional computers use transistors to store and manipulate information while they calculate. Those transistors do so by moving electrons from one side of a circuit to the other. The electrons are either here or there, so the circuit is either on or off.

But electrons can't travel faster than the speed of light, which really is the universe's speed limit. No electron can cross from one side of the circuit to the other faster than that speed.

But our factoring problem requires so many calculations, with so many electrons whizzing back and forth at the speed of light so many times across so many circuits, that even a conventional super-computer would take billions of years to deliver an answer.

So yes, there's a speed limit—the speed of light! But all is not lost. Quantum physicists believe they've found a way to avoid this limit. Which leads to my third question:

3. *Scientists will break the universe's speed limit by…*

    A. *building a new kind of circuit that solves the whole problem with one calculation.*
    B. *writing a faster program.*
    C. *creating a computer chip whose electrons travel faster than the speed of light.*

The best answer is… ______________________________.

Scientists believe that quantum physics offers a way to solve the entire problem by creating a subatomic circuit that finds an answer in one massive, incredibly rapid calculation. Boom!

To see how this is possible, forge onward into the Superposition Laboratory! There you'll begin to explore the strange laws of quantum physics.

Chapter 5: Introduction to the Quantum Labs

Tech companies around the world are doing their best to harness quantum physics to the ancient concept of a calculating machine.

Their efforts are still experimental. You're here to get an insider's view of that work-in-progress.

On today's tour, we'll visit one of our laboratories – **The Superposition Lab**. In each of our labs you'll perform thought experiments using quantum theory—in your mind, with imaginary equipment.

Here we develop ways to process more information more quickly using a mathematical entity called a "qubit." (That's short for "quantum bit.")

<u>Chapter 6: The Superposition Lab, A equals A</u>

The Superposition Lab is the first place (but not the last!) where you'll encounter ideas that seem contrary to nature.

Let's warm up with a question. Remember, if you don't know the answer, it's OK to guess.

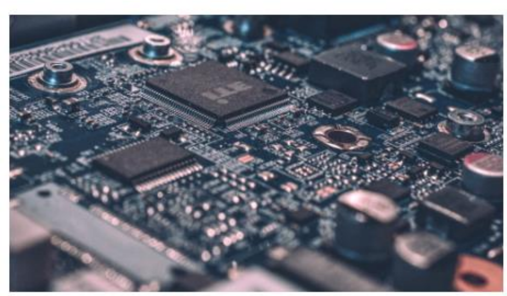
4. *There's a famous saying: "A = A" How would you interpret this?*
    - *A. Each letter of the alphabet has its own identity.*
    - *B. The simplest explanation for something is most likely true.*
    - *C. A thing can't have contradictory properties.*

The best answer is… _____________________________.

For our purposes, we'll interpret A = A as meaning that one thing cannot have two opposite properties at the same time. For example, it can't rotate right and rotate left at the same time.

Gottfried Leibniz coined the phrase "A = A" in the 17th century but it's still useful today.

Consider, for example, a circuit board in your cell phone or computer.



There, on a chip smaller than a postage stamp, millions of transistors are storing and manipulating information.

Each transistor is either OFF or ON. One or the other. So, transistors follow Leibniz's rule. They're never OFF and ON at the same time. A always equals A, and not also B.

Chapter 7: Transistors calculate with binary numbers

A circuit board uses a transistor's OFF or ON state to represent one of two numbers: zero and one. One or the other. Nothing else.

This is called "binary" counting because it uses only two numbers.

A computer needs three transistors in an ON state, to represent the number seven. 00111

We'll test the implications of this by performing a little thought experiment, the first of many you'll experience during your visit.

A thought experiment is an experiment that you conduct in your mind rather than on a lab table. But it works much the same as a physical experiment might: by following the steps of the Scientific Method.

