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Speaker: Tucker Hiatt — physics teacher at The Branson School and director of Wonderfest
Topic: From Galileo to Einstein — Classical Physics 101
Host: Juliana Gallin

(Portions of this transcript have been edited for clarity)

Juliana Gallin: Hello everyone, thanks for coming to Ask a Scientist tonight! I'm just curious, are there any new people here tonight? *[Hands raise]* Looks like about ten, maybe? Well great, thanks for coming, I'm glad you're here. Tonight's speaker is Tucker Hiatt, who teaches physics up at The Branson School in Ross, and the name of tonight's talk is "From Galileo to Einstein—Classical Physics 101." So tonight we're going to be going back to school. Are any of Tucker's students here tonight? I think I saw a couple earlier. I just have to point out that this guy's students actually want to hear what he has to say *at night, during summer vacation*—so I think that says a lot about him, and I'm really excited about hearing his talk myself.

Tucker is also the director of Wonderfest, which is a whole weekend of science talks, lectures, conversations, debates—that takes place the first weekend in November. One day is at Berkeley and the other day is at Stanford. It's a lot of fun and I think you should all check it out this year. Tucker will tell us a little more about it, and you can also visit wonderfest.org to find out more.

So let's get started. Welcome, Tucker! *[Applause]*

Tucker Hiatt: I'd also like to take a minute to thank Juliana, because you never ask for applause for yourself. *[Applause]*

Gallin: Aww, thank you.

Hiatt: And Les *[Bazaar Café owner],* thank *you* for all that you do. *[Applause]*

All right, we've decided to start with a quiz. Since I'm a teacher, not a scientist—this is an inappropriately named Ask a Scientist event—I'm going to start the way a teacher should never start a class: with a quiz. So we have five questions, and we have five identical prizes. One will go to the correct answerer of each question. And the prize is, in fact, a copy of this poster. *[Points to large poster on wall.]* It doubles as a car cover. *[Laughter]* It *is* big. Again, Wonderfest is the Bay Area Festival of Science. It happens on the first weekend of November each year. This year, Saturday, November 4th it's at Stanford, and then Sunday, November 5th it's at Cal. At Wonderfest there are pairs of researchers who have dialogues, and sometimes debates, on provocative scientific questions. If you like Ask a Scientist I think you'll like Wonderfest too. The website is wonderfest.org.

Ok, so the poster represents science as strata, with psychology being a stratum of ideas lying on top of, or being grounded in, biology. As far as we know, all psychological events are biological events. Biology, in turn, is grounded in chemistry. Chemistry in physics. And all the sciences rest upon a certain philosophy of science. This isn't philosophy in general, just the philosophy of science—the meaning of the word *theory,* the general scientific approach, and the premises of science. Here you also see, within each stratum, different levels of structure. Within psychology, there's a fairly deep idea about society, an idea about person, and an idea about neurons. So you see different levels of structure featured in each stratum. We're hoping that you want to answer the questions anyway, but there might be special zeal in your answers if you want to win a poster.

All right, so let's start with question number one.

Gallin: And we're just going to have people yell out the answers.

Hiatt: Yeah, I'm afraid it's going to get ugly. *[Laughter]* Ok, first, this is not a quiz question. Please raise your hand if you've ever studied physics at the college or even graduate level. *[Hands raise]* I would like you people to leave. *[Laughter]* Please! Come on, it's crowded in here tonight! All right, how about high school? Study high school physics? How about *no* formal study of physics? *[Hands raise]* Ahhh, you. I will take *your* questions. *[Laughter]*

All right. First quiz question: who is considered to be the first modern—vs. ancient—the first *modern* physicist?

Attendee: Newton!

Attendee: Galileo!

Hiatt: Who said Galileo? I think we've got to go with Galileo. All right.

Question number two: the term *metaphysics* pays indirect tribute to which ancient physicist?

Attendee: Aristotle?

Hiatt: Aristotle. Right here, yes. Aristotle wrote a series of books. The book that came after physics, just in his ordering of the books, is now known as *meta*physics—*after* physics. And the word even fits, it's the subject, perhaps, that's beyond physics, that experiment can't address.

