# Can you solve the prisoner&#39;s riddle?

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there is a riddle that is so  
counterintuitive it still seems wrong  
even if you know the answer here is the  
setup say there are 100 prisoners  
numbered 1 to 100 slips of paper  
containing each of their numbers are  
randomly placed in 100 boxes in a sealed  
room one at a time each prisoner is  
allowed to enter the room and open any  
50 of the 100 boxes searching for their  
number and afterwards they must leave  
the room exactly as they found it and  
they can't communicate in any way with  
the other prisoners if all 100 prisoners  
find their own number during their turn  
in the room they will all be freed but  
if even one of them fails to find their  
number they will all be executed the  
prisoners are allowed to strategize  
before any of them goes into the room so  
what is their best strategy if they each  
search for their own number randomly  
then each prisoner has a 50% chance of  
finding it so the probability that all  
100 prisoners find their numbers is  
equal to  
00000000000000 30 Z and then an eight to  
put this probability into perspective  
two people have a better chance of  
picking out the same grain of sand from  
all the beaches and deserts on Earth  
then by escaping this way with the right  
strategy there's a way to raise their  
chances to nearly 1 and three it  
improves their odds over random Chance  
by nearly 30 orders of magnitude so what  
is this mathematical strategy well if  
you don't already know the answer feel  
free to pause the video here and try it  
for yourself

# Why Did The Mars Helicopter Disappear?

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427 days into what should have been a 30-day mission, and it's turned into a nightmare.  
On the surface of Mars, 297 million kilometers away is Ingenuity, a tiny 680 gram helicopter.  
It's made from off-the-shelf parts you'd find at home.  
It's got bits from an Android smartphone, batteries from a cordless drill, and to everyone's surprise, it's been performing well so far.  
But something is wrong.  
See, the Martian winter is coming.  
At night, temperatures plummet to a frigid negative 85 degrees celsius.  
As Mars gets further away from the sun, the temperature keeps dropping, and it kicks up more and more violent dust.  
The sun is blotted from the sky.  
On her 427th day on Mars, they try to reach her, just like the day before, but they get no response.  
They try again, nothing.  
Back on Earth the team gathers at the Jet Propulsion Laboratory in Southern California.  
All the signs point to Ingenuity being dead.  
But there is still one thing, one final trick that can try to reestablish a connection.  
The first drone that's gonna fly on another planet.  
Six years ago, I visited JPL and saw Ingenuity before she left for Mars.  
At the time, NASA didn't really believe much in her mission.  
As Kenneth Farley, the project scientist of the Mars 2020 Perseverance mission said,  
I've personally been opposed to it...  
Spending 30 days working on a technology demonstration does not further the goals directly from the science point of view.  
In short, they thought it was a waste of time.  
Most projects to Mars get billions of dollars.  
Ingenuity got only 80 million, which is less than the budget of the movie The Martian.  
But this scrappy team of scientists were working to prove a crazy concept.  
And against the odds, they made it to Mars.  
On February 18th, 2021, the Perseverance Rover survives entry and lands on the Martian surface.  
Attached underneath is Ingenuity.  
This marks Sol Zero, her first day on Mars.  
They sever the umbilical cord and Ingenuity, affectionately known as Ginny by some on the team, prepares herself.  
Her mission is simple.  
Prove that flight on the red planet is possible.  
But with an atmosphere just 1% that of Earth, flying is really difficult.  
She must be ultra light, and her blades must spin at over 2,400 rotations per minute to generate enough lift.  
It's a design that no one is really sure about.  
For two months, they rigorously check her systems, running up the engine, testing navigation, and her control computer.  
Then, on Sol 58, they finally think they're ready.  
The blades spin up. And...  
she takes off, only 120 years after the Wright brothers on Earth.  
Humanity flies on another planet.  
Within days, they fly again, and then again, and again.  
In just one month, they complete five flights.  
So the mission has been accomplished.  
We were a tech demo, right, meaning a specified, narrow, 30-sol mission.  
Um, get in, get out, we're done, right?  
We go to a bar and party and that should be the end of it.  
But with success,  
comes new expectations.  
NASA tells them to keep going.  
Ingenuity's new mission is to assist Perseverance in the search for evidence of ancient life on Mars.  
So she will scout ahead, gathering data in areas too risky or costly for the rover to explore.  
For the team, this is great news, but it's also a problem.  
- There was no guarantee, you know, after flight five, we may be dead by flight seven, right?  
We may be dead by flight 10.  
We were kind of thrown into the deep end of the pool.  
We had no processes or no plans developed for such a thing.  
Until now, every flight had been carefully planned.  
They've all started from an area selected and analyzed by both satellites and the Perseverance Rover itself.  
These flights were tested hundreds of times in JPL's wind tunnel, and tens of thousands of times in simulation.  
But now that they have to keep up with the rover, they're flying into the unknown.  
Now, flying the helicopter isn't easy.  
At its closest, Mars is 56 million kilometers from Earth. Which means,  
there's at least a six minute round trip communications time delay,  
which is way longer than Ingenuity's two minute maximum flight time.  
So she has to fly autonomously.  
So what happens is the pilot programs in a route, and Ginny does the rest.  
But to start, JPL first needs to know exactly where she's located.  
You might think that they would use GPS, but for GPS to work on earth, you need at least 24 satellites for full coverage.  
And around Mars, there are only seven satellites total, so Ingenuity can't use this method.  
So instead what she does is far simpler.  
We have two cameras, a forward facing 13 megapixel camera, and then the one pointing down is the one that we use to navigate.  
The navigation camera takes 30 black and white images per second.  
Ingenuity's computer analyzes the image and identifies features on the surface.  
You can think of it sort of like an optical mouse.  
Like your optical mouse is on the mouse pad.  
It doesn't know where on the mouse pad it is, but when you move to the right, it knows you moved to the right.  
Because what it's doing is it's looking at features on the surface of the mouse pad and watching them move under its field of view.  
So Ingenuity is essentially doing the same thing.  
It's looking at the surface, it's picking out features like rocks and other things, and between camera images it says, oh, this rock moved this way, this thing over here moved this way, and from that you can compute a transform,  
to say my helicopter was here and now it's here relative to this image.  
Now this sounds good, but the method isn't 100% reliable.  
On Flight 6, the first time she leaves her testing area, Ingenuity detects an error.  
54 seconds into the flight, she starts wobbling wildly, tilting 20 degrees at a time.  
Her emergency alarms blare.  
We had black and white image, black and white image, black and white image, and we had a colored image come very closely to where that black and white image occurred in time.  
This color camera was added late in development, leaving little time for testing.  
And during this flight, one of the images arrives at the exact same moment as a black and white image.  
The system doesn't know what to do, so it drops the black and white image.  
This makes every following image one step behind.  
This means Ingenuity's cameras are giving her outdated information.  
So even when she's in the right spot, the computer thinks she's lagging behind and pushes her forward.  
So she overshoots, tilts too far, and then has to overcorrect in the other direction.  
This cycle repeats, making her wobble worse in a positive feedback loop.  
Now that is a problem, but it isn't fatal.  
The desyncing issue was like one camera frame off.  
If it had been more than that, I think you can imagine.  
imagine that it might have death spiraled.  
Instead, Ginny detects the problem and is able to emergency land before it gets too ugly.  
While safely on the ground, JPL discovers the error and quickly corrects it with a software patch.  
It's a close call, but they recover.  
Over the next dozen flights, they keep up with the rover and support the mission.  
That is, until Flight 19.  
We were about to fly that 19th flight, and I got a phone call the afternoon before, basically saying there's a dust storm brewing near Jezero crater.  
So we quickly canceled the flight and said well we're just going to hunker down and see what happens.  
They brace for impact.  
It lasts six days, with winds gusting up to 20 meters per second.  
That first dust storm in the middle of fall, the first Martian year that we were on the surface, it clobbered us.  
But... they make it through.  
Nervously, they try to make contact, and she survived.  
She hasn't died or toppled over, but now they have a new problem. Dust.  
Dust on Mars is no joke.  
I mean, for Ginny, there are two big problems.  
First, dust is covering her solar panels, reducing power by 18%.  
And second, it's clogging her mechanical components.  
We went to go fly, and when we went to wiggle the servos, they were actually stuck.  
They were kind of jammed from the dust.  
So that aborted the first attempt at flight 19.  
Now JPL had anticipated both of these problems, but they hadn't had the time or budget to fix them.  
So for the first, they just have to accept that they have reduced solar power and they adjust their flight durations accordingly.  
For the second, they find a workaround by repeatedly wiggling the servos until the joints clear.  
So she's able to keep flying, albeit wounded, and survival isn't getting any easier.  
See, every Martian night, the temperature drops precipitously.  
My friend Alex from the channel Astrum describes it well.  
