Sophia: You're listening to Brains On -- where we're serious about being curious.

Brains On is supported in part by a grant from the National Science Foundation.

Molly: Sophia, where are we right now?

Sophia: Well, according to this GPS we're on 7th and Minnesota in downtown St. Paul.

Molly: And only a few blocks from our studios. Should we go there now?

Sophia: Yeah.

Molly: Ok, let's go. You know, GPS is pretty amazing.

Sophia: And it's pretty much everywhere.

Molly: It's the thing that helps you know where you are -- exactly where you are.

Sophia: It's on smartphones, cars, planes, trucks, ships, tractors…But what is GPS exactly? And how does it work? We'll find out right now. Keep listening -- and we'll hustle back to the studio.

Molly: Whew! Annnd … we're back. We don't need GPS to tell us that this is Brains On from American Public Media. I'm Molly: Bloom. And my co-host today is 9-year-old Sophia Choo. Welcome Sophia!

Sophia: Thanks!

Molly: Sophia is here today to help me answer a question that was sent to us from Casey who lives in Porter Ranch, California.

Casey: My question is: How does the car GPS know where the car is going?

Molly: In order to understand how GPS works, we need to know first what it is.

Sophia: GPS stands for Global Positioning System.

Molly: And the information that the GPS uses to let you know where you are -- comes from space!

Sophia: Thanks to GPS satellites like this one!

SAT: I'm Block! Pleasure to meet you!

Sophia: GPS satellites are built here on Earth. So first, they need to get into space.

<<countdown, rocket sound>>

Satellite: We're launched into space by rockets. Here we go! Wooo! What a ride!

Molly: Once they're about 12,000 miles above the earth, a smaller rocket attached to the satellite gets it placed exactly where it's supposed to be.

Sophia: There are 31 GPS satellites orbiting Earth right now --

Other Satellites: Hey Block! Welcome! It's so great to see you! Hey, do you have the time?

Molly: Each one takes about 12 hours to orbit around the earth.

Sophia: And these satellites are basically radios --

Molly: They're constantly transmitting information via radio waves -- very specific information --

Sophia: The time and their location.

Satellite: It's 12:01 and 2 tenths of a second and I'm right here. It's 12:01 and 3 tenths of a second and now I'm here. It's 12:01 and 4 tenths of a second and now I'm over here.

Molly: Your GPS, whether that's part of your phone or part of a vehicle, receives that information from the satellite.

Sophia: Radio waves move as fast as the speed of light --

Molly: Which is very fast -- about 186,000 miles per second. So the satellite sends a transmission…

Satellite: It's 12:01 and 7 tenths of a second and I'm right here!

Sophia: And your phone receives it.

Phone: Ok! It was 12:01 and 7 tenths of a second when you sent that message -- but according to my clock it's 12:01 and 9 tenths of a second!

Molly: Since the phone knows how long it took the signal to travel and it knows the speed of light -- it can use the difference between the satellite's time and its own time to figure out how far away that satellite is from the phone.

Sophia: Imagine our satellite friend Block has a reallllly long piece of string tied to it.

Molly: And that string extends all the way back to earth.

Sophia: Now imagine you're holding the end of that string -- the end tied to the satellite is stuck but you can still move around while holding it.

Phone: So I could be here and holding it, or here… or here

Molly: We know that our phone is at the end of the string -- but the end of the string could be a lot of different places.

Phone: Or here, or here, or here, or here (voice gets faster and higher pitched).

Sophia: It could be anywhere inside a specific area - like a bubble.

Molly: And that's not that helpful if you're trying to figure out *exactly* where you are.

Sophia: So in order to narrow down its location the phone gets messages from four satellites at once.

Satellites: VOICES: It's 12:01 and 7 tenths of a second and I'm right here...etc…

Sophia: Now think about a string coming down to earth from each of those four satellites --

Molly: The end of each piece of string could be anywhere inside its own separate bubble --

Sophia: But the four bubbles created by each piece of string will overlap a tiny bit --

Molly: And where they overlap is where you and your phone are!