Question number three: what term describes a formal explanation, in science, of great scope and utility?

Attendees: Theory!

Hiatt: Theory. Good job. And it's interesting, I think, that that's not the conventional, everyday use of the word *theory,* right? We use the word *theory* in common language to mean something that's not far from just being a guess. But in science, it's sometimes said that "a theory is as good as it gets!" If you have the theory of gravitation, Newton's or Einstein's, you've got something really good there. Or the theory of electromagnetism, or the theory of evolution.

Question four: what physical theory denies the very possibility of *real* instant messaging?

Attendees: Relativity?

Hiatt: Who was the first to say relativity? Ahh, back there. Yes, *instant messaging* is a common term that means *fast* messaging. You know, where people are just typing in sentences. But *true* instant messaging is something that would mean, I guess, *instantaneous* messaging, which is apparently impossible. You may have heard some ideas in quantum mechanics argue that you *can* send messages faster than light, or even instantly, but I think we have to qualify that, at least according to the quantum mechanics experts that I've read—again I'm not one of them—that a *message* cannot be sent that way. A *signal* can't travel faster than the speed of light. So it's funny, the term *instant messaging* is a misnomer. It just can't happen.

Last question: this one's multiple choice, so it's going to be tough. And I need to draw something too. *[Draws picture on white board.]* Ok, what you see here is a scientist in a box. She's in her box there, and she's in deep space. There are, of course, stars around though, and maybe an occasional planet. If you're wondering how she's able to sit, there is a chair there and there's Velcro on her butt. *[Laughter]* And the idea here is that she's moving smoothly through space. By the way, this question comes via a truly great physics teacher here in San Francisco named Lewis Carroll Epstein. If any of you know his book called *Thinking Physics,* you're going to know the answer to this quiz question already, so please rule yourself out from competition.

So we have the scientist in a box, moving smoothly through space, far away from any stars. And we have another scientist, also with Velcro on her butt, and she, in her box, is *spinning* smoothly in space. And each scientist here has all the scientific "goodies"—as Lew Epstein puts it—all the "goodies" that she could dream of wanting. And the question is: which of these two scientists, if either, can detect her motion. Option 1: they both can detect their motion. Option 2—

Attendee: Are the boxes opaque?

Hiatt: It doesn't matter! Option 1: both can detect their motions. Option 2: neither can detect her motion. Option 3: only the first one can detect her motion. Option 4: only the second one can. Ok, in the spirit of the "answer free-for-all," how can we do this…

Attendee: Can you elaborate on "detect?" *[Laughter]*

Hiatt: As far as we know, any form of detection you want, including eyes. The question is, which of these two scientists can detect her motion in space. The one moving smoothly through space, the one spinning in space, both, or neither?

Nine-year-old attendee: Spinning!

Hiatt: We've got a spinner! Good job! *[Applause]* The idea is that only the spinner can detect her motion. How do you think, young man—suppose she had pigtails. If the box were spinning, how might she notice it, if she had pigtails? Yes, the pigtails would stand out. That's true if the box is spinning with her, or if she's just spinning inside the box. You've seen this with ice skaters. They can pull their arms in, but they can't pull their pigtails in. Those are going to hang out. And of course if the box is spinning very slowly, that might be too small an effect to notice. But if you had a very sensitive detector—a pigtail angle detector—you could figure it out.

So you wonder, what about the first person? She's got windows, for Pete's sake. Can't she just look out the window and see that occasionally a star goes by, or a planet? You'd think that she would then know that she's moving. But there's a deep problem with this that Galileo first discovered. And this is part of the reason that he's given credit for being the first modern physicist. I want to start explaining what Galileo's insight was by asking you a question: please raise your hand now if you can tell me, within say a hundred miles per hour, how fast you are moving right now.

Attendee: Relative to what?

Attendee: Six hundred miles an hour?

Hiatt: That's a pretty good clip. Any other offers?

Attendee: One thousand miles an hour?