With less atmosphere, Mars became far worse at retaining heat.  
When the surface starts to cool, there is no air to catch the escaping warmth.  
It is at the point where, if you were to stand on the planet's equator during its warmest time of the day, your feet might feel 23°C, while at your head, it would be 0°C.  
This means between day and night, Mars has some intense temperature swings.  
Temperatures there now range from highs of around 27°C down to a freezing minus 133°C at night.  
If you want to learn more about how this leads to entire planet-covering dust storms, Astrum has a whole video on the Martian climate.  
So these massive shifts in temperature are happening all the time.  
But as Ginny's mission progresses, Mars gets farther away from the Sun and enters the Martian winter.  
So it gets even colder at night, which is a problem.  
Many of Ingenuity's key electrical components are hand-soldered.  
And big temperature swings cause expansion and contraction of this metal, and so that can eventually break these connections.  
Also, inside the batteries, a liquid electrolyte solution allows lithium ions to move between the cathode and anode during charging and discharging.  
But if this solution freezes, JPL fears that the whole thing will stop working entirely.  
So what they do is keep all the components sensitive to the cold inside a warm box, which has resistance heaters that run during the night.  
You might spend 25 or 30% of your battery flying and the other 60 to 75% is all just staying warm at night.  
The problem is, the colder it gets, the harder the heaters have to work.  
And if they can't keep up, and the batteries cool too much, they become less efficient.  
So they supply even less power to the heaters.  
Performance can continue to degrade in a vicious death spiral.  
On the morning of May 3rd, the team at JPL goes about a normal day.  
They check the data from the previous downlink?  
Nothing.  
They try pinging ingenuity?  
Still nothing.  
Have they finally lost her?  
Did we just lose our $70 million helicopter on Mars?  
Is this the end of the mission?  
We thought this was it.  
So let's just make sure, before we close the door on ingenuity, we've thought of everything.  
Just keep working through it.  
They run through all the possible problems until they narrow it down to just one.  
The way she was designed, Ginny has an alarm clock that wakes her up.  
It stays awake for 15 minutes.  
If it doesn't hear anything after 15 minutes, it goes back to sleep, and it doesn't wake up until the next alarm.  
Their hypothesis is this:  
if the lack of sunlight forced Jenny to fully deplete her batteries, then during the night her heaters would have stopped and she would have powered off completely.  
When the sun rises, as long as her essential components still function, she may recharge enough to wake up.  
Only now her clock will have reset.  
So they run the calculations.  
If she's still alive based on when the sun comes up, she should be waking up at 11:45 a.m.  
Martian time.  
That is not the time they had been trying.  
So they change their search window and start calling out to Ginny around when they expect her to power up.  
They send out ping after ping until finally...  
she's alive!  
They check to see whether everything is still working.  
And despite the components in her warm box only being rated to negative 45 degrees, they survive being completely frozen.  
Well, all except for one.  
The inclinometer is dead.  
The inclinometer is what lets Ingenuity know her physical orientation in 3D space before flight.  
And that is pretty essential for getting the right heading.  
You can imagine if you're off in heading by 10 degrees, you could fly into a mountain.  
Without the inclinometer, there is no way for her to fly.  
So at first, the whole team is stumped, but then they have an idea because Ingenuity is made of phone parts, literally parts from phones people carry around every day.  
Her processor is from a Samsung Galaxy S5, and some of her sensors are from a Google Pixel 3.  
And these phones can do a lot of the things that an inclinometer can do.  
Inside every smartphone are at least three little micro-electromechanical systems aligned perpendicular to each other, like x, y, z.  
At their core is a small mass suspended by flexible arms.  
They work like springs and follow Hooke's law, F = -kx, where force is proportional to displacement.  
The mass also follows Newton's second law, F = ma.  
If you combine these equations, you get a = -kx/m.  
which links acceleration and displacement.  
Surrounding the mass are fixed arms.  
When a voltage is applied to the mass and arms, they form a capacitor, where epsilon and A stay constant, but as the mass moves, the distance between them changes with x.  
This alters the capacitance, which becomes more noticeable with multiple plates, hence why they have so many little arms.  
By measuring capacitance, you can determine displacement.  
And since displacement is proportional to acceleration, changes in capacitance allow us to measure acceleration.  
That's why these devices are called accelerometers, and by integrating acceleration over time, you can work out velocity and then position.  
This is how motion tracking works for screen rotation, gaming controls, and step counting.  
If you add gyroscopes, you get an inertial measurement unit, or IMU, and Ingenuity has the same IMU as the Google Pixel 3.  
So the team at JPL had an idea.  
They could reprogram the computer to use the IMU to replace the inclinometer.  
The inclinometer is really just accelerometers that allows us to tell the initial attitude of the vehicle in roll and pitch.  
And the IMU also has accelerometers, so in principle it gives you the same information.  
So from the clutches of failure, they get her running again.  
We got lucky in that the one instrument we could afford to lose was the one that died.  
But the IMU isn't space-grade.  
In fact, none of these off-the-shelf parts are, which means they're vulnerable to cosmic rays.  
On Mars, the thin atmosphere doesn't just make it harder to fly.  
It also means cosmic rays reach the surface more easily, and a single cosmic ray can strike a computer register and flip a bit inside the computer, which can lead to some strange behavior.  
It even happens here on Earth.  
It once added 4,096 unaccounted votes to a candidate in a Belgian election.  
Now on a Martian helicopter, flipping the wrong bit at the wrong time could mean losing control and crashing.  
So why doesn't that happen?   
If you'd asked  
somebody 10 years ago can you fly just the latest cell phone processor they'd be like no it'll last like two days and you'll be dead right  
It turns out that cosmic ray bit flips are not as big a deal as NASA thought.  
The off-the-shelf components hold up way better than they expected.  
And this is an important finding.  
Rather than going through all of the development cost of building up a processor from scratch to be radiation tolerant,  
our finding is you get a lot better bang for your buck by just going and basically buying batches of different processors and just qualling them.  
That means throw them through a radiation test campaign, look at the failure rates, figuring out,  
hey, this guy, we don't know why, but for whatever reason, this processor over here is great.  
It holds up, so we'll fly that.  
Now, using these surprisingly robust off-the-shelf parts, they survive the rest of the winter,  
but they're only barely able to stay within the communication range of the rover.  
-Springtime came.  
-Yeah.  
-The birds were chirping on the...  
-Talk about spring optimism, right?  
Like coming out of winter.  
With the increased sunlight, they can now fully recharge and return to their scientific mission.  
Over the next 41 flights, they image craters Perseverance can't make it to.  
They capture stunning images of the Martian horizon from above.  
they conduct daring aerodynamic tests and they begin to push the limits.  
They want to fly faster, but the faster they go, the quicker features move across the camera's field of view.  
And the vision navigation system just can't keep up with that.  
So JPL comes up with a solution.  
They fly higher.  
Then they can expand the field of view, which means features will move more slowly through frame.  
So, from an initial goal of a 10 meter altitude, they go up to 24 meters, and as a result,  
they're able to go from flying at 2 meters per second all the way up to 10 meters per second.  
Speed records, distance records, altitude records, just everything we could think of to push that flight envelope on Ingenuity,  
really make the most of this once-in-a-lifetime opportunity of having a helicopter on Mars.  
Everything is going swimmingly.  
Ginny and Perseverance have made it all the way to Nuretva Vallis, a river delta in Jezero Crater.  
But on Flight 71, there's a new problem, and it's worse than any of the ones that came before.  
Now, Ingenuity's only scientific payload is a camera, so she's taking hundreds of photos a day and sending them to JPL.  
And she's not alone.  
Perseverance does the same, including this selfie with Ingenuity.  
Honestly, they're the most chronically online duo on Mars.  
We always know exactly where they are, what they're up to, and they're constantly sharing photos.  
But really, how different is that from us?  
I mean, we spend most of our lives online, constantly sharing data.  
Except in our case, that data doesn't just sit in a NASA archive.  
It gets bought, sold, and used in ways we're not always aware of.  
That's why I've been using today's sponsor, Incogni.  
I created my account a year ago, and since then they've filed over 300 requests on my behalf,  
resulting in my data being removed from over 100 marketing and spam databases.  
If I tried to do that myself, it would have taken around 230 hours, literally weeks of work.  
That is time I can better spend making videos, which I'm sure you appreciate.  
So to try Incogni, visit incogni.com/veritasium.  
I'll put that link down in the description or you can scan this QR code.  
And when you do make sure to use code Veritasium to get 60% off your annual subscription.  
So head over to incogni.com/veritasium and protect your online data today.  
I want to thank Incogni for sponsoring this part of the video.  
And now back to Ingenuity.  
So we just had this one final thing to do.  