Phone: Ah! Here I am! I am here! Thanks satellites!

Satellites: You're Welcome!

Molly: This process of using the overlapping bubbles to find a location is called trilateration.

Sophia: It's possible that the GPS will be receiving signals from more than four satellites --

Molly And the more satellites, the more accurate it is.

Sophia: But it needs at least four to work.

Molly: GPS first became fully functional in the '90s, but scientist John Langer told us it's an idea that's been around for a while.

John: You navigate off stars -- if you could have artificial stars in the sky, you could perhaps navigate better with those. So they thought about different ways of using radios in space. There were a number of programs before GPS that did different experiments. In the '70s a lot of these programs came together and they came up with the idea for the global positioning system.

MOLLY: In order to send messages to your phone the satellite actually has to be able to see it -- there can't be anything big blocking the path between it and the phone.

John: When we first built system we only had four satellites. And that was quite a challenge because they're in different orbits. So they only line up over two particular places. One was in New Mexico and the other was in Norway. Now we have 31 satellites. So most of the time you have in view 8, 10, sometimes 12 satellites.

Molly: So in a sense, those satellites can see us…

Sophia: But they're so far up there that we can't see them with the naked eye.

Molly: Now, we're going to let these transmissions sink in for a moment and tune into a different frequency. It's time for the mystery sound! Here it is:

<<sound>>

Molly: Any guesses?

Sophia: It sounds like someone pressing a lot of buttons.

Molly: That's an excellent guess. To me it sounds like someone running on the sidewalk almost -- like footsteps. The answer is traveling to us over a great distance, so hopefully it will arrive by the end of the show.

GPS hinges on both the GPS satellites and our GPS devices here on earth knowing what time it is.

Sophia: And that time has to be exact -- and EXACTLY the same among our devices -- in order for GPS to work.

Molly: To do that, we need help from a very accurate clock called an atomic clock.

Marc: Hey guys, am I late?

Sophia: That depends.

Molly: Are you here to tell us about atomic clocks?

Marc: Yep

Molly: Then you're right on time…

Marc: Yes!

Sophia: Brains On producer Marc Sanchez has been looking into what makes atomic clocks tick.

Marc: That's right. And as you might have guessed from the name, it's ATOMS. Atoms are basically the building blocks of everything around us. All matter. Atoms make up molecules, molecules make up stuff like this water bottle, my glasses. Atoms are everywhere.

Sophia: How do atoms tell time?

Marc: Technically, they don't they tell time. I mean atoms make up this chair and this table, but neither are going to tell you the time. Give the table a listen -- anything?

Sophia: Nothing.

Marc: It's nothing o'clock according to that table. But, in atomic clocks, scientists have figured out a way to isolate specific atoms and get them moving really fast. And -- this is important -- they figured out how to measure that movement. I called up Dr. Demetrios Matsakis at the U.S. Naval Observatory. He's the chief scientist there. AND he's the guy who's in charge of time.

Demetrios Matsakis: An atomic clock is a clock that gets the basis of its time from the transitions of atoms. Atoms can exist in what we call states. Where they have some energy, and they might be oscillating or vibrating in a certain way. And if we count the oscillations we have a clock.

Marc: When something oscillates, it moves back and forth and back and forth… like a pendulum on a grandfather clock, or something else that you may be familiar with: a swing! Think about when you get to the highest point moving forward… your legs are in front of you and it feels like you stop just slightly. Then, with your legs tucked in tight, and you do the same thing moving backwards. One swing, back and forth, is one oscillation. The atoms in atomic clocks are doing the same thing, only a LOT faster. Do you know how many times a cesium atom oscillates in one second?

Molly and Sophia: Ummm…

Marc: Guesses?

Molly: 30!

S: 100?