1. ***Hypothesis*** *– First, you'll form a hypothesis. That's your best prediction of how the experiment might turn out. It's just a guess, although you'll try to make it a smart guess.*
2. ***Experiment*** *– Next, you'll mentally perform the experiment, and in your mind, you'll visualize the result.*
3. ***Conclusion*** *– Finally, you'll draw a conclusion based on the result you've observed.*

Let's walk through these steps with a practice thought experiment.

Remember, there's no pass or fail score for experiments. You just make your best hypothesis based on what know already, run the experiment to see what really happens, then learn from your results. Here goes!

Step 1: Hypothesis

This is where you state your hypothesis, which is your prediction how the experiment will turn out. In this case, knowing that it takes 3 transistors to *express the number 7 in binary, you predict that expressing the number 17 in binary will require…* ______________________________

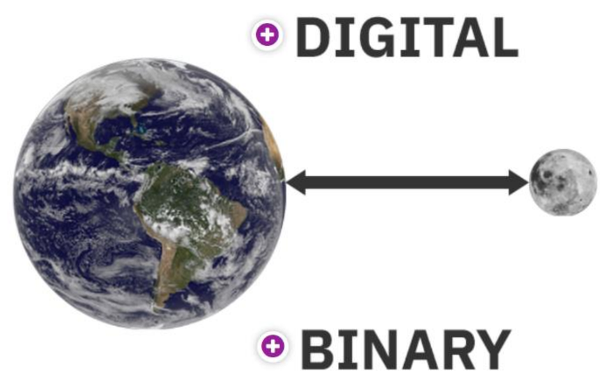
Step 2: Experiment

Hmm. It turns out that 17 in binary is written as 10001. So, it takes 5 transistors to express it, even though you could type it on a keyboard in 2 strokes.

What does this tell you?

Step 3: Conclusion

This experiment tells you that as numbers get larger, the number of transistors a circuit board needs to record and manipulate that number keeps growing larger and larger compared to the amount of digits that would express that number in decimal. Cool!



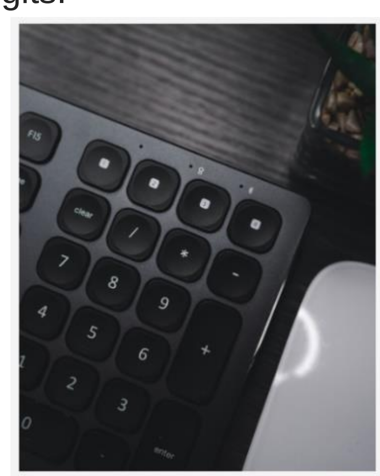
Suppose you're computing something to do with the average distance from the center of the Earth to the center of the Moon.

Let's see what happens when transistors in todays' computers must work with a really big number.

DIGITAL: The average distance from the Earth to the Moon is 384,400 kilometers. So, you type it into your imaginary computer using 6 keystrokes for its 6 digits.

BINARY: But the computer must translate that distance to the binary number 1011101110110010000, which requires 19 transistors, one recording each 1 or 0 binary digit.

If you calculate something using that number against, say, the speed of light in meters per year, divide the result into prime factors, and test that result against a simple base number—you'll wait longer than the life of the universe for your answer.

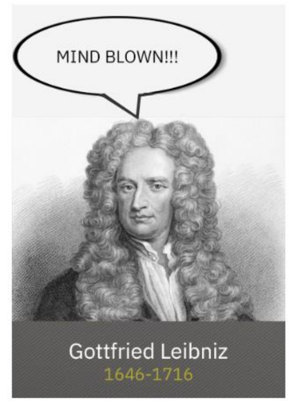


Unless Leibniz was wrong.

What if A could sometimes equal “maybe 0” and “maybe 1” at the same time? Two conflicting values? Is that possible?

It is—in quantum computing!

Read on to find out how, and why that matters.



Chapter 8: Can A equal both A and B?

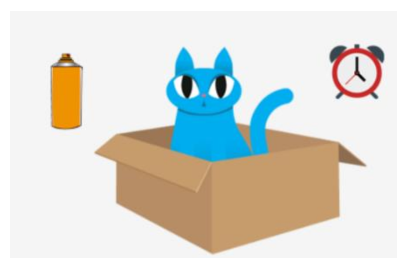
It seems impossible, but yes, “A” can sometimes equal two different things at the same time—under certain conditions—in the strange world of subatomic entities.