We needed to cross this sand dune and make it to Bright Angel to rendezvous with the rover.  
So on 71, we basically went up.  
We were flying.  
And then after about 10 seconds of flying with degraded navigation, we went into an emergency landing mode and sort of came down hard.  
They hailed Ginny and luckily she's still alive.  
In the error code they discover the problem.  
As she was flying over the dunes there just weren't enough rocks or landmarks for her camera to identify  
and without those references she quickly lost track of her position and had to make an emergency landing.  
It's similar to the camera issue from flight 6 but this time there's no software fix.  
They check for structural damage  
but suprisingly everything is still intact.  
So they attempt another flight, this time going straight up to scan the surroundings and then coming straight back down. Simple.  
We popped up, took pictures, and then on the way back down, we hit the same problems we did on 71.  
Only this time, it's fatal.  
Perseverance drives over and captures this image of her crash site.  
When we saw the blades broken, when we saw that first image after flight 72, that was heart wrenching.  
It was like, no, there's no way this mission can continue.  
That was very depressing.  
So why?  
Because 71 was also a crash landing for the same reasons.  
It was, you know, the NASA system was confused and drove us into the ground, but we came out of that apparently unscathed, and yet on 72, we self-destructed.  
This is the first air crash investigation on another planet, right?  
Yeah, that's right.  
First aircraft on another planet and then the first air crash investigation kind of go hand in hand.  
At the crash site, they find Ingenuity's blades scattered, but not in the way they expect.  
We noticed something interesting, which was there was no blade strike spot.  
Blades spinning this fast, when they hit the ground, right, they're going to create a spray.  
There's going to be a pattern, probably even visible from orbit, and we didn't see anything like that.  
So if the blades didn't strike the ground, then what happened?  
So this is an actual prototype blade from the development phase.  
This is essentially identical to the blades on Ingenuity.  
It's a carbon fiber composite with a foam core.  
It's incredibly light, if you want to feel it.  
Yeah.  
- Woah!   
That's actually great.  
That's like at least a quarter of what I expected just looking at it.  
It doesn't feel physical.  
So why did they break?  
Well, as the blades spin, the tips of the blades trace out a circle, which you can think of like a hula hoop.  
If there's a force up on the near side, you might expect the rotor to tilt immediately in this direction.  
But that is not actually what happens.  
See, the blade isn't stationary, it's moving really fast.  
So when you apply this force, it actually only moves after that point.  
So the maximum displacement occurs 90 degrees later.  
So, even though we push up on the near side, the blades tilt up on the right and down on the left.  
This effect is called precession, and it's the same principle that explains this spinning bike wheel demonstration.  
Now, Ingenuity has a second set of blades that are moving in the opposite direction.  
Which means that, when a force is applied, each set of blades experiences precession in the opposite direction.  
For the helicopter overall, these torques cancel out,  
but each individual blade still flexes because of that precession torque.  
That results in a stress concentration right about here where that final reinforcement tapers off.  
And so if you had a procession-based failure, you'd expect it to fail right here.  
And sure enough, that's exactly where you see it in the pictures.  
You can see sort of this jaggy place where the blade tip just got ripped off.  
So that is what happened on Flight 72.  
As Ginny came down hard, she hit a dune at an angle.  
The force was transmitted up through the body of the helicopter, and this created a procession torque that bent the rotors, and they snapped right where the reinforcement tapers down.  
This thing came down hard.  
It didn't destroy the landing gear.  
It didn't break the avionics.  
It didn't kill the servos.  
The swash plates are all fine.  
They're all intact.  
It's the rotors.  
That's the weak link.  
So that is the first thing they're changing on the next generation of Mars helicopter, which is called Chopper.  
You had a chance to hold the Ingenuity blade.  
This is the next-gen baby blade.  
It looks fairly similar with a couple of key differences.  
They reinforced the blades to withstand the torques caused by hard landings.  
Now they also have six rotors instead of two, which means Chopper can hold a lot, even carrying a scientific payload of its own.  
We've developed now a very lightweight radio that can communicate directly to orbit.  
Woah.  
So we're a free bird when it comes to exploring the planet now.  
-That's huge, that's huge!  
You were sort of trying to trail perseverance, right, and now you can go anywhere.  
Yep, we're our own spacecraft.  
In this blue box, you can shove about five kilograms of science payload and bring it anywhere on the planet on Mars.  
You can fly three kilometers per sol in a matter of minutes.  
That's really generated a lot of excitement in the science community.  
So this is a fifth scale model of Chopper.  
It's really two systems.  
So this is our Chopper platform, right?  
This is what's going to go on and explore the entire surface of Mars one day.  
That's the point of the concept.  
But underneath,  
is a mid-air helicopter delivery platform.  
See, Mars rovers all need complex sky cranes to land, but a helicopter is different.  
It just needs a platform to take off from.  
So the idea is we come down through the atmosphere, we have this jet pack that we need to slow us down to get us down to a regime that is controllable  
so that we can take off from that platform midair and land under our own power.  
For this, it needs rockets.  
3, 2, 1...  
Awesome!   
You're envisioning like a future of aviation all over Mars as a primary explorative.  
In my mind, it's absolutely going to happen in just a matter of time.  
There will be fleets flying, you know, throughout Mars.  
There will be airports on Mars one day, and we'll have aircraft the size of Chopper, more aircraft the size of Ingenuity, and even bigger than Chopper.  
NASA is thinking big thanks to Ingenuity, a project they once doubted.  
Because Ginny showed what is possible.  
In 1890, if you had said, I'm gonna fly, it's like, okay, that kooky guy in his garage, he thinks he can fly, he's gonna kill himself, right?  
After the Wright brothers, it's like, oh, okay, yeah, this is the thing that we're gonna do.  
And so that's the change in mentality that's occurred because of engineering.  
That's why, still sitting there on the surface of Mars, attached to the underside of Ingenuity is a tiny scrap, one square centimeter of muslin fabric.  
It was taken from the lower left wing of the first airplane, the right flyer.  
From the first flight on Earth, to the first flight on another planet.  
From Ingenuity's grave on Mars, her spirit lives on.  
Except...  
she isn't quite dead yet.  
She's acting as a weather station now, capturing photos every day, capturing temperature measurements every day, something no one would  
have ever predicted before flight 72 that if things don't go well, we just still have a functioning spacecraft.  
So she's a tank.  
The team couldn't be more proud of what Ingenuity's accomplished.  
Thanks for watching.

# Something Strange Happens When You Trust Quantum Mechanics

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As a 42 year old who's  
spent most of my life studying physics,  
I must admit  
that I had a big misconception.  
I believed that every object  
has one single trajectory  
through space, one single path.  
But in this video, I will prove to you  
that this is not the case.  
Everything is actually exploring  
all possible paths all at once.  
So let's start with a simple thought  
experiment.  
Say you're at a beach when all of a sudden  
you see your friend  
struggling out in the water.  
You want to go help them  
as quickly as possible.  
So which path  
should you take to get there?  
The shortest path is a straight line,  
so you could head directly towards him.  
But you can run faster than you can swim,  
and this path requires more swimming.  
So alternatively,  
you could run down the beach  
to minimize the  
distance through the water.  
But now  
the total  
distance is longer than it needs to be.  
So the optimal path,  
it turns out, is somewhere in between.  
To be precise, it depends on the speeds  
at which you can run and swim.  
Now, you might recognize this  
mathematical relationship because it is  
the exact same law that governs light  
passing from one medium into another.  
So light also takes the fastest  
path from point A to point B.  
What's weird about this is that as humans,  
we can see where we want to go  
and then figure out the fastest route.  
But light, I mean, how does light know  
how to travel  
to minimize its journey time?  
Now here is where  
my misconception comes in.  
I shine a laser beam.  
The light just goes in one direction.  
I throw a ball.  
The ball just goes in one direction,  
you know?  
I would have answered,  
there is nothing strange about this.  
Light sets off from point A  
in some direction.  
And then a little while later  
it encounters a new medium.  
And due to local interactions  
with that medium,  
it changes direction,  
ending up at point B.  
If you later find that of all the possible  
paths, light took the shortest time  
to get from A to B, I wouldn't  
think it was optimizing for anything.  
I would just think that's what happens  
when light obeys local rules.  
But now I will prove to you that light  
doesn't set out in only one direction.  
Instead, it really does explore all possible paths.  
And the same is true for electrons  
and protons.  
All quantum particles.  
So the fact that we see things on single,  
well-defined trajectories  
is, in a way, the most convincing illusion  
nature has ever devised.  
And the way it works all comes down to a  
quantity known as the action.  
In a previous video, we showed  
how an obscure scientist, Maupertuis,  
made an ad hoc proposal  
that there should be a quantity  
called action, which he defined  
as mass times velocity times distance.  