Marc: In one second a cesium atom oscillates 9,192,631,770 times.

Molly: We were way off.

Sophia: I was closer.

Molly: Yeah, you were closer than me!

Marc: In fact, we have all decided to base what we think of as a second on that exact number -- of a cesium atom oscillating back and forth.

Demetrios: The first atomic clock that was really functioning well was based on cesium. And that was in 1955. But we have atomic clocks built on other atoms as well, since then. We have ones that are built on rubidium, also calcium, strontium, mercury.

Molly: I have a kind of weird question.

Marc: My specialty.

Molly: Where would I even find a place to count atom oscillations? Do you just kind of shake atoms up in a jar or something?

Marc: In order to accurately count oscillations, atoms need to be in a very stable environment. So Inside of an atomic clock is vacuum chamber. That's where all the air and gases have been sucked out. Everything is still… the temperature is controlled. Nothing moves… except for…

Sophia: Atoms!

Marc: Right. GPS satellites, for example, use rubidium atoms. Scientists like Demetrios Matsakis insert those atoms in the vacuum. And he knows he can get them to oscillate an exact number of times by exciting the atom with radiation.

Molly: So thanks to atomic timekeepers all of our clocks tick together.

Marc: And this is really important when you think about the parts of our lives that depend on GPS. Airplanes use it to fly straight, banks use it to stamp every time you use an ATM or any transaction, power companies use it to keep electric grids in sync. And we all use it too. Sophie, you use it to get to school on time, right?

Sophia: Yeah.

Molly: Thanks Marc

Marc: No problem. Take it easy.

Sophia: Thanks, Marc!

Molly: We're working on a couple episodes right now and we want your help. We're looking into what makes fun fun and what makes gross gross. We want you to help us explain what fun and gross even are. Like, how would you explain what gross is to a robot? Or how would you explain what fun is? Send us your answers by heading to brains on dot org slash contact. We'll feature some of your answers in these upcoming episodes.

And that site -- brains on dot org slash contact -- is where you can send us all your drawings, mystery sounds and questions too. That's what Jake did.

Jake: My question is if there are three types of matter – solid, liquid and gas – what is light considered?

We'll answer that question during our Moment of Um at the end of the show. And we'll read the latest group of listeners to be added to the Brains Honor Roll. Keep listening!

Molly: You're listening to Brains On from American Public Media. I'm Molly: Bloom.

Sophia: And I'm Sophia Choo.

Molly: Now, the GPS data that comes from GPS satellites is available to everyone. The satellites are run by the government and their transmissions are public.

Sophia: In order for us to be able to harness the information and find our way around we need a GPS device or app that can interpret the transmissions for us.

Molly: When we were working on this episode, you were most interested in finding out about the voice of the GPS. Where did you think the voice came from?

Sophia: I thought it came from a robot, honestly.

Molly: Sophia talked to Karin Tuxen-Bettman from Google Maps to find out exactly where it came from.

Karin Tuxen-Bettman: The way that Google Maps builds this voice is a couple of steps. Number one: We start by building a good map. And then the second thing we do is we build a special algorithm. And an algorithm is kind of a fancy word for a recipe. The computer is trying to solve a problem and so it needs basically a recipe for how to solve it. Now, when you're on a computer some people will see the instructions for how to get to one place from another written out in text. How we get from text to the voice is pretty interesting solution. First, the team here at Google that works on the voice navigation, they record a real person speaking specially designed lines. Basically, many, many different direction words, direction sentences and they chop up all those lines and words and they make a database of very small chunks of speech. So this is a real person's voice but it's recorded. And then all those little pieces of speech are all chopped up and made into a giant database. So when you Sophia want to go from school to home, using a smartphone for example, you can then ask google maps for directions and turn on the voice navigation. And then at that moment the system searches the database for all those tiny pieces of speech and then glues them together: turn right here, turn left on Park Street, turn right on Main Street. And then that's what's spoken out to you over the phone. So there's a lot of stuff happening in just a few seconds.

