what if?

Serious Scientific Answers to Absurd Hypothetical Questions

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what if?

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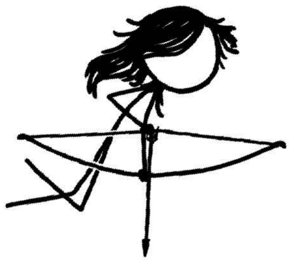
QUESTIONS



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INTRODUCTION

THIS BOOK IS A collection of answers to hypothetical questions.

These questions were submitted to me through my website, where—in addition to serving as a sort of Dear Abby for mad scientists—I draw xkcd, a stick-figure webcomic.

I didn't start out making comics. I went to school for physics, and after graduating, I worked on robotics at NASA. I eventually left NASA to draw comics full-time, but my interest in science and math didn't fade. Eventually, it found a new outlet: answering the Internet's weird—and sometimes worrying—questions. This book contains a selection of my favorite answers from my website, plus a bunch of new questions answered here for the first time.

I've been using math to try to answer weird questions for as long as I can remember. When I was five years old, my mother had a conversation with me that she wrote down and saved in a photo album. When she heard I was writing this book, she found the transcript and sent it to me. Here it is, reproduced verbatim from her 25-year-old sheet of paper:

Randall: Are there more soft things or hard things in our house?
Julie: I don't know.
Randall: How about in the world?
Julie: I don't know.

Randall: Well, each house has three or four pillows, right?

Julie: Right.

Randall: And each house has about 15 magnets, right?

Julie: I guess.

Randall: So 15 plus 3 or 4, let's say 4, is 19, right?

Julie: Right.

Randall: So there are probably about 3 billion soft things, and . . . 5 billion hard things. Well, which one wins?

Julie: I guess hard things.

To this day I have no idea where I got "3 billion" and "5 billion" from. Clearly, I didn't really get how numbers worked.

My math has gotten a little better over the years, but my reason for doing math is the same as it was when I was five: I want to answer questions.

They say there are no stupid questions. That's obviously wrong; I think my question about hard and soft things, for example, is pretty stupid. But it turns out that trying to thoroughly answer a stupid question can take you to some pretty interesting places.

I still don't know whether there are more hard or soft things in the world, but I've learned a lot of other stuff along the way. What follows are my favorite parts of that journey.

RANDALL MUNROE

what if?

GLOBAL WINDSTORM

Q. What would happen if the Earth and all terrestrial objects suddenly stopped spinning, but the atmosphere retained its velocity?

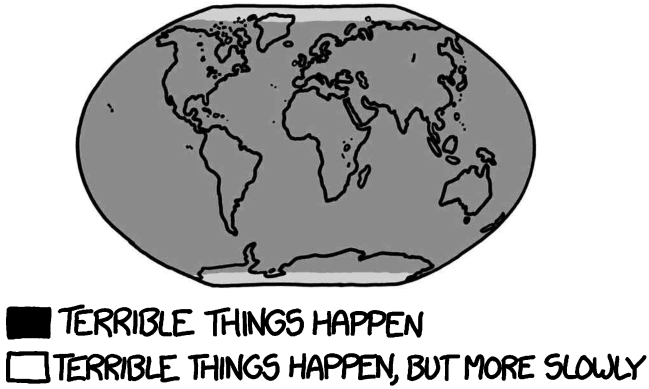
—Andrew Brown

A. NEARLY EVERYONE WOULD DIE. *Then* things would get interesting.

At the equator, the Earth's surface is moving at about 470 meters per second—a little over a thousand miles per hour—relative to its axis. If the Earth stopped and the air didn't, the result would be a sudden thousand-mile-per-hour wind.

The wind would be highest at the equator, but everyone and everything living between 42 degrees north and 42 degrees south—which includes about 85 percent of the world's population—would suddenly experience supersonic winds.

The highest winds would last for only a few minutes near the surface; friction with the ground would slow them down. However, those few minutes would be long enough to reduce virtually all human structures to ruins.



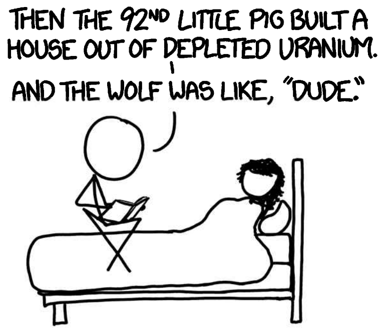
My home in Boston is far enough north to be just barely outside the supersonic wind zone, but the winds there would still be twice as strong as those in the most powerful tornadoes. Buildings, from sheds to skyscrapers, would be smashed flat, torn from their foundations, and sent tumbling across the landscape.

Winds would be lower near the poles, but no human cities are far enough from the equator to escape devastation. Longyearbyen, on the island of Svalbard in Norway—the highest-latitude city on the planet—would be devastated by winds equal to those in the planet's strongest tropical cyclones.

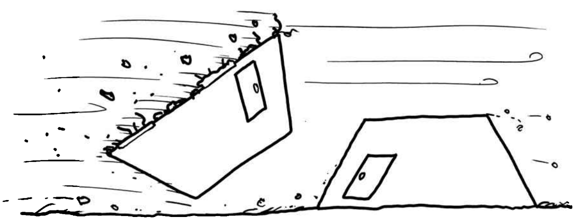
If you're going to wait it out, one of the best places to do it might be Helsinki, Finland. While its high latitude—above 60°N—wouldn't be enough to keep it from being scoured clean by the winds, the bedrock below Helsinki contains a sophisticated network of tunnels, along with a subterranean shopping mall, hockey rink, swimming complex, and more.

No buildings would be safe; even structures strong enough to survive the winds would be in trouble. As comedian Ron White said about hurricanes, "It's not *that* the wind is blowing, it's *what* the wind is blowing."

Say you're in a massive bunker made out of some material that can withstand thousand-mile-per-hour winds.



That's good, and you'd be fine . . . if you were the only one with a bunker. Unfortunately, you probably have neighbors, and if the neighbor upwind of you has a less-well-anchored bunker, your bunker will have to withstand a thousand-mile-per-hour impact by *their* bunker.



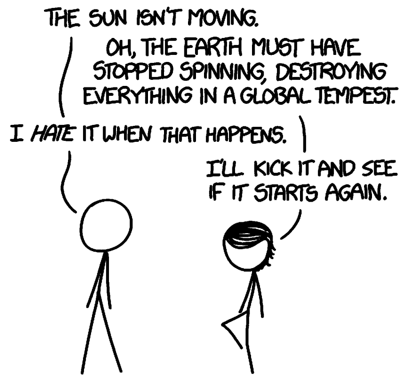
The human race wouldn't go extinct.[1] In general, very few people above the surface would survive; the flying debris would pulverize anything that wasn't nuclear-hardened. However, a lot of people below the surface of the ground would survive just fine. If you were in a deep basement (or, better yet, a subway tunnel) when it happened, you would stand a good chance of surviving.

There would be other lucky survivors. The dozens of scientists and staff at the Amundsen–Scott research station at the South Pole would be safe from the

1 I mean, not right away.

winds. For them, the first sign of trouble would be that the outside world had suddenly gone silent.