Hiatt: Ok, I heard a few folks ask a question, which is always a good, cocky response to a teacher who thinks he knows too much—to ask a question right back at him. And in this case it's the best answer that we know how to give. And the question that was asked is, "Relative to what?" How fast are you moving—well, relative to what?! You and I are at rest, our speed is zero, relative to this room. But we're moving at a good clip relative to the center of the earth. If we're at the equator we'd be going about a thousand miles per hour relative to the center of the earth. At this latitude it's something like four or five hundred miles per hour. But you've got to specify the reference frame. How fast are you moving—*relative to what?* The center of the earth is a long way away. It's not clear that we're moving relative to it, but you've come to believe that the earth does turn. How about the sun? I've heard that we're moving at something like seventeen miles per second relative to the sun—that's not counting the rotation of the earth, just the orbital speed of the earth around the sun. And the sun is moving around the center of the galaxy at a tremendous clip—but again, when asked how fast you're moving, you've got say, "Relative to what?" Otherwise the question just doesn't make sense. You're not being rude to the teacher, you're helping the teacher understand the difficulty of the question. And Galileo was the first person to really understand the difficulty of that question.

Let's pursue this a little more. Suppose you're pulled over by the CHP. The officer asks, "Hey, how fast were you going?" Now, it's clear you do not respond, "Relative to what?" *[Laughter]* The understanding with those road signs is that the 55 miles per hour is in reference to the local piece of ground where the sign is posted. It's 55 miles per hour relative to that section of the earth, not relative to the center of the earth, or the sun, or the Milky Way. I don't suspect anyone's ever gotten away with that approach to the speeding ticket. But you see the problem. You're going say, 70 miles per hour relative to the ground, and then you say, all right, but now I know I'm *really* moving. *I'm* really the one that's moving and the ground is *not* moving. But that's a sticky wicket. Maybe some of you have been in a really smooth car, something like a Lexus that's really got very little vibration, on a very smooth road, and sometimes you forget that you're moving. You look outside the window and you see these telephone poles fly by and you say, ah yes, I remember now, I am in a car. *[Laughter]* But it's that relative motion that tells you that you're moving. And our bias is to believe that the earth doesn't move. But you know that it does—it rotates and it goes around the sun. *Relative* motion is certainly a fact, but *absolute* motion seems not to be. There is no absolute reference for speeds. So say on *Star Trek*—I'm an old school *Star Trek* guy, I grew up with Spock and Kirk and Sulu—when Kirk would turn to Sulu and say, "Sulu, what's our speed?" Sulu would say, "Warp 7, Captain." And—well back then I didn't—but now I would suggest that Kirk ask, "Relative to what, Sulu?" Because unlike a car, spaceships don't have little wheels that rub against the ground and turn at a certain speed. That's the only way you know how fast your car is going, or the fact that it's cutting through the air. But in an absolute sense, you don't know that you're moving. You might say, don't Kirk and Sulu and Spock know that they're moving relative to space? If they rolled down the window and put their hand out, wouldn't they feel the space rush by? *[Laughter]* No. Space is nothing. It's *no thing.* You can't move relative to space. There are stars in space, and they move relative to each other, but there is no such thing as "moving through space."

See, when I drew this box here, I drew this twinkie dust behind it as if the box were zooming through something that permeates all of space. *[Indicates motion lines in illustration on white board.]* But as far as we know there is no such stuff. There is no universal stop sign against which we can measure speeds.

In the ocean we have the water. In a plane, we measure the speed relative to the air you're going through. But in space there's no such thing. There are atoms of hydrogen around, but *they're* in relative motion—there is no stop sign, nothing to get a handle on. Not the sun, not the center of the Milky Way, not the center of our local supercluster of galaxies. There's just no absolute frame of reference. No absolute stop sign. Motion really is relative—and it's so hard to believe that, that I've got a fun demonstration for you. This is a low friction track. *[Indicates a long track with a cart that slides along it.]* It's got a cart on it with wheels that have very good bearings, so the cart moves quite smoothly. Mounted on top of the cart is a cannon—not a scary cannon, but one like this, with a little yellow ball that can get shot out and, I hope, go straight up. So when the cannon's triggered, the ball goes right up and falls back down into this foam-padded container. It's a self-catching cannon.