And he claimed that everything  
always follows the path that minimizes  
the action.  
Hamilton later showed that this action  
is equivalent to the integral  
over time of kinetic energy  
minus potential energy.  
Action was useful and an alternative way  
of solving physics problems,  
especially when Newton's laws  
get too cumbersome.  
But then, around the turn of the 20th  
century, action showed up at the heart  
of a scientific revolution:  
the birth of quantum mechanics.  
It all started with electric  
lighting in Germany.  
Think about what it's like in the 1890s,  
right?  
Electricity being more widely available,  
at least in urban sectors.  
And things like, you know, light bulbs.  
They were new.  
They were literally the hot new thing.  
Germany wanted to replace all their gas  
street lights with electric light bulbs.  
So an important question was  
how do you maximize  
the visible light  
given off by a hot filament?  
Scientists at a German research  
institute, the PTR, studied  
how much light different materials  
emitted as a function of temperature.  
At low temperatures, each material  
gave off its own characteristic spectrum,  
mostly in the infrared,  
but above about 500°C  
all materials started to glow  
in the same way,  
with an almost identical  
distribution of light.  
The hotter the object,  
the more energy was emitted  
at every wavelength, and the peak  
of the distribution shifted to the left.  
But they still didn't understand  
how it worked theoretically.  
So that was sort of the next step, right?  
If you can understand how it works  
theoretically,  
then you can use that theory  
to potentially design your products.  
They started by imagining  
the simplest object possible,  
one that would absorb all light  
that falls onto it  
and perfectly emit radiation  
based on its temperature.  
They came up with a hole in a metal cube.  
This hole is a perfect blackbody  
because any light that shines onto  
it will go straight in, bounce  
around inside, and eventually be absorbed.  
But this also makes it a perfect emitter.  
Any radiation inside the cube can escape  
through the hole unimpeded.  
Theorists reasoned that electrons  
in the walls of the cube  
would wiggle around,  
emitting electromagnetic waves.  
These waves  
would then bounce off the other walls.  
When you have two waves  
of the same frequency,  
where one travels to the right  
and the other to the left,  
they can interfere in such a way  
that they create places  
where there's no wave amplitude  
those are nodes, and places where there is  
maximum wave amplitude,  
the anti nodes. Waves like this are called  
standing waves  
because they don't really move left  
or right  
and inside a cavity,  
given enough time and reflections.  
It is only these standing waves  
that survive.  
All the other ones just cancel out.  
So a sort of order emerges from the chaos.  
In two dimensions, standing waves  
look something like this.  
For shorter wavelengths  
or higher frequencies, you can fit more  
and more different vibrational modes.  
Inside this cube,  
so that in three  
dimensions, the total number of modes  
is proportional to frequency cubed,  
or one over lambda cubed.  
The expectation was  
there would be more and more waves  
inside the cube,  
the shorter the wavelength.  
This led directly to the Rayleigh-Jeans law.  
At longer wavelengths.  
It matched the experimental data  
pretty well,  
but at shorter wavelengths  
the theory diverged from experiment.  
In fact, it predicted  
that at the shortest wavelengths,  
an infinite amount of energy  
would be emitted.  
This, for obvious reasons, became known  
as the ultraviolet catastrophe.  
The person to solve  
this problem was Max Planck,  
but Planck almost didn't  
make it into studying physics,  
because when he was 16 years old,  
he went up to his professor and asked him,  
well,  
maybe I could do a career in physics.  
To which his professor responded  
that he'd better find another field  
to do research in, because physics  
was essentially a complete science.  
You know, there was just a few tiny  
little problems that they had to clean up.  
But besides that, it was over.  
But Planck didn't listen.  
By 1897, he was a professor himself,  
and for the next three years he struggled  
to find a theoretical explanation  
for blackbody radiation.  
He tried approach after approach,  
but no matter what, he tried.  
Nothing worked.  
He said I was ready to sacrifice  
every one of my previous convictions  
about physical laws.  
Then, in a quote ‘act of desperation’,  
he did something  
no one had thought to try.  
According to classical physics,  
the energy of an electromagnetic wave  
depends only on its amplitude,  
not its wavelength or frequency.  
And it could take any arbitrary value.  
So any atom could emit  
any wavelength of light  
with an arbitrarily  
small amount of energy.  
But Planck tried restricting the energy  
so that it could only come in multiples  
of a smallest amount.  
A quantum.  
And he made the energy of  
one quantum  
directly proportional to its frequency.  
E equals hf, where h is just a constant.  
Think about what this does  
to the radiation coming from the blackbody  
at a given temperature.  
The atoms in the cavity  
have a range of energies.  
Some have a little bit.  
A few have a lot, and most of their energy  
somewhere in between.  
For long wavelength  
low frequency radiation, the energy  
HF of one quantum is small,  
so all of the atoms have enough energy  
to emit this wavelength,  
and the spectrum matches  
the really gene's prediction very well.  
But at shorter  
wavelengths, higher frequencies,  
the energy of a quantum increases.  
And now not all of the atoms have  
enough energy to emit that wavelength.  
This is why experiment diverges  
from the classical prediction.  
The spectrum peaks  
and then starts to fall because fewer  
and fewer atoms have enough energy  
to emit one quantum of that radiation.  
And there comes a point  
when none of the atoms have enough energy  
to emit one quantum.  
So here the spectrum must drop to zero.  
With this approach, Planck got a new formula  
for the radiation spectrum.  
Now all that was left for him to do  
was to tune the parameter h.  
And when he did this just right,  
he got his formula to match up  
perfectly with experiment.  
But he was sort of troubled  
by his own formula because to him  
it was just a mathematical trick.  
He had no clue why it worked.  
It was purely formal.  
And most importantly,  
he had no clue what this H represented.  
I mean, he had introduced a new  
physical constant without any reason.  
He wrote a theoretical interpretation  
had to be found at any cost,  
no matter how high.  
So from that moment  
on, he dedicated himself to finding one.  
He later reflected that after some weeks  
of the most strenuous work of my life,  
light came into the darkness  
and a new undreamed of perspective  
opened up before me.  
He introduces  
what we now call Planck's constant,  
and it has the units of action. Planck's  
constant, h  
is a quantum of action.  
Planck later proposed that any time  
any change happened in nature,  
it would be some whole multiple  
of this quantum of action.  
So it's kind of spooky, this breakthrough  
that starts the ball rolling toward  
quantum theory brings action in not energy  
and not force. Action. Gives you a hint.  
At first, the quantum of action  
got little attention.  
That is, until a 26 year old patent clerk  
came on the scene.  
In 1905, Albert  
Einstein claimed that Planck's theory  
wasn't just a mathematical trick.  
It was telling us  
that light actually comes in discrete  
packets,  
or photons, each with an energy HF.  
Einstein used this insight  
to explain the photoelectric effect  
how light can eject electrons from metal,  
but only when  
the frequency is high enough.  
If the frequency is too low,  
no electrons will be emitted  
regardless of the intensity.  
The idea of quantization spread.  
Eight years later,  
Niels Bohr was trying to understand  
how an atom is stable  
if it has a positive charge in the center  
and negative electrons whizzing around it.  
Why don't they just spiral  
into the nucleus, radiating their energy  
as they go?  
And what he wants to do is,  
he says there's something fishy  
about something being discrete  
that seems to be the new ambiguous weirdo  
lesson of the new quantum of action. Bohr  
realizes that as the electron  
goes around the nucleus,  
it has an angular momentum.  
Mass times velocity times radius.  
So angular momentum  
has the same units as action.  
And so what he decides to do is discretize  
the orbital angular momentum.  
For no good reason  
he says, let me slap that on and say,  
and imagine the electron can only be in  
one unit, two units,  
three units of the same quantity H.  
And because it's talking about motion  
in a circle, the factors two pi come in.  
So is really nh over two pi,  
what we now call an h bar.  
This comes out of nowhere.  
There seems like  
absolutely no good reason why  
angular momentum should be quantized.  
But by doing it, Bohr finds the correct  
energy levels of the hydrogen atom.  
When an electron jumps from a higher orbit  
to a lower one, the energy difference  
is given off as a photon  
of a particular color of light.  
Exactly reproducing the hydrogen spectrum.  
And that was a pretty startling thing  
to have fall out.  
I think that really was compelling.  
Take some quantity with the unit of action  
and apply some, again, kind of ad hoc,  
discretization or quantization to it.  
Now, although it worked  
spectacularly well,  
no one can make sense of it.  
That is until 11 years later.  
For his PhD,  
Louis de Broglie was contemplating  
the recent discoveries in physics.  
And his big insight was that if light  
could be both a wave and a particle,  
then maybe matter  
particles could also be waves.  
He proposed that everything.  
Electrons, basketballs, people,  
absolutely everything has a wavelength.  