The mysterious silence would probably distract them for a while, but eventually someone would notice something even stranger:



The air

As the surface winds died down, things would get weirder.

The wind blast would translate to a heat blast. Normally, the kinetic energy of rushing wind is small enough to be negligible, but this would not be normal wind. As it tumbled to a turbulent stop, the air would heat up.

Over land, this would lead to scorching temperature increases and—in areas where the air is moist—global thunderstorms.

At the same time, wind sweeping over the oceans would churn up and atomize the surface layer of the water. For a while, the ocean would cease to have a surface at all; it would be impossible to tell where the spray ended and the sea began.

Oceans are *cold*. Below the thin surface layer, they're a fairly uniform 4°C. The tempest would churn up cold water from the depths. The influx of cold spray into superheated air would create a type of weather never before seen on Earth—a roiling mix of wind, spray, fog, and rapid temperature changes.

This upwelling would lead to blooms of life, as fresh nutrients flooded the upper layers. At the same time, it would lead to huge die-offs of fish, crabs, sea turtles, and animals unable to cope with the influx of low-oxygen water from the depths. Any animal that needs to breathe—such as whales and dolphins—would be hard-pressed to survive in the turbulent sea-air interface.

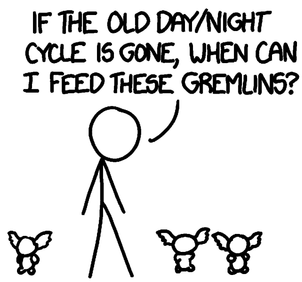
The waves would sweep around the globe, east to west, and every east-facing shore would encounter the largest storm surge in world history. A blinding cloud of sea spray would sweep inland, and behind it, a turbulent, roiling wall of water would advance like a tsunami. In some places, the waves would reach many miles inland.

The windstorms would inject huge amounts of dust and debris into the atmosphere. At the same time, a dense blanket of fog would form over the cold ocean surfaces. Normally, this would cause global temperatures to plummet. And they would.

At least, on one side of the Earth.

If the Earth stopped spinning, the normal cycle of day and night would end. The Sun wouldn't completely stop moving across the sky, but instead of rising and setting once a day, it would rise and set once a *year*.

Day and night would each be six months long, even at the equator. On the day side, the surface would bake under the constant sunlight, while on the night side the temperature would plummet. Convection on the day side would lead to massive storms in the area directly beneath the Sun.[2]

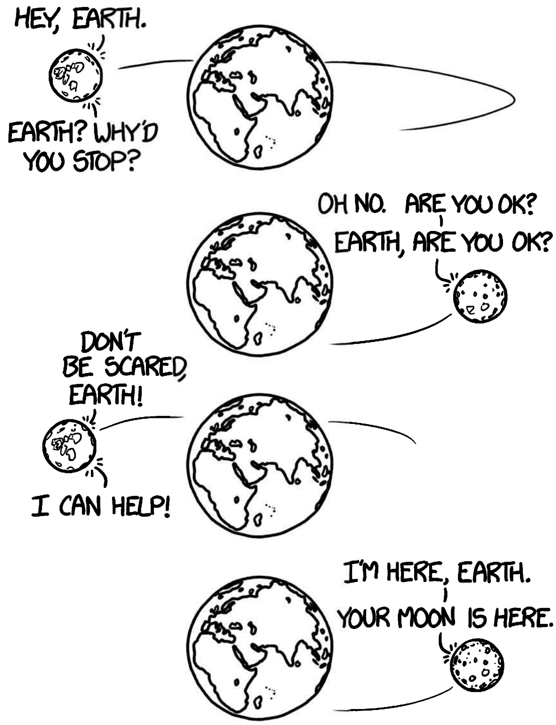


In some ways, this Earth would resemble one of the tidally locked exoplanets commonly found in a red dwarf star's habitable zone, but a better comparison might be a very early Venus. Due to its rotation, Venus—like our stopped Earth—keeps the same face pointed toward the Sun for months at a time. However, its thick atmosphere circulates quite quickly, which results in the day and the night side having about the same temperature.

Although the length of the day would change, the length of the month would not! The Moon hasn't stopped rotating around the Earth. However, without the Earth's rotation feeding it tidal energy, the Moon *would* stop drifting away from the Earth (as it is doing currently) and would start to slowly drift back toward us.

2 Although without the Coriolis force, it's anyone's guess which way they would spin.

In fact, the Moon—our faithful companion—would act to undo the damage Andrew's scenario caused. Right now, the Earth spins faster than the Moon, and our tides slow down the Earth's rotation while pushing the Moon away from us.[3] If we stopped rotating, the Moon would stop drifting away from us. Instead of slowing us down, its tides would accelerate our spin. Quietly, gently, the Moon's gravity would tug on our planet . . .



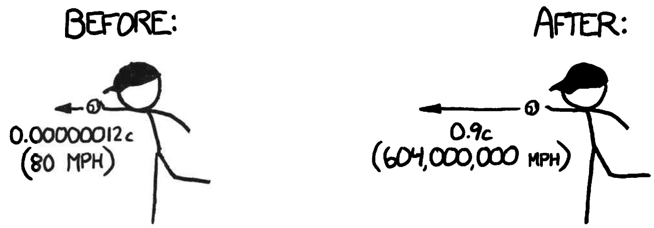
. . . and Earth would start turning again.

3 See "Leap Seconds," *http://what-if.xkcd.com/26*, for an explanation of why this happens.

RELATIVISTIC BASEBALL

Q. What would happen if you tried to hit a baseball pitched at 90 percent the speed of light?

—Ellen McManis

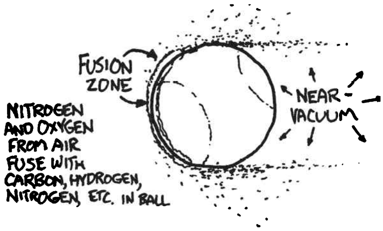


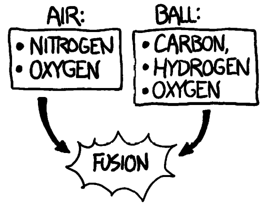
Let's set aside the question of how we got the baseball moving that fast. We'll suppose it's a normal pitch, except in the instant the pitcher releases the ball, it magically accelerates to 0.9c. From that point onward, everything proceeds according to normal physics.

A. THE ANSWER TURNS OUT to be "a lot of things," and they all happen very quickly, and it doesn't end well for the batter (or the pitcher). I sat down with some physics books, a Nolan Ryan action figure, and a bunch of videotapes of nuclear tests and tried to sort it all out. What follows is my best guess at a nanosecond-by-nanosecond portrait.

The ball would be going so fast that everything else would be practically stationary. Even the molecules in the air would stand still. Air molecules would vibrate back and forth at a few hundred miles per hour, but the ball would be moving through them at 600 *million* miles per hour. This means that as far as the ball is concerned, they would just be hanging there, frozen.