Which leads us to the concept of **superposition**. We’ll dig into this concept using a thought experiment.

Here’s our setup.

You’re looking at a comfy, cat sized box with our friend Schrodinger inside it.

Also inside is a timer that might, or might not, go *ding!* during the next few minutes. We have no way of knowing when it will sound!



Please admire the fashionable blue color of Schrodinger’s fur. But you’d better do it quickly, because if the timer goes off during our experiment this spray can will douse poor Schrodinger with orange paint!

We will close the box, and then we are unable to see what is happening inside.

Schrodinger is shrinking until our cat is the size of a single electron!

We wait…and wait…and wait…not knowing when the timer will go off…when suddenly…imagine that time freezes!

All the clocks in the universe stop for a moment to give you time to think about what's happening.

This is where the real, mind-bending experiment begins!

Let's start our thought experiment.

Remember, there's no pass or fail score for experiments. You just make your best hypothesis based on what know already, run the experiment to see what really happens, then learn from your results. Here goes!

Step 1: Hypothesis
The box is still closed. Maybe the timer went off or maybe it didn't. So, you predict that right now Schrodinger's fur is the color…

A. *Blue*
B. *Orange*
C. *Blue + Orange = Brown*
D. *All colors mixed together = White*

Step 2: Experiment
I bet this will surprise you. When you run the experiment, it turns out that none of the possible hypotheses are true!

Inside the box, before you open it to look, Schrodinger is really, truly, 50% ***all-orange*** *and 50%* ***all-blue*** *— at the same time. Schrodinger is in a state of maybe****: maybe this and maybe that!***

Step 3: Conclusion
Here's what I'm telling you. It's possible for a subatomic particle (or a subatomic cat) to exist in a state of probability, having two or more values at once without being settled on either one. This is called ***superposition****.*

Don't open the box. At least, not yet. Sorry to hold you in suspense, but we'll return to the cat-in-the-box mystery later in our tour.

I can tell you right now though that quantum scientists have found ways to zap a subatomic particle so that, like Schrodinger's fur in the box, it has **two sets of probable properties** instead of one definite property.

This is impossible in classical physics. An ice cube can't be sort of on fire and sort of freezing cold at the same time. But it's possible at the atomic level!

The mathematical idea that describes a subatomic particle in a superposed state is called a qubit. (a quantum bit)

Scientists are learning how to create qubits from subatomic particles like photons, or even microscopic atomic structures like diamond crystals. And whatever they're made of, qubits can calculate certain kinds of mathematical problems amazingly quickly!

Chapter 9: Qubits calculate exponentially faster

To see why superposed particles can calculate more quickly than transistors, we'll dig more deeply into what's happening when a subatomic particle has two sets of probabilities for a property superposed—in other words, when it's a qubit.

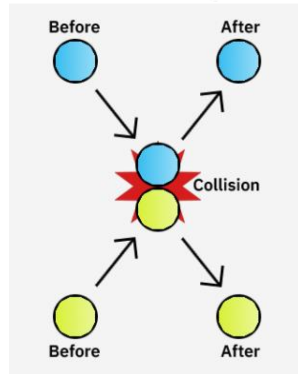
Keep in mind that this is relatively new science. We use math to predict how something like superposition works, but we don't know exactly how or why it works, at least, not the way we know that when a baseball hits a bat, the wood of the bat whacks the cloth of the ball and sends it soaring over the ballpark.

There are mysteries. Remember how classical physics said that matter and waves are different?