And he defined this wavelength  
analogously to light as Planck's  
constant,  
divided by the particles momentum or  
mass times velocity.  
Now, if an electron is a wave,  
the only way it could stay bound  
to a nucleus in an atom is  
if it exists as a standing wave.  
That requires  
that a whole number of wavelengths  
fit around the circumference of the orbit.  
You could have one wavelength  
or two wavelengths or three, and so on.  
So the circumference two pi  
r must be equal  
to some multiple n times the wavelength.  
We can sub in de Broglies expression  
for the wavelength to get the two pi  
r equals NH over mv,  
but we can rearrange this to get the mvr.  
The angular momentum  
is equal to NH over two pi.  
That is  
precisely Bohr's quantized  
angular momentum condition.  
But now we have a good physical reason  
why it's quantized.  
Because electrons are waves  
and they must exist as standing  
waves to be bound in atoms  
because they want to have constructive  
interference, have a stable orbit back.  
That's pretty good.  
You get a dissertation out of that.  
That's pretty good.  
It is this wave nature of quantum objects.  
That means they no longer  
have a single path through space.  
Instead,  
they must explore all possible paths.  
Now, I have thought about  
and taught the double slit experiment  
hundreds of times  
without fully realizing this implication.  
In the double slit experiment.  
I feel like the mental thing  
that I'm doing in my head is like, okay,  
well, the beam is not perfectly straight,  
and of course it's going to intersect  
both of those slits because they're really  
close together. You know?  
But then  
I heard this story about a professor  
teaching the double slit experiment,  
and it makes everything so clear.  
So the professor starts by explaining  
the setup.  
Electrons are fired one at a time  
through two slits  
to be detected at a screen.  
Now, because you can't say for certain  
which slit the particle went through,  
quantum mechanics tells us  
it must go through both at the same time.  
So to get the probability of finding  
a particle somewhere on the screen,  
you simply add up  
the amplitude of the wave  
going through one slit, with the amplitude  
of the wave going through the other slit  
and square it.  
But that's when a student raised his hand.  
What if you add a third slit?  
Well, you just add up the amplitudes  
of the waves  
going through each of the three slits,  
and you can work out the probability.  
The professor wanted to  
continue,  
but then the student interjected again.  
What if you add a fourth slit and a fifth?  
The professor, who is now clearly losing  
his patience, replies, I think it's clear  
to the whole class that you just add up  
the amplitudes from all the slits.  
It's the same for six, seven, etc.  
but now the bold student  
pressed his advantage.  
What if I make it infinite slits  
so that the screen disappears?  
And then I add a second screen  
with infinite slits  
and a third and a fourth.  
The student's point was clear.  
Even when we're not doing  
a double slit experiment,  
when it's just light or particles  
traveling through empty space,  
they must be exploring all possible paths.  
Because this is exactly how the math  
would work if you had infinite screens,  
each with infinite slits.  
You have to add up the amplitude  
from each slit.  
That's just the way it works.  
According to the story,  
the student was Richard Feynman,  
and while the story is made  
up, the logic is flawless.  
Because if you believe  
in the double slit experiment  
that you can't tell which of the two slits  
the particle went through,  
then you have to consider the possibility  
that it goes through both.  
By that same logic, any time  
any particle goes from place  
one to place two.  
You have to consider  
all the possible paths  
it could take to get there, including ones  
that go faster than the speed of light,  
including ones that go back in time,  
and including ones that go  
to the other side of the moon and back.  
I feel like I can't go to the sun  
and back.  
You have to restrict it  
to be local, right?  
So the math doesn't do that.  
I mean, you could see that  
just in the double slit experiment, right?  
And we'll do light because then there's  
no funky business with the speed.  
If you're going to say like,  
this path interferes with this  
path and these distances  
are different, right.  
And so clearly  
they can’t have the same speed.  
So you need to consider  
paths that have different speeds.  
Feynman's way of doing quantum mechanics  
suggests that anything going from  
one place to another is connected  
in every possible way.  
And the internet is kind of like that too  
connecting us to anything,  
anywhere, at any time.  
At least in theory,  
there are still artificial barriers  
like geo blocks and country restrictions  
that block off parts of the internet.  
But fortunately, there's today's sponsor,  
NordVPN, which can help knock down  
those barriers.  
Just connect to one of their thousands of  
servers, for example, this one in the US.  
And it looks as if you're accessing  
the internet from there.  
The team and I   
travel a lot to make these videos,  
and using a VPN is a game changer.  
It allows us to access the news sites   
and articles we need, no matter  
where in the world we are.  
And personally, I also love that NordVPN  
allows me to stay up  
to date with how the Canucks  
are doing back in Canada.  
Not very well at the moment.  
Canucks have a real shot  
at the Cup this year.  
But to try NordVPN  
for yourself,  
sign up at nordvpn.com/veritasium.  
Click that link in the description  
or scan this QR code.  
And when you do,  
you get a huge discount on a two year plan  
and an additional four bonus months  
for free.  
It's the best deal and it also comes  
with a 30 day money back guarantee.  
So head to nordvpn.com/veritasium  
to try it out risk free.  
I want to thank NordVPN  
for sponsoring this part of the video.  
And now let's get back to Feynman's crazy  
way of doing quantum mechanics.  
So according to Feynman,  
any time a particle, a photon, or even a  
macroscopic object moves from point 1 to point 2,  
it has some chance to take any path.  
And as preposterous as it might sound.  
He found that we need to include  
all these paths in our calculation,  
where each path is weighted the same.  
So why  
then, do we not see all those crazy paths?  
Well, that's because we still need  
to add up their amplitudes.  
For simplicity,  
imagine we only have three paths.  
Then here's what we're going to do.  
First, let's take this one.  
When the particle wave starts  
following it, we start a stopwatch.  
It goes around and around very fast,  
and when it gets to the end point,  
we hit stop.  
We'll do the same for the other two paths.  
And then we add up  
the arrows, square the result.  
And that is  
then proportional to the probability  
the particle took those paths  
to get there.  
In this case  
the arrow and square are pretty small, so  
the probability of the particle going from  
1 to 2 using these paths is small.  
Compare that with these three paths.  
For example.  
Well now the arrow is much larger.  
And this is important.  
The larger the resulting arrow, the higher  
the probability of that event happening.  
Now in these examples the stopwatch is not  
actually measuring time.  
Instead it measures  
something called the phase.  
Just as in the double slit experiment,  
when a wave takes a different path  
from point 1 to 2, it will end up there  
with a different phase.  
And this phase is what determines  
the amplitude of the wave at that point.  
Mathematically, we can write the amplitude  
our stopwatch as e to the I phi,  
where phi is the phase.  
As the particle wave follows a path,  
its phase increases.  
Winding the vector around.  
So now the big question is how much  
does the phase change for each path?  
Well, to answer that, imagine  
we split up the path into many tiny  
sections, each one  
so small that it's effectively straight.  
Then in each  
section, the particle wave goes  
a distance delta x and a time delta t,  
and the increase in phase  
is easy to compute.  
It just depends on the wavelength  
and frequency of the wave.  
To find the total increase in phase  
for the whole path,  
we just add up all the little phase  
increases of all the individual sections.  
But we can sub in lambda equals  
h over mv from de Broglie,  
and using e we can sub in for frequency.  
We can also simplify by writing h over two  
pi as h bar.  
To get this expression.  
Then we can take delta t to the right.  
And if we make delta  
t infinitesimally small,  
then we can replace this  
sum with an integral.  
But now Dx by Dt is just velocity.  
So we can write this as m b squared.  
Now we know that in the simplest case  
the total energy  
e is just kinetic plus potential energy.  
And subbing that in we're left  
with the integral  
over time of kinetic energy  
minus potential energy.  
But wait a second.  
That is just the classical action.  
So it's action that determines  
how fast the stopwatch turns.  
As the particle moves along a trajectory,  
its action increases,  
and that is what increases the phase.  
And what's important to note is that h  
bar is tiny.  
It's about ten to the -34 joule seconds,  
which is way  
smaller than the action  
of any everyday object.  
That means the phase of ordinary objects  
on ordinary paths  
spins around zillions of times,  
eventually pointing  
in some random direction.  
If you consider a slightly different path,  
the action may be slightly different  
say 0.01 joule seconds different.  
That doesn't seem like much,  
but divide it by h bar  
and the arrow will spin around  
ten to the 32 more times.  
So again, it will just point  
in some random direction.  
This is what  
happens  
to almost all of the possible paths.  
So when you add up the phases,  
they just cancel out.  
They destructively interfere.  
The only exception is for the paths  
closest  
to the path of least action,  
because these paths are at a minimum.  
So if you make tiny changes to the path  
to first order,  
the action doesn't change.  