The ideas of aerodynamics wouldn't apply here. Normally, air would flow around anything moving through it. But the air molecules in front of this ball wouldn't have time to be jostled out of the way. The ball would smack into them so hard that the atoms in the air molecules would actually fuse with the atoms in the ball's surface. Each collision would release a burst of gamma rays and scattered particles.[1]





These gamma rays and debris would expand outward in a bubble centered on the pitcher's mound. They would start to tear apart the molecules in the air, ripping the electrons from the nuclei and turning the air in the stadium into an expanding bubble of incandescent plasma. The wall of this bubble would approach the batter at about the speed of light—only slightly ahead of the ball itself.

The constant fusion at the front of the ball would push back on it, slowing it down, as if the ball were a rocket flying tail-first while firing its engines. Unfortunately, the ball would be going so fast that even the tremendous force from this ongoing thermonuclear explosion would barely slow it down at all. It would, however, start to eat away at the surface, blasting tiny fragments of the ball in all directions. These fragments would be going so fast that when they hit air molecules, they would trigger two or three more rounds of fusion.

After about 70 nanoseconds the ball would arrive at home plate. The batter wouldn't even have seen the pitcher let go of the ball, since the light carrying that information would arrive at about the same time the ball would. Collisions with the air would have eaten the ball away almost completely, and it would now be a bullet-shaped cloud of expanding plasma (mainly carbon, oxygen, hydrogen, and nitrogen) ramming into the air and triggering more fusion as it went. The shell of x-rays would hit the batter first, and a handful of nanoseconds later the debris cloud would hit.

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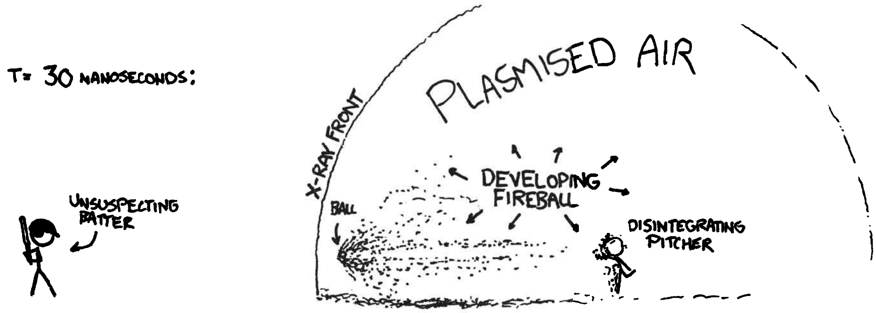
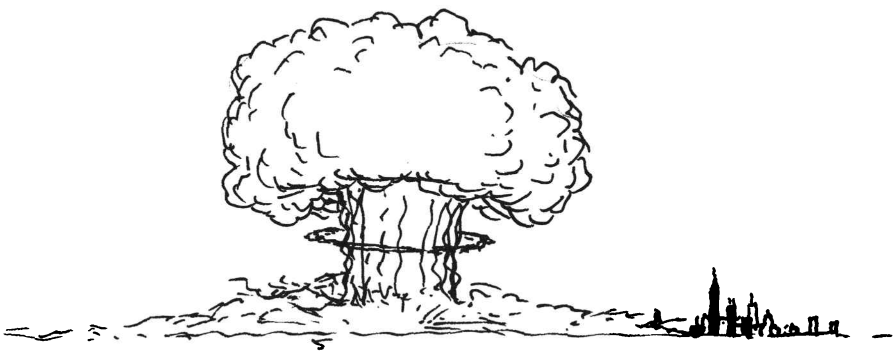
1 After I initially published this article, MIT physicist Hans Rinderknecht contacted me to say that he'd simulated this scenario on their lab's computers. He found that early in the ball's flight, most of the air molecules were actually moving too quickly to cause fusion, and would pass right through the ball, heating it more slowly and uniformly than my original article described.



When it would reach home plate, the center of the cloud would still be moving at an appreciable fraction of the speed of light. It would hit the bat first, but then the batter, plate, and catcher would all be scooped up and carried backward through the backstop as they disintegrated. The shell of x-rays and superheated plasma would expand outward and upward, swallowing the backstop, both teams, the stands, and the surrounding neighborhood—all in the first microsecond.

Suppose you're watching from a hilltop outside the city. The first thing you would see would be a blinding light, far outshining the sun. This would gradually fade over the course of a few seconds, and a growing fireball would rise into a mushroom cloud. Then, with a great roar, the blast wave would arrive, tearing up trees and shredding houses.

Everything within roughly a mile of the park would be leveled, and a firestorm would engulf the surrounding city. The baseball diamond, now a sizable crater, would be centered a few hundred feet behind the former location of the backstop.



Major League Baseball Rule 6.08(b) suggests that in this situation, the batter would be considered "hit by pitch," and would be eligible to advance to first base.

SPENT FUEL POOL

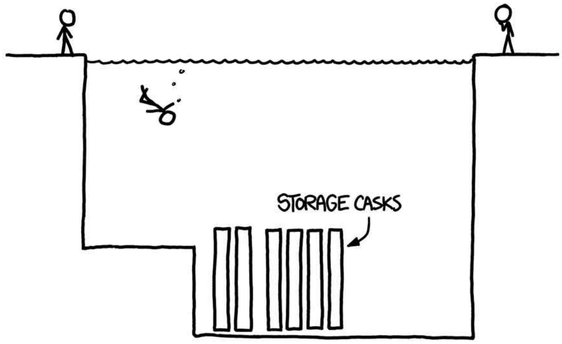
Q. What if I took a swim in a typical spent nuclear fuel pool? Would I need to dive to actually experience a fatal amount of radiation? How long could I stay safely at the surface?

—Jonathan Bastien-Filiatrault

A. ASSUMING YOU'RE A REASONABLY good swimmer, you could probably survive treading water anywhere from 10 to 40 hours. At that point, you would black out from fatigue and drown. This is also true for a pool without nuclear fuel in the bottom.

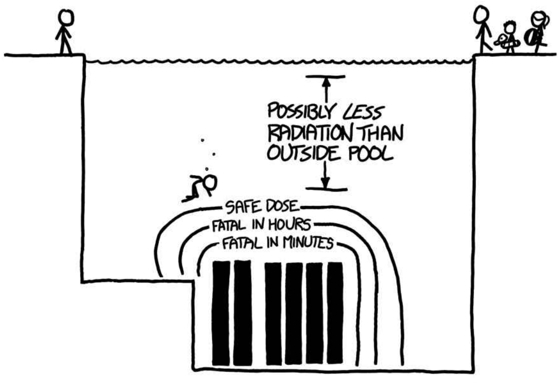
Spent fuel from nuclear reactors is highly radioactive. Water is good for both radiation shielding and cooling, so fuel is stored at the bottom of pools for a couple of decades until it's inert enough to be moved into dry casks. We haven't really agreed on where to put those dry casks yet. One of these days we should probably figure that out.