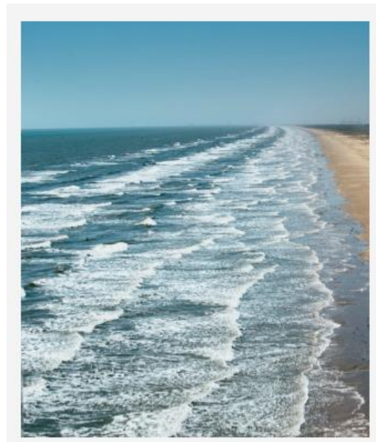
We now think that matter and waves are aspects of the same thing!

Here's a case where A really does equal A—but in an entirely new way.

Sometimes elementary particles act like they're made of matter. They can have mass, they can be in a particular place, and when they encounter other particles, they might change direction like tiny balls that bounce off something.

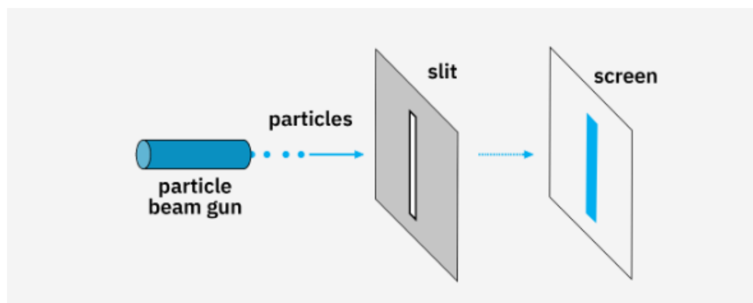


But sometimes elementary particles act, instead, like waves of energy, as if the fabric of the universe is wiggling up and down like waves on the ocean.

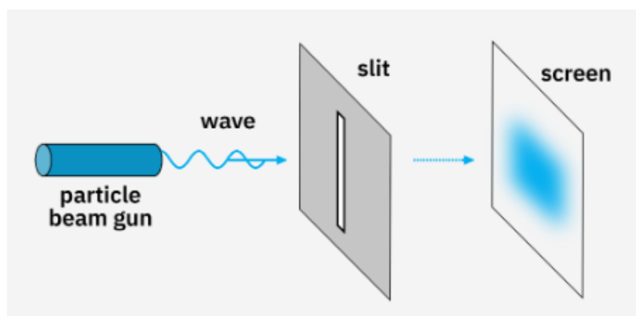


It's easy to see how differently matter and waves behave.

If you shoot a tiny bit of matter through a slit, it goes through in a straight line and hits a target at one point.



But if you send a wave through the same slit, it spreads out into a smear on the target.



Scientists are learning how to create qubits that hold double-state wave functions long enough to function like supercharged computer transistors.

These are the qubits that will perform calculations at blinding speed in tomorrow's quantum computers.

We've been saving the best part for last. Earlier you learned that a qubit can hold twice as much information as a transistor. That gives quantum computers an edge over classical computers.

But if you tie many qubits together using another property called **entanglement**, you can enormously amplify that advantage!

In the Entanglement Lab you'll experiment with subatomic behavior so strange that Albert Einstein, one of the most famous physicists of all time, called it "spooky!".

Before we enter the next lab, let's finish learning about superposition with a review quiz.

1. Which of the following really makes up a qubit?
    a. Mathematics
    b. Catnip
    c. Photons
    d. Electrons

2. Which of the following is a reason that some say that quantum physics defies Leibniz's Rule?
    a. A=A but UP=2
    b. Qubits are mathematical, not alphabetical
    c. Liebniz said that the simplest explanation for something is the most likely.
    d. A superimposed subatomic particle can have two contradictory sets ov value probabilities.

3. Superposition happens when a subatomic particle has which of the following?
    a. Spin
    b. Mass
    c. Uncertainty
    d. Dual sets of probability values

4. Inside the sealed, subatomic box, before the timer went off, what color was the cat?
    a. Probability values of orange and blue
    b. Blue mixed with orange
    c. Blue
    d. Orange

5. Which of the following is a qubit's most useful attribute for quantum computing?
    a. Radioactivity
    b. Spin
    c. Superposition
    d. Polarization

Join us on our next tour when we exit the Superposition Lab and enter the Entanglement Lab.