The cannon is armed when I turn this little light on here. That means that the cannon will be triggered if a little light beam, made by an LED, a light emitting diode, is broken. And there is just such a projection here on this post that will break the beam and will make the cannonball fire straight up. Now, I'm going to mount this cannon on the cart here, and try to prove to you that it fires straight up by cocking it—but before I do this I want to tell you about a saying among science teachers: If it's green and slimy it's biology. If it stinks and explodes it's chemistry. And if it doesn't work it's physics. *[Laughter]*

So…the cannon's armed, the ball's in there, there's a little projection here that's going to break the beam and make the cannonball go straight up. *[Cannon shoots the ball up into the air but doesn't quite catch it.]* Close…close. *[Makes an adjustment]* This should do it. *[Cannon successfully shoots the ball into the air in a straight line and catches it as it falls straight back down. Applause.]* Oh yeah. Now what I'm going to do is put the cart in uniform horizontal motion. And a question that's often asked in a physics class, and I'm going to put a different spin on it, is, "What do you expect the ball to do when the cart is moving horizontally?" And that's a rhetorical question, just think about the answer to yourself here. What I'm going to do is give the cart a push like this *[slides it along the track],* it'll go past the trigger, which will shoot the ball straight up, and it seems that most people believe that one of two things will happen: either the ball will go straight up and right back down as the cart moves away, or somehow, somewhat magically, the ball will "remember" that the cart is moving *[laughter]* and manage to land back in the cart in its new position.

Ok, do we all have an idea of what's going to happen? Let's try it. Now remember the slogan: if it doesn't work, it's physics. *[Ball is shot out of the moving cart, moves in a parabolic arc, and is caught perfectly by the moving cart at its new location on the track. Applause!]* You know, that takes no skill at all. *[Laughter]* What did I do, I just shoved the cart! But thank you. So what this means is that somehow the ball did "remember" the motion of the cart. But wait a minute, I thought motion was relative—what was the cart moving relative to? Well, the cart was moving relative to the track. So the ball went up, and it retained this horizontal velocity of the cart. The ball did somehow remember the constant speed to the left that the ball had when it came out of the barrel. In a sense, the cannon is firing the ball straight up, but the cannon's also—since it's moving to the left—giving the ball some initial leftward velocity. And so—

Attendee: But the ball was also moving at the time it went up, not just the cart.

Hiatt: That's right. The ball was in the cart, and the cart was moving, so the ball was moving. The ball had that leftward velocity and it retained it as it went up in the air and came back down. But what about this relativity business? Can we actually think that this ball wasn't moving? What would happen if I cocked the cannon again, and now if there were more room if I very carefully grabbed the *track* and moved the it—the cart would stay put and the trigger would then make the ball shoot up and it would go back down in a straight line as *we* would see it, but *relative to the track* the ball would be following an arc. Can you see that? Ok, earlier we had the cart moving relative to the track. We also had the track moving relative to the cart. Let's do the same experiment from the point of view of this little guy right here. *[Indicates tiny toy figurine.]* This is our friend, Yellowhead. Yellowhead is going to ride on the cart, and let's see what happens from his point of view. He sees a cocked cannon, he knows the cannon is going to fire straight up, the ball is going to go straight up and fall back down into the waiting mouth of the cannon. We've said that there's no such thing as absolute speed. So this guy, if we really believe Galileo, this guy is not going to know that he's moving. As far as he's concerned, there is a room full of people, there's a track going by, and the track happens to have a trigger on it that's going to make the cannonball go up. Let's watch. *[The moving cannon shoots and catches the ball, with Yellowhead riding on the cart.]* From our point of view, the cannonball had a trajectory like this. *[Indicates a parabolic arc.]* But for the little guy here, from Mr. Yellowhead's point of view, the ball simply went straight up and down, *and you and I and the track* went from the left to the right. We all have this bias, we want to say ok, but the cart was *really* moving. But we have to add: *relative to the room.* The cart was not *really moving,* because there's no such thing as *real motion.* There's no deep reality to constant speed.