Here's the geometry of a typical fuel storage pool:



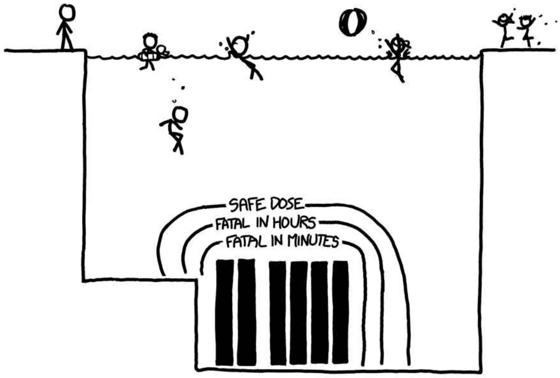
The heat wouldn't be a big problem. The water temperature in a fuel pool can in theory go as high as 50°C, but in practice it's generally between 25°C and 35°C—warmer than most pools but cooler than a hot tub.

The most highly radioactive fuel rods are those recently removed from a reactor. For the kinds of radiation coming off spent nuclear fuel, every 7 centimeters of water cuts the amount of radiation in half. Based on the activity levels provided by Ontario Hydro in this report, this would be the region of danger for fresh fuel rods:



Swimming to the bottom, touching your elbows to a fresh fuel canister, and immediately swimming back up would probably be enough to kill you.

Yet outside the outer boundary, you could swim around as long as you wanted—the dose from the core would be less than the normal background dose you get walking around. In fact, as long as you were underwater, you would be shielded from most of that normal background dose. You may actually receive a lower dose of radiation treading water in a spent fuel pool than walking around on the street.



Remember: I am a cartoonist.
If you follow my advice on safety around nuclear materials,
you probably deserve whatever happens to you.

That's if everything goes as planned. If there's corrosion in the spent fuel rod casings, there may be some fission products in the water. They do a pretty good job of keeping the water clean, and it wouldn't hurt you to swim in it, but it's radioactive enough that it wouldn't be legal to sell it as bottled water.[1]

We know spent fuel pools can be safe to swim in because they're routinely serviced by human divers.

However, these divers have to be careful.

On August 31, 2010, a diver was servicing the spent fuel pool at the Leibstadt nuclear reactor in Switzerland. He spotted an unidentified length of tubing on the bottom of the pool and radioed his supervisor to ask what to do. He was told to put it in his tool basket, which he did. Due to bubble noise in the pool, he didn't hear his radiation alarm.

When the tool basket was lifted from the water, the room's radiation alarms went off. The basket was dropped back in the water and the diver left the pool. The diver's dosimeter badges showed that he'd received a higher-than-normal whole-body dose, and the dose in his right hand was extremely high.

The object turned out to be protective tubing from a radiation monitor in the reactor core, made highly radioactive by neutron flux. It had been accidentally

1 Which is too bad—it'd make a hell of an energy drink.

sheared off while a capsule was being closed in 2006. It sank to a remote corner of the pool, where it sat unnoticed for four years.

The tubing was so radioactive that if he'd tucked it into a tool belt or shoulder bag, where it sat close to his body, he could've been killed. As it was, the water protected him, and only his hand—a body part more resistant to radiation than the delicate internal organs—received a heavy dose.

So, as far as swimming safety goes, the bottom line is that you'd probably be OK, as long as you didn't dive to the bottom or pick up anything strange.

But just to be sure, I got in touch with a friend of mine who works at a research reactor, and asked him what he thought would happen to someone who tried to swim in their radiation containment pool.

"In *our* reactor?" He thought about it for a moment. "You'd die pretty quickly, before reaching the water, from gunshot wounds."

WEIRD (AND WORRYING) QUESTIONS FROM THE WHAT IF? INBOX, #1

Q. Would it be possible to get your teeth to such a cold temperature that they would shatter upon drinking a hot cup of coffee?

—**Shelby Hebert**

Q. How many houses are burned down in the United States every year? What would be the easiest way to increase that number by a significant amount (say, at least 15%)?

—**Anonymous**

NEW YORK–STYLE TIME MACHINE

Q. I assume when you travel back in time you end up at the same spot on the Earth's surface. At least, that's how it worked in the *Back to the Future* movies. If so, what would it be like if you traveled back in time, starting in Times Square, New York, 1000 years? 10,000 years? 100,000 years? 1,000,000 years? 1,000,000,000 years? What about forward in time 1,000,000 years?

—Mark Dettling

1000 years back

Manhattan has been continuously inhabited for the past 3000 years, and was first settled by humans perhaps 9000 years ago.

In the 1600s, when Europeans arrived, the area was inhabited by the Lenape people.[1] The Lenape were a loose confederation of tribes who lived in what is now Connecticut, New York, New Jersey, and Delaware.

A thousand years ago, the area was probably inhabited by a similar collection of tribes, but those inhabitants lived half a millennium before European contact. They were as far removed from the Lenape of the 1600s as the Lenape of the 1600s are from the modern day.

To see what Times Square looked like before a city was there, we turn to a remarkable project called **Welikia,** which grew out of a smaller project called **Mannahatta.** The Welikia project has produced a detailed ecological map of the landscape in New York City at the time of the arrival of Europeans.

The interactive map, available online at *welikia.org,* is a fantastic snapshot of a different New York. In 1609, the island of Manhattan was part of a landscape of rolling hills, marshes, woodlands, lakes, and rivers.

The Times Square of 1000 years ago may have looked ecologically similar to the Times Square described by Welikia. Superficially, it probably resembled the old-growth forests that are still found in a few locations in the northeastern US. However, there would be some notable differences.

There would be more large animals 1000 years ago. Today's disconnected patchwork of northeastern old-growth forests is nearly free of large predators; we have some bears, few wolves and coyotes, and virtually no mountain lions. (Our deer populations, on the other hand, have exploded, thanks in part to the removal of large predators.)

The forests of New York 1000 years ago would be full of chestnut trees. Before a blight passed through in the early twentieth century, the hardwood forests of eastern North America were about 25 percent chestnut. Now, only their stumps survive.

You can still come across these stumps in New England forests today. They periodically sprout new shoots, only to see them wither as the blight takes hold. Someday, before too long, the last of the stumps will die.

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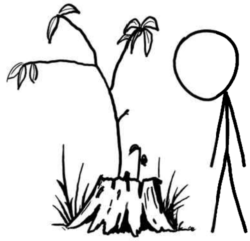
1 Also known as the Delaware.



Wolves would be common in the forests, especially as you moved inland. You might also encounter mountain lions[2,3,4,5,6] and passenger pigeons.[7]

There's one thing you would *not* see: earthworms. There were no earthworms in New England when the European colonists arrived. To see the reason for the worms' absence, let's take our next step into the past.

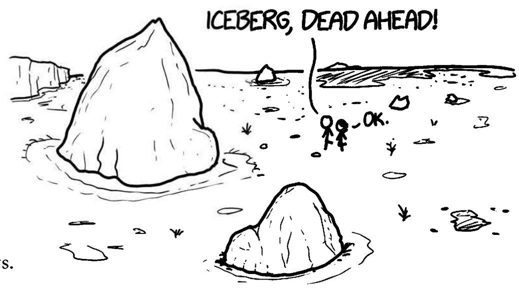
10,000 years back

The Earth of 10,000 years ago was just emerging from a deep cold period.