And so for other paths that are very close  
to the path of least action,  
their arrows point  
in basically the same direction.  
They constructively interfere.  
And that is why those are the paths  
we see.  
This explains how light knows where to go.  
I mean, it doesn't.  
It just explores all possible paths,  
but the past we end up seeing are the ones  
that interfere constructively.  
And those are the paths of least action.  
So really,  
this is how classical mechanics emerges  
from quantum mechanics.  
It's why a ball follows the trajectory  
it does, and how planets orbit the sun.  
They don't really have a precise  
trajectory.  
Instead, everything explores  
all possible paths.  
It's just that massive particles  
have large actions compared to hbar,  
so that only paths extremely close  
to the true path of least action survive.  
Which is why they're much more particle  
like.  
If you go to much smaller particles  
like electrons or photons,  
the actions are much smaller,  
and so there's more of a spread  
in which trajectories  
they actually end up taking.  
Now, you might say,  
I still don't believe you,  
but Casper has this incredible demo  
that should convince you 100%  
that this is really how the world works.  
To do it, I've taken a light,  
a mirror and a camera.  
Now there are infinitely many paths  
that the light could take.  
And according to Feynman,  
we have to add the contributions of each them.  
Including paths that go like this.  
Now, you might say he's crazy.  
I'm not crazy. That's what happens.  
Another possibility is I could come here  
and go.  
Or it could come here and go.  
Or it could come  
where you'd like it to come and go.  
And it can go over here  
and go and so on and so on.  
And these are all possibilities.  
And every single one of these paths  
has their own little arrow.  
So what we can do is we can look at all  
those arrows and see where they line up.  
And so if I turn on this light,  
that's exactly where you see it reflects  
that at the angle of incidence  
is equal to the angle of reflection.  
But now what I'm going to do  
is I'm going to cover up that spot  
so that we no longer  
see the light reflect.  
And then I'm going to prove  
that really Feynman is right.  
That really light  
also goes like this.  
It's just that most of the time,  
those effects are cancelled out.  
Now that sounds impossible, right?  
But let's zoom in to this tiny piece  
right here.  
Then we see all these different paths  
and all the arrows just go around  
and around in circles.  
So when you add them up,  
they all just cancel out.  
But what if I cover up about half of them  
like so.  
Well, now when I add up those arrows you  
suddenly do see a large resulting arrow.  
And so if I can somehow cover up  
this mirror in many, many tiny strips,  
then I should be able to get the light  
to reflect like this.  
And I can do that with this piece of foil  
right here on this piece of foil.  
There are about a thousand lines  
per millimeter, and that should be enough  
to get this effect.  
So let me turn off the lights.  
So let's see  
I'm going to turn it on in 321.  
We see it.  
That is so cool.  
It actually looks a lot weirder  
than I was expecting it to.  
I was expecting more like, one spot,  
but there's many, many spots  
where it's reflecting.  
Oh, okay. Okay.  
And just to show,  
I haven't been cheating you, right  
underneath is my finger.  
And even with the light  
on, you know, we see the light reflect.  
And if we remove the cover,  
then what do we see?  
Yeah, we see exactly the normal reflection  
where it's always supposed to go,  
which is right there.  
And then we've got  
now all these extra reflections,  
all these extra bits  
where the pattern just lines up.  
So very, very cool.  
When I was talking about this  
with a friend, actually,  
he said, yeah,  
but you're using a diffraction grating.  
That's kind of like cheating.  
You get all these other reflections  
right now  
and this light is just  
going in all directions.  
And so there's one other thing.  
I've been super, super curious to try.  
I also want to do this with a laser  
where I shine the laser right next to it.  
And then if light does take every possible  
path, we should also see it  
come off here.  
It probably shouldn't work.  
I actually have a laser right over here  
and we can see when I shine it.  
It really does.  
Just go to one spot  
and you can see where that spot is.  
It's right over there, which is about the  
same place where we had our reflection.  
And you can also see right now if  
we look at this view that you cannot see  
the laser light at all.  
Right.  
Like I could see the laser, but I have to  
bring it out all the way over here.  
And then I'm able to sort of  
see the light.  
But if I just put it up here,  
you can see the reflection.  
Now, what I'm going to do next  
is I'm going to put  
this foil, this magic foil,  
and I'm going to put it over here  
and we can turn off this.  
And now let's see what happens  
when I turn on the laser.  
Wait wait wait wait.  
No way,  
no way.  
It works.  
It works. Wait. What?  
Look where the laser is going.  
Oh, my God, it actually works.  
What? What?  
This is definitely the coolest demo  
I've ever done.  
So what I was doing is I was holding  
the laser, and I can show you right now.  
I was shining it down, like, this way off.  
And you could still see it reflect.  
But if I take this away, it disappears.  
And if I put this back, it appears  
so that it shows really that we cannot  
get rid of the area which gives zero  
that it really is canceling out.  
And if we do clever things to it,  
we can demonstrate the reality of the  
reflections from this part of the mirror.  
So light and by extension,  
everything really does  
explore all possible paths.  
It's just that most of the time  
the crazy paths destructively interfere.  
That's because the actions of nearby paths  
change rapidly.  
Now, I've studied physics  
for most of my life,  
and I feel like I never really appreciated  
how important action  
and the principle of least action are.  
But now I think I finally get it.  
And I finally get why.  
If you ask theoretical physicists  
what they're working  
on, they'll rarely talk about energy  
or forces.  
Most of the time,  
they'll talk about action.  
Nobody in particle physics approaches  
particle physics  
from a viewpoint other than least action.  
But we teach physics historically,  
and no least action  
is almost like the new kid on the block  
for understanding physics.  
And so, yeah, we build up to it.  
But in reality,  
I think life's a lot easier once  
you realize this underlying principle,  
because when you do,  
then all you have to do is write down  
the correct Lagrangian  
so you get the right action and out come  
the laws of physics.  
So you've got a separate Lagrangian  
for classical mechanics,  
for special relativity,  
for electrodynamics, and so on.  
It's a single mathematical framework  
that, once you've learned it,  
then you can apply it in different places  
in exactly the same way.  
The hunt  
for the theory of everything, right.  
The thing that will encompass  
all of physics  
in reality, what people are asking is  
what is this Lagrangian  
that can spit out all of the laws  
of physics in this universe?  
That's really what they're asking.  
The moment  
we haven't really found that right.  
Because we can  
we can sticky tape things together,  
but we don't know if that's the proper  
mathematical structure.  
So that's what people are hunting for.

# The Google Interview Question Everyone Gets Wrong

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There is this famous Google interview  
question that everyone gets wrong.  
You're shrunk down to the size of a nickel  
and put into a blender.  
The blades will start spinning in 60 seconds,  
so what do you do?  
I would like to think I could duck down  
and miss the blades  
Break the thing at the bottom maybe?  
Push the blades?  
Ask nicely for the blender  
not to be turned on.  
Tie my clothes together, and then like  
use it as a rope I guess?  
If I was lighter I could maybe catch a draft up?  
- Just accept defeat.  
- I mean, I'm the size of a nickel  
what quality of life is that?  
Okay, resonance.  
I'm going to run to one wall,  
push on it, run to the other wall. Push on it.  
Run to the other wall, so  
I'm going to tip the container over.  
Honestly, the thing I would think about  
is trying to get to the very center  
of the blades.  
It's spinning around me, but  
the actual RPM is probably not that high,  
if I'm standing in the middle.  
I tie my clothes to one of the tips  
of the blades as it’s starting up.  
Yeah, I get it to swing  
me around and then I woooo!  
But these answers don't cut it.  
Now, I first heard about this problem  
in this book.  
It describes how each year Google received  
about 3 million applications,  
but they would only hire 7000 people.  
That's a 0.2% acceptance rate.  
So one way to screen out  
millions of applicants was to use brainteasers,  
and the interviewers  
would make these up for fun.  
We didn't get a list, at that time of  
what questions to ask.  
We would share questions among each other.  
Some of them gained traction,  
questions like:  
How many golf balls can fit in a 747?  
Or, how much should you charge  
to wash all the windows in Seattle?  
But the blender question  
really stuck with me, and I'm not alone.  
- Just lay back and enjoy that breeze.  
The best model in the world is only going to  
run maybe 10 or 11 hours,  
so we're getting out and when we do, we're better off for it because whatever doesn't kill you makes you stronger.  
- The question has been hotly debated  
in Reddit comment sections.  
There are so many different answers,  
but which one is the best?  
I try to hide underneath the blades,  
I guess.  
Hide under the blade, probably  
Great first reaction,  
but maybe that doesn't solve your problem  
entirely.  
Now you're just stuck inside of a spinning  
blender, so maybe you want to escape.  
Can I climb the walls?  
Are there defects in the walls that are  
sufficiently large for me to grip on to?  