Sophia: Why does the voice have to sound like a robot instead of a more like a human?

Karin: There are some words that the algorithm might come across that aren't in their database as a full word so the algorithm is programmed to predict how it would be pronounced and that would be done with several different chunks sounding out different syllables -- it would piece together and glue together multiple syllables to make that word. That's when you start getting sometimes that more robotic or unfamiliar sound to certain words. But it's the team's goal to make it sound as natural possible so it's just like your friend telling you how to get from one place to another.

Sophia: I would like to know about the new car that doesn't need a person driving it and how it can drive itself.

Karin: They're working on a driverless car, just testing it on a small-scale right now, with the goal of different sensors on the outside of the car are able to sense activity all around but also able to control the car and brake if another car in front of them is braking and things like that. GPS is a huge part of that car so that the car knows where it is in relation to everything else. It's pretty amazing and who knows? Maybe if we talk, Sophia, in 10 years, we'll both be driving driverless cars.

Sophia: There are 31 GPS satellites in orbit -- but what happens if one of them stops working?

Molly: Scientists can do things from the ground like send commands and reconfigure them -- but if something goes really wrong with it they can't bring it down to earth fix it…

Sophia: And they can't go up to space to fix it either…

Molly: So the satellites become space junk. Here's scientist John Langer again.

John Langer: When a GPS satellite wears out, when it's at the end of its lifetime and we can't use it anymore, we have to find a way to dispose of it. We can't bring it down so what we do is we push it up a little bit. Every satellite carries with it a little tiny rocket that's just used for disposal. We push it up into an orbit that no one would ever want to put something in. So all around the Earth is this called "disposal orbit," which is full of old GPS satellites.

Sophia: GPS satellites are medium altitude satellites.

Molly: There are lower altitude satellites like the space station and weather satellites -- and there are geosynchronous satellites.

Sophia: Those ones are so far up that they appear to be stationary in the sky.

Molly: Those are used for TV, radio and other communications.

Sophia: I asked John Langer how many satellites have become space junk.

John Langer: There are probably tens of disposed GPS satellites, less than 100. In other orbits like the ones that give you TV, there are 100s and 100s of disposed satellites. That seems like a lot but those distances are very, very big.

Molly: So once a GPS satellite is nudged out of the way…

Sophia: They send up another one to take its place.

Satellite: Here we go!

Satellites: It's 12:01 and two tenths, and I'm right here…

Molly: It's time to go back to the mystery sound. Let's hear it one more time.

<<sound>>

Molly: Any final guesses?

Sophia:It kind of sounds like someone starting up a lawn mower.

Molly: Ooh, that's a good one. We'll bring it back to Demetrios -- the time keeper who helped explain atomic clocks. He has the answer.

Demetrios: That's the sound of a pulsar. Pulsars are neutron stars. They're what remains of a star after it goes supernova. When the star explodes it pushes the outer part of it out in a blaze of a glory and the inner part condenses to form a rapidly spinning object about 10 miles in diameter and weighing maybe as much as the sun. Pulsars can spin as slowly as once a second or as quickly as a thousand times a second. And then they spin around -- they have hotspots that give off radiation. When that radiation passes in front of us -- if it goes by like a lighthouse beam -- we see a spike or a pulse.

Molly: So just like scientists use the oscillations of atoms in an atomic clock, there's another kind of clock where scientists can use these pulses to keep time. And the sound you're hearing is these pulses of radiations. It's what microwaves sound like.

<<sound>>

Molly: Your GPS device or app knows where you are by getting transmissions from satellites.

Sophia: Those satellites send two pieces of information: the time and their location.

Molly: Knowing how long it took that information to travel from space, allows us to find our location on earth…

Sophia: There are 31 GPS satellites orbiting Earth --

Molly: And you need at least four to help you pinpoint your location --

Sophia: That process is called trilateration.