The great ice sheets that covered New England had departed. As of 22,000 years ago, the southern edge of the ice was near Staten Island, but by 18,000 years ago it had retreated north past Yonkers.[8] By the time of our arrival, 10,000 years ago, the ice had largely withdrawn across the present-day Canadian border.

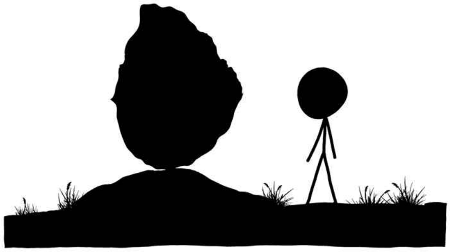
The ice sheets scoured the landscape down to bedrock. Over the next 10,000 years, life crept slowly back northward. Some species moved north faster than others; when Europeans arrived in New England, earthworms had not yet returned.

As the ice sheets withdrew, large chunks of ice broke off and were left behind.

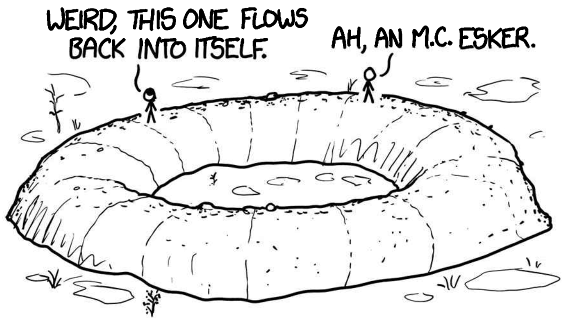


2 Also known as cougars.
3 Also known as pumas.
4 Also known as catamounts.
5 Also known as panthers.
6 Also known as painted cats.
7 Although you might not see the clouds of trillions of pigeons encountered by European settlers. In his book *1491,* Charles C. Mann argues that the huge flocks seen by European settlers may have been a symptom of a chaotic ecosystem perturbed by the arrival of smallpox, bluegrass, and honeybees.
8 That is, the current site of Yonkers. It probably wasn't called "Yonkers" then, since "Yonkers" is a Dutch-derived name for a settlement dating to the late 1600s. However, some argue that a site called "Yonkers" has always existed, and in fact predates humans and the Earth itself. I mean, I guess it's just me who argues that, but I'm very vocal.

When these chunks melted, they left behind water-filled depressions in the ground called **kettlehole ponds.** Oakland Lake, near the north end of Springfield Boulevard in Queens, is one of these kettlehole ponds. The ice sheets also dropped boulders they'd picked up on their journey; some of these rocks, called **glacial erratics,** can be found in Central Park today.



Below the ice, rivers of meltwater flowed at high pressure, depositing sand and gravel as they went. These deposits, which remain as ridges called **eskers,** crisscross the landscape in the woods outside my home in Boston. They are responsible for a variety of odd landforms, including the world's only vertical U-shaped riverbeds.



100,000 years back

The world of 100,000 years ago might have looked a lot like our own.[9] We live in an era of rapid, pulsating glaciations, but for 10,000 years our climate has been stable[10] and warm.

A hundred thousand years ago, Earth was near the end of a similar period of

9 Though with fewer billboards.
10 Well, *had* been. We're putting a stop to that.

climate stability. It was called the **Sangamon interglacial,** and it probably supported a developed ecology that would look familiar to us.

The coastal geography would be totally different; Staten Island, Long Island, Nantucket, and Martha's Vineyard were all berms pushed up by the most recent bulldozer-like advance of the ice. A hundred millennia ago, different islands dotted the coast.

Many of today's animals would be found in those woods—birds, squirrels, deer, wolves, black bears—but there would be a few dramatic additions. To learn about those, we turn to the mystery of the pronghorn.

The modern pronghorn (American antelope) presents a puzzle. It's a fast runner—in fact, it's much faster than it needs to be. It can run at 55 mph, and sustain that speed over long distances. Yet its fastest predators, wolves and coyotes, barely break 35 mph in a sprint. Why did the pronghorn evolve such speed?

The answer is that the world in which the pronghorn evolved was a much more dangerous place than ours. A hundred thousand years ago, North American woods were home to *Canis dirus* (the dire wolf), *Arctodus* (the short-faced bear), and *Smilodon fatalis* (sabre-toothed cat), each of which may have been faster and deadlier than modern predators. All died out in the Quaternary extinction event, which occured shortly after the first humans colonized the continent.[11]

If we go back a little further, we will meet another frightening predator.

1,000,000 years back

A million years ago, before the most recent great episode of glaciations, the world was fairly warm. It was the middle of the Quaternary period; the great modern ice ages had begun several million years earlier, but there had been a lull in the advance and retreat of the glaciers, and the climate was relatively stable.

The predators we met earlier, the fleet-footed creatures who may have preyed on the pronghorn, were joined by another terrifying carnivore, a long-limbed hyena that resembled a modern wolf. Hyenas were mainly found in Africa and Asia, but when the sea level fell, one species crossed the Bering Strait into North America. Because it was the only hyena to do so, it was given the name *Chasmaporthetes*, which means "the one who saw the canyon."

Next, Mark's question takes us on a great leap backward in time.

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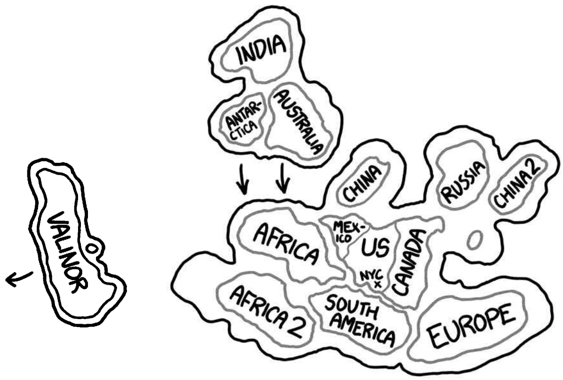
11 If anyone asks, total coincidence.

1,000,000,000 years back

A billion years ago, the continental plates were pushed together into one great supercontinent. This was not the well-known supercontinent **Pangea**—it was Pangea's predecessor, **Rodinia.** The geologic record is spotty, but our best guess is that it looked something like this:



In the time of Rodinia, the bedrock that now lies under Manhattan had yet to form, but the deep rocks of North America were already old. The part of the continent that is now Manhattan was probably an inland region connected to what is now Angola and South Africa.

In this ancient world, there were no plants and no animals. The oceans were full of life, but it was simple single-cellular life. On the surface of the water were mats of blue-green algae.

These unassuming critters are the deadliest killers in the history of life.

Blue-green algae, or **cyanobacteria,** were the first photosynthesizers. They breathed in carbon dioxide and breathed out oxygen. Oxygen is a volatile gas; it causes iron to rust (oxidation) and wood to burn (vigorous oxidation). When cyanobacteria first appeared, the oxygen they breathed out was toxic to nearly all other forms of life. The resulting extinction is called the **oxygen catastrophe.**

After the cyanobacteria pumped Earth's atmosphere and water full of toxic oxygen, creatures evolved that took advantage of the gas's volatile nature to enable new biological processes. We are the descendants of those first oxygen-breathers.