Here's another way of putting this. *[Tosses and catches ball while walking.]* As I walk along here, I'm throwing this ball up and down. It takes no more skill to throw a ball like this, when I'm standing still, than to do so when I'm walking. Believe me, I'm not very coordinated. Just like when you're in an airplane and you ask the flight attendant for one of those pathetically small containers of nuts. When she tosses it to you, it retains the speed of the plane. The nuts don't go flying backwards at 500 miles an hour. *[Laughter]* Well, you could say that you're in this little reference frame, and what do the nuts know about speed? Right? Yellowhead sees the ball go up and down. I *[walking and tossing ball]*, right now, see the ball go up and down. In my reference frame, the path of the ball is a straight line up and down. The ball *really is* going just up and down, for me. That's *my* reality. But you guys see the ball describing a parabolic arc. That's *your* reality. The path of an object through space is relative. It depends on the observer. You guys see a parabola, I see a straight line. What's the path *really* like? That's an impossible question. You've got say, "Relative to what?" There are reference frames relative to which it's a *very long* parabola—a reference frame moving fast relative to the ball is going to seem horizontal, a very drawn out parabola. You guys see a rather steep parabola, while I see no parabola at all. But we all want to say, come on, what's the *real* path through space? And we've got to understand that there is no such thing. There's no deep reality to paths through space. This is one of the aspects of the subject of relativity. What's amazing though, is this is just Galilean relativity. Einsteinian relativity gets weirder.

So, *no real paths through space.* That doesn't mean that everything is relative. Sometimes philosophers, understanding special relativity, want to go a little farther. Maybe in philosophy everything is relative, but not in physics. Here we found, for instance, that spinning was not relative. You saw that because she was spinning, she would know that she was spinning. Whereas here, the scientist moving through space—whatever that means—doesn't know. She can't figure it out. She can look out her window and see stars going by, but that's it. It's stars going by. It doesn't mean that she's moving. Nothing can tell her that she's moving. There are no speedometers on spaceships; they make no sense. Unless you're saying: relative to earth, relative to the sun, relative to the center of the Milky Way. *But,* there are accelerometers in space, things that measure the change of speed, or even just the change of direction. And that seems to be absolute. That is, we can always measure that. You know when you're accelerating. Your pigtails stand out, for instance, or you get that queasy feeling in your stomach. Not everything's relative, but speed is.

Should we have some questions now? I could talk forever.

Attendee: I have a question, I heard that the speed of light is constant. Can't you measure your motion against the speed of light?

Hiatt: Yes. This is relativity theory. This is Einstein talking, not Galileo. And this is a hundred years of exquisitely careful experiment talking, because what Einstein discovered was just unbelievable. The answer seems to be that light is a thing that *does* have an absolute speed, but that *everybody* measures that speed as being the same. If I chuck this ball as fast as I can—let's say I've got a good arm and I can throw it at a hundred miles an hour—we're all going to agree that it's going a hundred miles an hour. But somebody driving in this direction, along with the thrown ball, at fifty miles per hour, is going to look out the window and see the ball moving at just fifty miles per hour. When you run along *with* the ball, it's not moving as fast. That's why when somebody's throwing a dodgeball at you, you run away. *[Laughter]* Because then the ball isn't going to hit you going as fast. In a sense, your speed subtracts from the speed of the ball. So running alongside that ball changes your perception of that ball's speed.