Molly: And since it all hinges on accurate time,

Sophia: We rely on atomic clocks to keep everything synchronized.

Molly: That's it for this episode of Brains On!

Sophia: This episode was produced by Marc Sanchez, Sanden Totten and Molly Bloom.

Molly: We had engineering help from Veronica Rodriguez and production help from Abby Samuel. Special thanks to Sam Choo, Collin Campbell, Meg Martin, Nikki Tundel, Jon Gordon, Eric Ringham, MIke Mulcahy, Kate Smith and Curtis Gilbert.

Sophia: You can always listen to past episodes at our website brains on dot org --

Molly: And you can send your questions, drawings and high fives to brains on dot org slash contact. Now before we go it's time for our Moment of Um…

Jake: Hi. My name is Jake from Lancaster, Pennsylvania. If there are three types of matter – solid, liquid and gas – what is light considered?

James Kakalios: That is a great question. So gas, liquid, solid – different phases of matter – all have one thing in common: they're all matter. They all have mass. Whereas in physics we study two thing: we study matter and we study energy. This is James Kakalios, physics professor at the University of Minnesota, and author of *The Physics of Superheroes* and *The Physics of Everyday Things.* Light is a form of energy and it's an unusual form of energy. Light can be considered an electromagnetic wave, oscillating electric and magnetic fields. But it's not a wave the way other waves are like water waves on the oceanfront or lake shore. Those waves can't exist without the water whereas light doesn't need anything in order to propagate. If it's a wave, physicists used to ask, what is it that's waving? And the thing that's waving are electric and magnetic fields which don't actually require anything to exist, which is a good thing for us because the light coming from the sun has to pass through the vacuum of outer space and if it needed some medium in order to propagate we would be all in the dark here wondering, "Why doesn't someone turn on the lights?"

Molly: These names light up my life. It's the Brains Honor Roll. These are the amazing listeners who have shared questions, ideas, mystery sounds and drawings with us. They make this show what it is.

Pablo from Durham, North Carolina; Atticus and Finn from Mifflinburg, Pennsylvania; Cole and Catherine from Brentwood, California; Katalina from Rochester, New York; Sophia from Fresno, California; Keyon from China; Xavier from Alaska; Leon from Rohnert Park, California; Ulysses and Tycho from Seattle; Joshua from Belleville, Illinois; Olivia from Calgary; Luc from Ho Chi Minh City, Vietnam; Wyatt and Aubrey from Aptos, California; Mason from Orono, Maine; Max and Arlo from California; Maxima from Tinley Park, Illinois; Alex, Jacob, Malcolm and Charlie from San Jose, California; Eve from Naugatuck, Connecticut; Meekai from Barrie, Ontario; Ziggi from San Francisco; Amelia from Fremont, California; Drew from Laguna Niguel, California; Niamh, Aiofe and Kira from Kilkenny, Ireland; Harper and Nolan from Chicago; Braydon from Minneapolis; Pablo from Tennessee; Eliot from Seattle; Matilda and Coralie from Bethlehem, Pennyslvania; Freeda, Hadassah, and Rafaella from New Hemsted, New York; Tavleen from Bangalore, India; Phillip from Fenton, Missouri; Bryon from Monroe, North Carolina; Alexander and William from Colonia, New Jersey; Eleanor from Fort Collins, Colorado; Sam and Giselle from Centerville, Ohio; Elena from Minneapolis; Oonah and Cormac from Providence, Rhode Island; Cora from Columbus, Ohio; MIchael, Benedict and Gregory from Havertown, Pennsylvania; Landon from West Palm Beach, Florida; Freya from Akron, Ohio; Esther and Lucas from Guadalajara, Mexico; Milla from Washington, DC; Charlie from Los Angeles; and London from Topanga, California.

Molly: That's it for this episode. We'll be back soon with more answers to your questions. Thanks for listening!