Many details of this history remain uncertain; the world of a billion years ago is difficult to reconstruct. But Mark's question now takes us into an even more uncertain domain: the future.

1,000,000 years forward

Eventually, humans will die out. Nobody knows when,[12] but nothing lives forever. Maybe we'll spread to the stars and last for billions or trillions of years. Maybe civilization will collapse, we'll all succumb to disease and famine, and the last of us will be eaten by cats. Maybe we'll all be killed by nanobots hours after you read this sentence. There's no way to know.

A million years is a long time. It's several times longer than *Homo sapiens* has existed, and a hundred times longer than we've had written language. It seems reasonable to assume that however the human story plays out, in a million years it will have exited its current stage.

Without us, Earth's geology will grind on. Winds and rain and blowing sand will dissolve and bury the artifacts of our civilization. Human-caused climate change will probably delay the start of the next glaciation, but we haven't ended the cycle of ice ages. Eventually, the glaciers will advance again. A million years from now, few human artifacts will remain.

Our most lasting relic will probably be the layer of plastic we've deposited across the planet. By digging up oil, processing it into durable and long-lasting polymers, and spreading it across the Earth's surface, we've left a fingerprint that could outlast everything else we do.

Our plastic will become shredded and buried, and perhaps some microbes will learn to digest it, but in all likelihood, a million years from now, an out-of-place layer of processed hydrocarbons—transformed fragments of our shampoo bottles and shopping bags—will serve as a chemical monument to civilization.

The far future

The Sun is gradually brightening. For three billion years, a complex system of feedback loops has kept the Earth's temperature relatively stable as the Sun has grown steadily warmer.

In a billion years, these feedback loops will have given out. Our oceans, which nourished life and kept it cool, will have turned into its worst enemy. They will have boiled away in the hot Sun, surrounding the planet with a thick blanket of

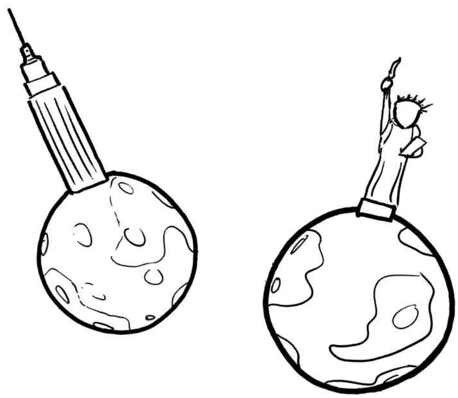
12 If you do, email me.

water vapor and causing a runaway greenhouse effect. In a billion years, Earth will become a second Venus.

As the planet heats up, we may lose our water entirely and acquire a rock vapor atmosphere, as the crust itself begins to boil. Eventually, after several billion more years, we will be consumed by the expanding Sun.

The Earth will be incinerated, and many of the molecules that made up Times Square will be blasted outward by the dying Sun. These dust clouds will drift through space, perhaps collapsing to form new stars and planets.

If humans escape the solar system and outlive the Sun, our descendants may someday live on one of these planets. Atoms from Times Square, cycled through the heart of the Sun, will form our new bodies.



One day, either we will all be dead, or we will all be New Yorkers.

SOUL MATES

Q. What if everyone actually had only one soul mate, a random person somewhere in the world?

—Benjamin Staffin

A. WHAT A NIGHTMARE THAT would be.

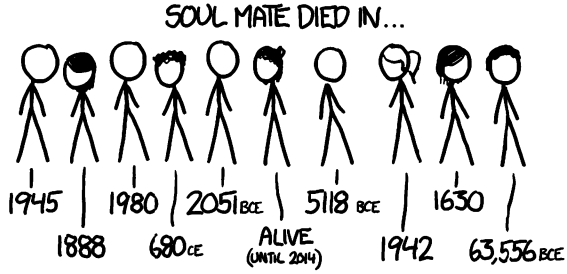
There are a lot of problems with the concept of a single random soul mate. As Tim Minchin put it in his song "If I Didn't Have You":

Your love is one in a million;
You couldn't buy it at any price.
But of the 9.999 hundred thousand other loves,
Statistically, some of them would be equally nice.

But what if we did have one randomly assigned perfect soul mate, and we *couldn't* be happy with anyone else? Would we find each other?

We'll assume your soul mate is chosen at birth. You don't know anything about who or where they are, but—as in the romantic cliché—you recognize each other the moment your eyes meet.

Right away, this would raise a few questions. For starters, would your soul mate even still be alive? A hundred billion or so humans have ever lived, but only seven billion are alive now (which gives the human condition a 93 percent mortality rate). If we were all paired up at random, 90 percent of our soul mates would be long dead.



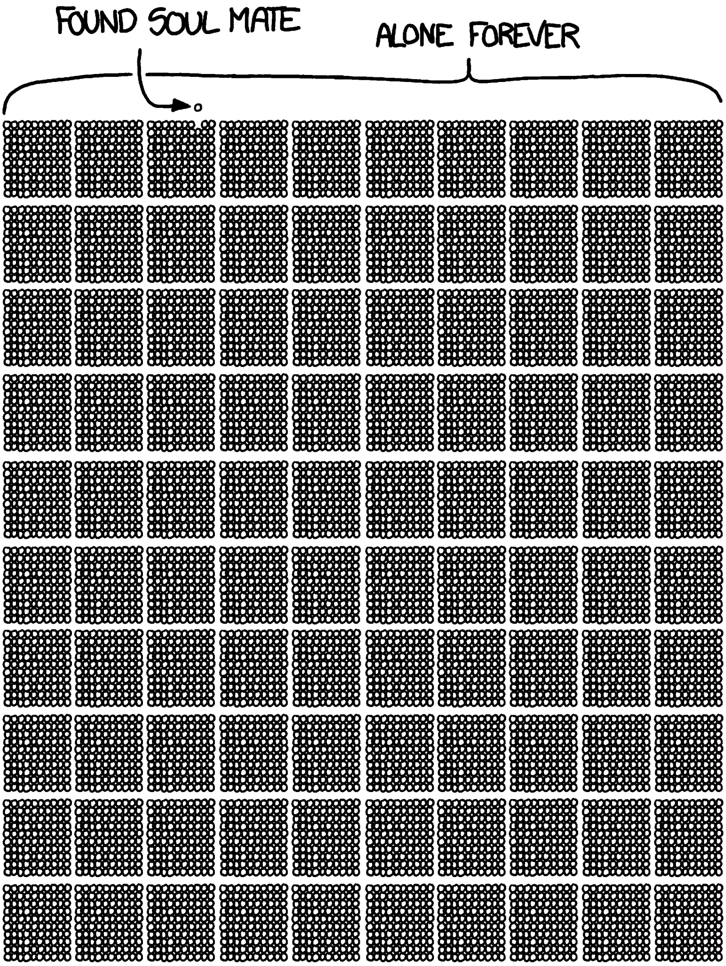
That sounds horrible. But wait, it gets worse: A simple argument shows we can't limit ourselves just to past humans; we have to include an unknown number of future humans as well. See, if your soul mate is in the distant past, then it also has to be possible for soul mates to be in the distant future. After all, *your* soul mate's soul mate is.