So let's try it with a light beam. This is a tougher experiment, this is why we had to wait until the 20th century to test this. You turn a flashlight on and we all see the beam come out at that magical number, the speed of light: 300 million meters per second. Very fast. Around the world seven times in a second. So you've got to have a good stopwatch. Let's suppose you have a mechanism that can measure the speed of light, and sure enough we do it, the light beam comes out, 300 million meters per second. And now you climb in your spaceship and move relative to the Bazaar Café, in the same direction as the light beam, at 150 million meters per second—one half the speed of light. You would expect, as you're racing by, this same light beam whose speed we're measuring as 300 million meters per second—you would expect to measure that same beam as going half the speed of light relative to you. *But that's not what you get.* There's been no more carefully done experiment in all of physics, than this kind of experiment. And every time, we find that no matter how fast *you're* moving relative to the source of the light beam, that beam is moving at 300 million meters per second! Whether you're going towards it, away from it, at right angles to it, it doesn't matter. Everybody measures all light beams, everywhere, moving at 300 million meters per second—even if the measurers are moving relative to each other! That's the bizarre part. We're measuring the speed of the same beam of light, you and I, but we're moving relative to each other. We've *got* to come up with different answers for the speed of the beam! We come up with different answers for the speed of a ball, the speed of a train, the speed of a cloud, anything…*but not light.* Light is exquisitely different. Einstein was the first person to realize this. And he built upon that premise the entire special theory of relativity, which has some bizarre implications, even stranger than that there are no absolute paths through space. I cannot say that that ball is *really* describing a parabola. In some reference frames it's a straight line and in others it's a very drawn-out parabola. The special theory of relativity has even weirder implications.

But yes, you can always tell the speed of a beam of light, or if you like, *your speed* relative to light. You're moving at 300 million meters per second relative to every light beam in the universe, as far as we know. Congratulations. *[Laughter]*

Attendee: Is the speed of light the same for all parts of the universe? And why doesn't light have an infinite speed?

Hiatt: I think to be fair, we have to admit that we haven't gotten around very far in the universe. You know, we've been to the moon *[laughter]* and the speed of light is the same there. But we *have* seen light coming from vastly different parts of the universe, and that light, we believe, is affected by its long journey. But no effect that we see needs to be explained by a change in the speed of light. As far as we know, light everywhere and at all times—even when going into the event horizon of a black hole—has a speed that is invariant. If you locally measure it, the speed of light will always be 300 million meters/second. Now again, it would be really nice to be able to do that experiment everywhere. But given that we can only base our assertions on what we see, so far, everything we see is consistent with that idea.

Attendee: So why is light different from everything else?

Hiatt: Ahh. So is there anything else that has this property of invariance of speed? Of speed not depending on the speed of the observer? There are other things. For instance…well, other particles. You know that there is this problem of light. Light, you've heard, is both a wave and a particle. What I find is that this duality, this ambiguity, of light is hard to understand mainly because a lot of folks don't really understand waves. Baseballs are particles; that we get. But waves are very strange things. So I would urge you, if you want to understand that wave-particle duality of light, first just study a little bit about waves, and I'm not equipped today to help you there.

So the particle theory of light says that light is made of photons. That's the name given to the little chunks of light that always travel at this enormous speed, 300 million meters/second. There are other particles that are responsible for the action of forces. The photon is responsible for all the electric and magnetic forces. There are other particles that are responsible for forces though, like gravity. You know that gravity is a force. You've heard of the gravitational field, we say that the earth has a gravitational field around it and anything in that field will fall towards the earth. Well, it turns out that just as with light, there are two ways to think about gravity: a field and a particle model. The particle of gravity is called the *graviton*—that when the earth is pulling on a mass, pulling it downward, the earth and the mass are exchanging gravitons. There really is, I'm told, a way to make good sense out of that statement. *[Laughter]* Well, gravity is a pretty tough thing to explain! How does the earth do it? Yeah, sure, they exchange gravitons. *[Laughter]* But gravitons, like photons, travel at the speed of light. And their speed is invariant, it doesn't depend on the speed of the observer.

There are other forces, too: two other forces in nature. And we have evidence that the particles that mediate those forces travel at speeds that are also invariant, namely the speed of light. There's something really special about the speed of light. It has something to do with the very structure of space and time. But you know, there's nothing like Newton to bring an audience to its knees. *[Laughter]* When we come back from the break we'll get to Newton.

Attendee: My question was: what about Newton?