Do I have Van der Waals forces that are  
strong enough to connect me to the wall?  
Am I, like, essentially a tiny gecko?  
A gecko can stick  
to the wall of a blender,  
even though neither its foot, nor  
the glass are charged.  
The gecko's foot has to be pressed  
firmly against the glass,  
so its atoms are within a few nanometers  
of the glass atoms.  
Then, at any moment one atoms electrons  
aren't uniformly spread about the nucleus,  
they might be slightly more on one  
side than the other.  
This makes the atom momentarily  
slightly positively charged  
on one side and slightly  
negatively charged on the other.  
The glass atom next to it experiences  
the pull of this charge imbalance,  
and so a similar charge  
imbalance is induced on the glass atom,  
and therefore the electrons in the glass  
atom are drawn  
to the nucleus of the gecko  
atom, and vice versa.  
So there is a very weak attractive force  
between neutral atoms.  
This is known as a Van der Waals force,  
and it's what makes geckos stick to walls.  
It's the same force  
that holds graphite together.  
There's no actual bonding between  
the layers of graphene in a pencil.  
It's like a stack of paper.  
The layers only stick because of Van  
der Waals forces.  
Now these forces are pretty weak.  
But since we're so small, maybe  
they'd be enough to help us climb out.  
This I can almost certainly say,  
we wouldn't be sticking at that scale,  
and that's because the Van der Waals  
type interactions are still small.  
And I studied climbing, so that of these types of  
scale, cockroach and gecko, you know,  
it turns out that you have to get  
very special to do that.  
Geckos have millions of tiny  
branches on their feet that increase  
their surface area  
and allow them to mold to surfaces.  
Our hands aren't like that,  
but ants and cockroaches  
don't rely on Van der Waals forces,  
and they can still climb up walls.  
So maybe a miniature human could too?  
The mechanism of a cockroach foot,  
and I used to know all that  
cockroach feet, is absolutely gorgeous,  
Same with an ant, by the way.  
There's two little claws, the tarsal claws  
those are things  
that slap down on a surface and really do slap  
when climbing meters a second... slap and  
engage, despite having no adhesion,  
they have very sophisticated,  
frictional attachment.  
Those claws can grip almost anything,  
even glass.   
While glass feels smooth to us,  
It's actually covered in tiny surface  
imperfections.  
At insect scale,  
these features are significant.  
- Ants basically have climbing gear.  
- Oh yeah.  
They're like, using these little  
like axes basically to pick their way in.  
We don't have the attachment disks  
or whatever that would be,  
or like the special claws  
or the Van der Waals forces.  
Well, we have claws, if you're that scale,  
our fingers are claws.  
We have only really got... we have  
two claws, really.  
And then our feet  
aren't great at climbing, I don't know.  
Well, again, at that scale though,  
I don't know, right?  
Imagine putting a little sharp, spike into your foot  
and sharpen your  
shoes, wear high heel shoes.  
You'll be good to go.  
So now I'm climbing in heels.  
But there's still a problem.  
I mean, I'll have to be pretty careful  
placing each hand and foot slowly.  
It's going to take longer  
than 60 seconds to get out.  
And in that time,  
the blades will have started spinning.  
One mistake and I'm a smoothie.  
So Google was looking  
for a different answer.  
Now we’re going to the physics building.  
Maybe they know?  
Yeah. I really got nothing. I’m stumped.  
This is so embarrassing.  
We’re in our last year of our degree, we should  
definitely know this!  
I feel like I could probably swing running  
around the sides and yeeting myself out.  
Okay, if we're just talking about the entropy,  
it should increase at some point.  
So some sort of chaos should be...  
None of the system will stay un-disrupted...  
Take that as a limit to infinity  
and I'll be chilling...  
Like using that logic  
if I just like extrapolate...  
Now that's still too big for me  
to Quantum Tunnel or anything like that.  
- Whoa whoa whoa whoa.  
I mean, that is really overthinking it.  
It's actually not that complicated.  
- Do you want to hear the best answer I've heard yet?  
- Sure.  
Just jump.  
Just jump?  
How would that work?  
- Just jump!  
- How?  
-Does that work like that?  
- Jump where?   
- Out of the blender, just go up.  
- So whoever told you that is...   
- ...crazy, right?  
Yeah, does that makes sense to you?  
No, it doesn't, but...  
do you want to hear why that works?  
Yeah, tell me how it works.  
Jumping out of a blender seems impossible  
because at nickel size,  
the wall of a blender is 15x  
your height.  
It'd be like leaping over an eight story building.  
But watch these clips...  
Did you notice it?  
A horse, a dog and a squirrel.  
They all jump to about the same height.  
This is exactly what Alfonso Borrelli,  
the father of biomechanics,  
looked at in the 17th century.  
As he put it, in the same conditions,  
smaller and lighter animals  
make bigger jumps relative to their body.  
if the other conditions are equal,  
and indeed the limbs and the other organs  
are in the same proportion,  
the dog will jump as far as the horse.  
Now, sure, there is variation.  
A species whose survival depends on  
jumping will be optimized for it,  
while others, like turtles and elephants,  
they don't jump at all.  
But when you consider the huge variations  
in size,  
I mean a horse is 1500 times  
heavier than a squirrel.  
It's incredible that they jump to  
around the same height.  
And it's not because squirrels  
are super muscly or something.  
Horses and squirrels have similar muscle  
to weight percentages,  
and insects have even less muscle  
relative to their weight.  
Why do you think an ant can lift  
50 times its own body weight?  
Like, is it any more muscular? No  
you guys hit the gym.  
Come on. Like  
you're more muscular than an ant.  
So how are small things so strong?  
Well if you look closely at a muscle. It’s made up of tiny units called sarcomeres.  
They act like miniature springs.  
How far a muscle compresses depends on  
how many of these springs are in series.  
But the strength of a muscle depends  
only on how many are working in parallel.  
The thicker the muscle, the more springs  
in parallel, and the greater the strength.  
Therefore strength depends  
on the cross-sectional area of a muscle.  
And as animals shrink,  
this cross-sectional area  
scales down  
with the square of their height.  
But an animal's weight  
is proportional to its volume,  
so that scales  
with the cube of their height.  
So as you scale down, weight decreases  
faster than strength,  
and as a result, smaller animals have much  
higher strength to weight ratios.  
I mean, you could probably lift,   
your own weight,  
like if you were to put your own body  
weight on your back and squat that, you could now lift...   
100 hundred times.  
Yeah. Let's go!  
And for us, stuck in that blender,  
that extra strength  
relative to our weight  
means we could jump right out.  
Your surface area  
decreases with the square.  
You'd be like a little superman.  
- I see, okay!  
- That's really cool.  
So I could jump, like,  
literally out of a blender.  
You could jump out of a blender.  
But in movies and games  
where people are shrunk,  
they almost never show it like that.  
Honey, I Shrunk the Kids It was one of my favorite movies  
when I was a kid.  
I loved that.  
Tiny people struggle picking up scissors.  
They almost get crushed by raindrops.  
If it was scientifically accurate, they’d actually be overpowered.   
Most people don't think of this  
when they first hear the question.  
The answer almost seems too simple.  
When you ask the right questions,  
you define the problem.  
There's some really obvious solutions  
that work, and that's  
actually true for a lot of problems  
in the real world too.  
Now I'm all for obvious solutions,  
but from the start,  
the answer of jumping out  
didn't sit right with me.  
Even this idea of like, I'm  
going to jump out of the blender like that  
doesn't make sense to me,  
because jumping is not just like,  
okay, how strong  
you are relative to your weight.  
It's also timing  
and your kinetics and all that.  
So like, how long can you be in  
touch with the ground?  
How much can you apply that force in  
one burst like over a really short period?  
Would it be  
fair to say you're overthinking things?  
You got to suspend your disbelief  
somewhere.  
I think if you like, factor in all the  
potential challenges a human would have.  
Just like if they just all of a sudden  
that size, they don't have  
like time to practice using their legs  
and stuff in that new environment.  
Like, I don't give them very good  
chances of jumping out.  
Sometimes there are people  
who make everything more complex  
than it needs to be,  
and that can be problematic.  
I would like to see like,  
you know, realistic modeling of,  
we scale me down 100 times.  
Like, can I jump higher?  
I want to see someone do  
those physics equations, yeah,  
you could jump higher, but you couldn’t jump  
100x higher, you know?  
So that's why we got the researchers  
at Georgia Tech's biomechanics lab to investigate.  
While, they're figuring that out,  
let me tell you about today's  
sponsor, Incogni.  
Every time you browse the internet,  
sign up for a newsletter, or even just buy  
something online.  
Your personal data is collected,  
it is stored.  
And sometimes sold  
without your permission.  
So how do you escape?  