So let's assume your soul mate lives at the same time as you. Furthermore, to keep things from getting creepy, we'll assume they're within a few years of your age. (This is stricter than the standard age-gap creepiness formula,[1] but if we assume a 30-year-old and a 40-year-old can be soul mates, then the creepiness rule is violated if they accidentally meet 15 years earlier.) With the same-age restriction, most of us would have a pool of around half a billion potential matches.

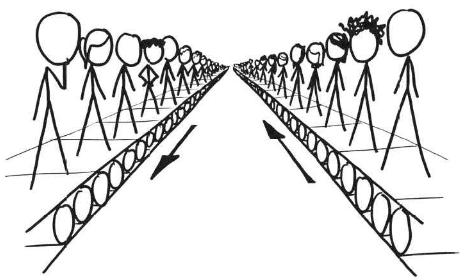
But what about gender and sexual orientation? And culture? And language? We could keep using demographics to try to narrow things down further, but we'd be drifting away from the idea of a random soul mate. In our scenario, you wouldn't know *anything* about who your soul mate was until you looked into their eyes. Everybody would have only one orientation: toward their soul mate.

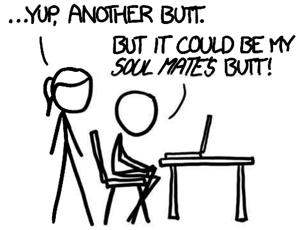
The odds of running into your soul mate would be incredibly small. The number of strangers we make eye contact with each day can vary from almost none (shut-ins or people in small towns) to many thousands (a police officer in Times Square), but let's suppose you lock eyes with an average of a few dozen new strangers each day. (I'm pretty introverted, so for me that's definitely a generous estimate.) If 10 percent of them are close to your age, that would be around 50,000 people in a lifetime. Given that you have 500,000,000 potential soul mates, it means you would find true love only in one lifetime out of 10,000.

1 xkcd, "Dating pools," *http://xkcd.com/314*.



With the threat of dying alone looming so prominently, society could restructure to try to enable as much eye contact as possible. We could put together massive conveyer belts to move lines of people past each other . . .





. . . but if the eye contact effect works over webcams, we could just use a modified version of ChatRoulette.

If everyone used the system for eight hours a day, seven days a week, and if it takes you a couple of seconds to decide if someone's your soul mate, this system could—in theory—match everyone up with their soul mates in a few decades. (I modeled a few simple systems to estimate how quickly people would pair off and drop out of the singles pool. If you want to try to work through the math for a particular setup, you might start by looking at derangement problems.)

In the real world, many people have trouble finding any time at all for romance—few could devote two decades to it. So maybe only rich kids would be able to afford to sit around on SoulMateRoulette. Unfortunately for the proverbial 1 percent, most of their soul mates would be found in the other 99 percent. If only 1 percent of the wealthy used the service, then 1 percent of that 1 percent would find their match through this system—one in 10,000.

The other 99 percent of the 1 percent[2] would have an incentive to get more people into the system. They might sponsor charitable projects to get computers to the rest of the world—a cross between One Laptop Per Child and OKCupid. Careers like "cashier" and "police officer in Times Square" would become high-status prizes because of the eye contact potential. People would flock to cities and public gathering places to find love—just as they do now.

But even if a bunch of us spent years on SoulMateRoulette, another bunch of us managed to hold jobs that offered constant eye contact with strangers, and the rest of us just hoped for luck, only a small minority of us would ever find true love. The rest of us would be out of luck.

Given all the stress and pressure, some people would fake it. They'd want to join the club, so they'd get together with another lonely person and stage a fake soul mate encounter. They'd marry, hide their relationship problems, and struggle to present a happy face to their friends and family.

A world of random soul mates would be a lonely one. Let's hope that's not what we live in.

2 "We are the zero point nine nine percent!"

LASER POINTER

Q. If every person on Earth aimed a laser pointer at the Moon at the same time, would it change color?

—Peter Lipowicz

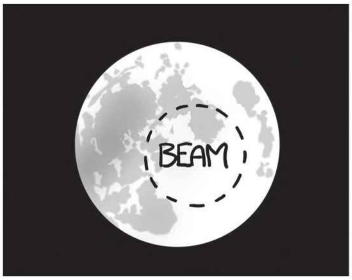
A. NOT IF WE USED regular laser pointers.

The first thing to consider is that not everyone can see the Moon at once. We could gather everyone in one spot, but let's just pick a time when the Moon is visible to as many people as possible. Since about 75 percent of the world's population lives between 0°E and 120°E, we should try this while the Moon is somewhere over the Arabian Sea.

We could try to illuminate either a new moon or a full moon. The new moon is darker, making it easier to see our lasers. But the new moon is a trickier target, because it's mostly visible during the day—washing out the effect.

Let's pick a quarter moon, so we can compare the effect of our lasers on the dark and light sides.

Here's our target.



The typical red laser pointer is about 5 milliwatts, and a good one would have a tight enough beam to hit the Moon—though it'd be spread out over a large fraction of the surface when it got there. The atmosphere would distort the beam a bit, and absorb some of it, but most of the light would make it.

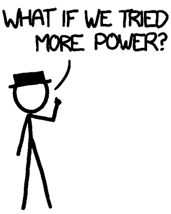
Let's assume everyone has steady enough aim to hit the Moon, but no more than that, and the light spreads evenly across the surface.

Half an hour after midnight (GMT), everyone aims and presses the button.

This is what happened:

Well, that's disappointing.

It makes sense, though. Sunlight bathes the Moon in a bit over a kilowatt of energy per square meter. Since the Moon's cross-sectional area is around 10^{13} square meters, it's bathed in about 10^{16} watts of sunlight—10 petawatts, or 2 megawatts per person—far outshining our 5-milliwatt laser pointers. There are varying efficiencies in each part of this system, but none of it changes that basic equation.



A 1-watt laser is an extremely dangerous thing. It's not just powerful enough to blind you—it's capable of burning skin and setting things on fire. Obviously, they're not legal for consumer purchase in the US.

Just kidding! You can pick one up for $300. Just do a search for "1-watt handheld laser."

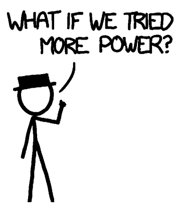
So, suppose we spend the $2 trillion to buy 1-watt green lasers for everyone. (Memo to presidential candidates: This policy would win my vote.) In addition to being more powerful, green laser light is nearer to the middle of the visible spectrum, so the eye is more sensitive to it and it seems brighter.

Here's the effect:

Dang.

The laser pointers we're using put out about 150 lumens of light (more than most flashlights) in a beam 5 arc-minutes wide. This lights up the surface of the Moon with about half a lux of illumination—compared to about 130,000 lux from the sun. (Even if we aimed them all perfectly, it would result in only half a dozen lux over about 10 percent of the Moon's face.)