Hiatt: All right. Let me tell you Newton's three laws of motion. And I imagine, right away eyes are going to glaze over, some of you are having horrible flashbacks to high school physics. But then again, *you're here.* I really appreciate that.

So, Newton's first law. The trouble with Newton's first law is that it's impossible to demonstrate. Newton's first law says that an object moves in a straight line at constant speed unless acted on by an unbalanced force. So we're got to work around the words there. First, what's a force; a force is just a push or a pull. And whether it's a push or a pull depends largely on where you're standing at the time the force acts. Forces are measured in pounds or, in metric units, in newtons. A newton is about a quarter pound. *[Tugs on the hook of a force meter.]* If I pull here with one newton of force, it's not much. This scale goes all the way up to 20 newtons. Forces, measured in newtons or pounds, are very hard to define, but I think we all have a good intuitive notion of what a force is. So again, Newton's first law: an object moves in a straight line, at constant speed, unless acted on by an unbalanced force. I said it was impossible to demonstrate this because—well, I would like to be able to get a situation where there's *no* force. Where *nothing* is exerting a force on this cart. You might say, "Well gravity's acting on it!" Yeah, but gravity is counterbalanced by the upward support force of this track. The real culprit here is friction. These wheels are pretty good, but I can't eliminate friction entirely. It seems impossible, and that's why I said it's impossible to demonstrate that most desirable case of Newton's first law: the object just cruising, in a straight line, forever. You just can't do it. But the more and more we reduce friction, the closer we get to the case of constant speed.

Now, what about not moving at all? An object moves at constant speed unless acted on by an unbalanced force. Well here, there's no friction. There's gravity, but the support force balances that out. So you'd think now it should be moving at a constant speed…

Attendees: It is!

Hiatt: Yeah, zero! Its speed is not changing. So Newton's first law, I hope, makes sense to you. But appreciate that if you're not really buying it, you're not alone. Aristotle, one of the smartest people ever to walk the earth, didn't get it. It's just too hard to see that. That things move in a straight line, at constant speed, unless acted on by a force. Aristotle thought that the natural motion of things was, in a sense, to go home, to go back to the ground. Since material objects were all made of earth, they wanted to go back home and so they just naturally came to rest on the earth.

Physics is sticky. Newton's first law, often where courses begin, is hard to understand and impossible to demonstrate fully.

What happens when forces *do* act? When forces act, then speed changes. Speed can change, or—think about the scientist in the box here—direction can change. Her pigtails' direction is changing all the time. A change in speed and/or direction is called a change of *velocity.* Velocity puts those two ideas together. For most people, velocity and speed are synonymous, but in physics there's an important distinction of velocity being speed *with* direction thrown in.

Newton's second law says that force causes change in velocity. Whenever there's just, say, one force acting on an object, that thing is going to change speed. What about this? *[Indicates stationary cart.]* No change of speed. There must be no force acting on this object. Of course there's gravity acting, but the other force I mentioned before is the support force. There's no net, or total, force acting on this cart. That's the full statement of Newton's second law: the *net* force on an object causes its change in velocity, its acceleration. And notice that word, *cause.* Sometimes in physics this law is expressed mathematically: acceleration = net force / mass. Mass is the measure of resistance to acceleration. This cart has half a kilogram of inertia here—resistance to changes in motion, resistance to acceleration. *[Adds weights to the cart.]* Here's two half kilograms. Now there's twice as much resistance to acceleration. For the same force, the more mass I have, the less I accelerate. Mass is in the denominator here, the bigger it is the smaller the ratio. As math goes, this is not too tough. But still it's pretty confusing when you have to think about what force means, you have to add up the forces, and you've got to remember that acceleration is the rate of change of velocity. And in fact velocity itself is a rate of change of position. So acceleration is the rate of change of a rate of change. That's a complicated idea! I'm just pointing this out because this law is so powerful, this describes, I think, how perhaps all macroscopic change happens in the universe. All the masses of which the universe is made—from stars, to planets, to people, to atoms—have motions that change only when we look at the net force that acts on them. This is a remarkably powerful formula, and why Newton is often regarded as being the greatest physicist. I'm quite sure Einstein would agree. The insights that Newton had are just astounding. Today we talk about Newtonian mechanics, as opposed to quantum mechanics.