Well, with your permission, Incogni  
contacts data brokers on your behalf  
and requests using proper legal language  
that they delete  
your personal information.  
So instead of spending countless hours  
trying to track these companies  
down yourself, Incogni  
does all that hard work for you.  
I started using Incogni  
and within just a week  
my inbox was less overrun  
and my phone even got fewer spam calls.  
After a month,  
my dashboard showed even more removals.  
Companies I had never  
even interacted with, but who  
somehow had my personal information.  
If you want to try the easy way  
to escape the clutches  
of data brokers, visit  
incogni.com/veritasium.  
You can click that link down  
in the description or scan this QR code.  
Make sure to use Code Veritasium  
to get 60% off  
your annual subscription  
to take control of your data today.  
That's incogni.com/veritasium.  
Now let's see how that  
simulation is coming along.  
Okay, so we have our simulated blender.  
We’re 2 centimeters tall and we have to jump at least 30 centimeters to get out.  
I was like, well, what about me?  
Like, I'm pretty,  
you know, embarrassingly non-athletic.  
What if I do this? So I did it right here  
next to my desk.  
My partner sort of measured my jump height,  
and I know how much I weigh  
and all that stuff.  
So what would it look like for me?  
If we have a person  
that weighs 84kg, is squatting  
15cm and has a jump height of 27cm.  
That person, if they were scaled down  
to 1% of their original size,  
they would jump 42cm high.  
The simple simulation  
shows a jump height of 42cm.  
So you would make it out.  
But we need to add in air resistance.  
Since our cross-sectional area is now  
100 times larger relative to our weight,  
drag should have a greater effect  
at nickel size.  
If it was 42cm jump height  
before for the jumper, with drag...  
considering drag, then it's about 39cm.  
So we do decrease in jump height a little bit.  
But that drag calculation  
is assuming you jump perfectly vertically.  
But what if you're a bit uncoordinated  
and you flip onto your side mid jump?  
Well, then you're exposing  
ten times the surface area  
and that increases  
the amount of air resistance.  
Like if somehow you flipped,  
and you're still moving up like this.  
Like what is the air resistance then?  
So doing that,  
that means 22 centimeter jump height.  
Oh. So we don't we don't.  
Oh. Darn.  
If you start getting overconfident  
and you wanted to do,  
like, a backflip while you're at it,  
then you're going to mess it up. Yeah.  
Don't backflip out of the blender   
is a good piece of advice.  
Don't try and show off.  
You're trying to not get chopped up.  
Just like, just go headfirst.  
It's not so much getting out  
of the blender.  
It's what happens next.  
You've got two nickel sized men free  
in the world. Think of the posibilities.  
The simulation came back,   
You can jump out of the freaking blender.  
Alright, okay.  
I'm glad we went through this,  
this exercise.  
Do you want me to do another month  
of research on this?  
No. You know, like you've done it.  
You've done enough.  
You've done enough. I'm convinced.  
I feel like jumping is  
an unsatisfactory answer.  
It was unsatisfactory  
when you mentioned it in the first place.  
And you went through  
and you got the simulation,  
you got the model, and you're like, look,  
you know, our little guy can jump 40cm.  
Are you convinced now?  
And I'm like, I guess.  
But like, my spidey sense was tingling.  
- Oh was it now!  
- There is something going on...  
You're telling me  
that I have to apply a force  
in 1/1000 of a second,  
and I have to undergo  
278 G's?  
I'm not going to survive that.  
So what I'm getting now is that, like,  
my intuition was good.  
I think everyone's intuition was like,  
you can't jump out of a blender.  
I think they're right.  
And you may say,  
well, that's overthinking it,  
but that's the whole point of the brain  
teaser is to overthink it is to get to  
that point where you're thinking about it  
in the detail of like,  
what would actually be feasible.  
A whole lot of things would go wrong.  
Our hearts have to generate  
a certain amount of pressure  
to get the blood, you know, going up  
to our head and going all the way down.  
If you take the human heart  
and shrink it down,  
it's not going to be able  
to generate the same kinds of forces.  
I think it would be a catastrophe,  
in a smaller size. Controlling  
air pressure inside these countless sacks  
inside of our lungs.  
There's an exquisite balance there.  
Now, you try to take that same design  
and squeeze it down.  
I would be skeptical that you'd be able  
to keep the passageways open.  
You wouldn't even be able  
to think this through, because you just  
wouldn't have the brain structures that we have.  
You can't fit 86 billion neurons in a nickel sized volume.  
You can't scale cells down either.  
That's the thing. Like cells are cells.  
I mean, jumping out would be, to me,  
seems like your only option, but I don't  
think you're going to be able to jump  
because you can't breathe  
and your heart can't pump blood,  
so you just keel over and die  
before you can make your jump.  
Okay, so if you're a biologist,  
you think we die.  
If you're a physicist, you can decide  
whether we'd be little supermen or,  
as I believe, incapable  
of fully harnessing our extra strength.  
What did Borelli know?  
He didn't even have blenders.  
He doesn't know the stress.  
But if you're an interviewer at Google,  
you might not even care what the answer is.  
I think one of the misconceptions  
that candidates have is  
when I'm asked this question, it's  
because they want to see  
if I can solve this problem.  
That's actually not quite right.  
There are five attributes  
people are looking for.  
There's addressing ambiguity,  
There's breaking down the problem,  
being creative, being smart,  
and then communication.  
- So I guess like none of those five are  
whether it's correct.  
- Right.   
We’re the idiots who went  
and tried to figure out what's the best  
of those answers.  
Um, yes!  
Google realized that asking these types of questions  
didn't make much sense.  
Laszlo Bock, the senior vice president  
of people operations at Google, said this:  
On the hiring side, we found that brain  
teasers are a complete waste of time.  
How many golf balls  
can you fit into an airplane?  
How many gas stations are in Manhattan?  
A complete waste of time.  
They don't predict anything.  
They serve primarily  
to make the interviewer feel smart.  
But I just feel like there's that moment  
where you're like,  
so are you going to admit you're wrong?  
And I'm like, nyah, you know, I think  
this is further to like, I'm not wrong.  
This is crazy.  
This question is crazy.  
And I think it goes to your very point.  
Your very point,  
which is that like brain teasers like this  
are not good ways to assess whether people  
know what they're talking about.  
So although brain teasers aren't useful  
to assess  
job applicants,  
they are useful for something.  
I mean, every time we ask this question  
to people on the street,  
to physics students and to scientists,  
they lit up.  
They had to try to see the world  
from a new perspective.  
And it's exactly this way of thinking  
that has led to  
some of the biggest scientific  
discoveries.  
Einstein used thought experiments  
to come up with his theory of relativity.  
Euler's solution  
to the bridges of Königsberg puzzle  
is what inspired graph theory.  
And when Schrödinger wanted to illustrate  
his problems with quantum mechanics,  
he imagined a cat in a torture box.  
The blender question is admittedly silly,  
but silly  
questions can yield profound answers  
and show us new things.  
I think in order to learn something new,  
you have to be willing  
to embrace the ridiculous  
and just go with it.

# This Is The Perfect Bowling Strategy

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hitting the headpin square on is not the  
perfect  
strategy if you hit the head pin Square  
on going straight you're unlikely to  
knock down all the pins you could end up  
with a split where the ball goes through  
the middle or with the ball deflecting  
off to one side after hitting the head  
pin chances for a strike are much higher  
if the center of the ball hits the pins  
just to one side of the head pin board  
17 and a half in which case the ball  
takes out the 1 three five and nine pins  
which take out the others so we want the  
ball to hit the one pin the three the  
pin behind the one which is the five pin  
and then the nine or the eight and the  
nine you want the ball to hit all of  
those pins yeah now the pins don't  
always fall this way but the PIN shape  
helps pins roll in circles like eggs  
which help knock down the  
others seven P right baby come on don't  
miss you wanted it you got it but to  
have an over 90% chance of getting a  
strike the center of the ball has to hit  
with an error smaller than half a board  
needless to say throwing a ball 60 ft  
straight at a Target smaller than a dime  
is a tough task especially to do it  
consistently the spot between the head  
pin the one that's in the center and the  
three pin which is just right of that  
that gap's pretty narrow but as the ball  
hooks more now we basically shift over  
and now that space is considerably wider  
if you can hit the pins not head on but  
at an angle of 6° you dramatically  
increase your chances of knocking them  
all down now the margin for error is  
greater the ball can be coming in  
anywhere from board 17 to 18 and 1/2 6°  
may not sound like a lot but it's  
actually extremely difficult to hit the  
problem is if you wanted to throw the  
ball straight at the pins and hit them  
at 6° you would have to be bowling from  
3/4 over on the next Lane and that is  
impossible what with the two in between  
and all so the solution is you've got to  
curve the ball on one lane