By comparison, the full moon lights up the Earth's surface with about 1 lux of illumination—which means that not only would our lasers be too weak to see from Earth, but if you were standing on the Moon, the laser light on the landscape would be fainter than moonlight is to us on Earth.

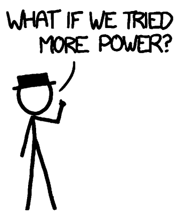


With advances in lithium batteries and LED technology over the last ten years, the high-performance flashlight market has exploded. But it's clear that flashlights aren't gonna cut it. So let's skip past all of that and give everyone a Nightsun.

You may not recognize the name, but chances are you've seen one in operation: It's the searchlight mounted on police and Coast Guard helicopters. With an output on the order of 50,000 lumens, it's capable of turning a patch of ground from night to day.

The beam is several degrees wide, so we would want some focusing lenses to get it down to the half-degree needed to hit the Moon.

It's hard to see, but we're making progress! The beam is providing 20 lux of illumination, outshining the ambient light on the night half by a factor of two! However, it's quite hard to see, and it certainly hasn't affected the light half.



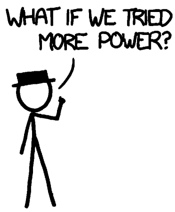
Let's swap out each Nightsun for an IMAX projector array—a 30,000-watt pair of water-cooled lamps with a combined output of over a million lumens.

Still barely visible.

At the top of the Luxor Hotel in Las Vegas is the most powerful spotlight on Earth. Let's give one of them to everyone.

Oh, and let's add a lens array to each so the entire beam is focused on the Moon:

Our light is definitely visible, so we've accomplished our goal! Good job, team.



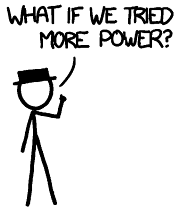
Well . . .

The Department of Defense has developed megawatt lasers, designed for destroying incoming missiles in mid-flight.

The Boeing YAL-1 was a megawatt-class chemical oxygen iodine laser mounted in a 747. It was an infrared laser, so it wasn't directly visible, but we can imagine building a visible-light laser with similar power.

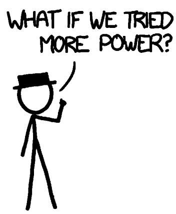
Finally, we've managed to match the brightness of sunlight!

We're also drawing 5 petawatts of power, which is double the world's average electricity consumption.



Okay, let's mount a megawatt laser on every square meter of Asia's surface. Powering this array of 50 trillion lasers would use up Earth's oil reserves in approximately two minutes, but for those two minutes, the Moon would look like this:

The Moon would shine as brightly as the midmorning sun, and by the end of the two minutes, the lunar regolith would be heated to a glow.



Okay, let's step even more firmly outside the realm of plausibility.

The most powerful laser on Earth is the confinement beam at the National Ignition Facility, a fusion research laboratory. It's an ultraviolet laser with an output of 500 terawatts. However, it fires only in single pulses lasting a few nanoseconds, so the total energy delivered is equivalent to about a quarter-cup of gasoline.

Let's imagine we somehow found a way to power and fire it continuously, gave one to everyone, and pointed them all at the Moon. Unfortunately, the laser energy flow would turn the atmosphere to plasma, instantly igniting the Earth's surface and killing us all. But let's assume that the lasers somehow pass through the atmosphere without interacting.

Under those circumstances, it turns out Earth would *still* catch fire. The reflected light from the Moon would be four thousand times brighter than the noonday sun. Moonlight would become bright enough to boil away Earth's oceans in less than a year.

But forget the Earth—what would happen to the Moon?

The laser itself would exert enough radiation pressure to accelerate the Moon at about one ten millionth of a gee. This acceleration wouldn't be noticeable in the short term, but over the years, it would add up to enough to push it free from Earth orbit . . .

. . . if radiation pressure were the only force involved.

Forty megajoules of energy is enough to vaporize a kilogram of rock. Assuming Moon rocks have an average density of about 3 kg/liter, the lasers would pump out enough energy to vaporize 4 meters of lunar bedrock per second:

$$\frac{5 \text{ billion people} \times 500 \frac{\text{terawatts}}{\text{person}}}{\pi \times \text{Moon radius}^2} \times 20 \frac{\text{megajoules}}{\text{kilogram}} \times 3 \frac{\text{kilograms}}{\text{liter}} \approx 4 \frac{\text{meters}}{\text{second}}$$

However, the actual lunar rock wouldn't evaporate that fast—for a reason that turns out to be very important.

When a chunk of rock is vaporized, it doesn't just disappear. The surface layer of the Moon becomes a plasma, but that plasma would still block the path of the beam.

Our laser would keep pouring more and more energy into the plasma, and the plasma would keep getting hotter and hotter. The particles would bounce off each other, slam into the surface of the Moon, and eventually blast into space at a terrific speed.

This flow of material effectively turns the entire surface of the Moon into a rocket engine—and a surprisingly efficient one, too. Using lasers to blast off surface material like this is called laser ablation, and it turns out to be a promising method for spacecraft propulsion.

The Moon is massive, but slowly and surely the rock plasma jet would begin to push it away from the Earth. (The jet would also scour the face of the Earth clean and destroy the lasers, but we're pretending that they're invulnerable.) The plasma would also physically tear away the lunar surface, a complicated interaction that's tricky to model.

But if we make the wild guess that the particles in the plasma exit at an average speed of 500 kilometers per second, then it will take a few months for the Moon to be pushed out of range of our laser. It would keep most of its mass, but escape Earth's gravity and enter a lopsided orbit around the sun.

Technically, the Moon wouldn't become a new planet, under the IAU definition of a planet. Since its new orbit would cross Earth's, it would be considered a dwarf planet like Pluto. This Earth-crossing orbit would lead to periodic unpredictable orbital perturbation. Eventually it would either be slingshotted into the Sun, ejected toward the outer solar system, or slammed into one of the planets—quite possibly ours. I think we can all agree that in this case, we'd deserve it.

Scorecard:

And that, at last, would be enough power.

PERIODIC WALL OF THE ELEMENTS

Q. What would happen if you made a periodic table out of cube-shaped bricks, where each brick was made of the corresponding element?

—Andy Connolly

A. THERE ARE PEOPLE WHO collect elements. These collectors try to gather physical samples of as many of the elements as possible into periodic-table-shaped display cases.[1]

Of the 118 elements, 30 of them—like helium, carbon, aluminum, iron, and ammonia—can be bought in pure form in local retail stores. Another few dozen can be scavenged by taking things apart (you can find tiny americium samples in smoke detectors). Others can be ordered over the Internet.

All in all, it's possible to get samples of about 80 of the elements—90, if you're willing to take some risks with your health, safety, and arrest record. The rest are too radioactive or short-lived to collect more than a few atoms of them at once.

But what if you *did*?

The periodic table of the elements has seven rows.[2]

1 Think of the elements as dangerous, radioactive, short-lived Pokémon.

2 An eighth row may be added by the time you read this. And if you're reading this in the year 2038, the periodic table has ten rows but all mention or discussion of it is banned by the robot overlords.