So, notice the equals sign here. But If I were to *say* this equation in English, I would use the word *cause*. Acceleration is *caused by* forces. And mathematically it's equal to force over mass, but the word “cause” doesn’t appear in mathematics. Nobody says there’s “cause” going on in the quadratic equation or the Pythagorean theorem. Cause and effect are ideas unique to physics. And this formula explains, or at least describes, cause and effect exquisitely. In my class we spend a couple weeks studying this and it’s still hard. But if you see that if you could find out the net force on an object, and you could then understand how its speed changes, that’s a big chunk of Newton’s second law.

How about Newton’s third law and then we’ll take a break. This one almost everyone can recite. It has something to do with action and…

Attendees: …reaction.

Hiatt: Reaction, yes. But we’ve been talking about forces—what are *actions?* Well, in fact, Newton’s third law has to do with forces. The vague term *action* is used, I think, because often people try to refer to Newton’s third law, say, in politics. Where every political action has a reaction. All right *maybe* there, but it’s not hard and fast there of course. But in physics it seems hard and fast *and* it only applies to forces. Newton’s third law says that forces always come in pairs. There’s never been a lonely force. *[Laughter]* Forces always come in pairs, and those pairs are always equal in size -- i.e., in magnitude or in number of newtons -- and are opposite in direction. *[Adds another rolling cart to the track.]* So *this* cart can exert a force. It’s got a spring-loaded plunger that shoots out like this. What I’m going to do is have this cart push on the other. *[Carts start out together in the center of the track, the plunger is sprung, and both push off in opposite directions down the track.]* I assert that the forces are equal—that is, that the force with which this cart, the one with the plunger, pushed on the other cart was equal to the force with which the other cart pushed on the plunger cart. It looked like it, because they went apart at the same speed more or less. But you’ve got to be careful, because speed isn’t force. You can’t see forces. You can feel them, but you can’t see them. And I’m not involved in this—how am I going to know the forces are the same? Well I can perceive forces if I can see how speed *changes*. So let’s watch the change of speed here.

Attendees: Are the masses the same?

Hiatt: Yeah, are the masses the same? *[Lifts the carts and shakes them to “feel” their relative inertia.]* Yes. *[Laughter]* Tough crowd! So here we go again. Cart number one pushes on cart number two. Notice the force comes into existence—and I maintain *two* of them come into existence—one pushing this way and one pushing that way, and then they disappear. Force is not one of those mysterious “conserved” quantities (like energy and momentum). Forces come into existence and disappear all the time. But whenever they come into existence there’s always that buddy force, that partner force.

Let’s try changing the mass, for you wiseacres who think that the carts aren’t the same. All right, I’m going to really pile on the mass. *[Adds an extra half kilogram weight to one of the carts.]* So, one kilogram. Now, I maintain that the forces are still the same. This cart will push on the other one just as hard as this one pushes back. You might try it, by the way, with a neighbor. *[Laughter]* If I push Mike here, my buddy, on the forehead, with my finger, it’s not obvious at all that the same size force acted on him and acted on my finger. But that’s because fingers and foreheads have different sensitivities to touch, to contact. Try a good head butt. *[Laughter]* If we do a head butt—and this is funny because you’ll often see this in bad martial arts movies—in a head butt where it’s just forehead to forehead, it’s *guaranteed* the force on each head is exactly the same. So unless the hero has a steel plate in his head to protect his brain, it’s a silly move. Don’t do a head butt. Unless maybe you can catch the bridge of his nose with your forehead—the forces are the same, but the susceptibility to injury is quite different.

So, I could also try this. Here's another scale here, a cheapo one, but it also is calibrated in newtons of force. And I can hook these guys together, and pull, and I think you can see the little dials moving…no matter what I do, the number readings on these two scales are the same. I can't try to pull one harder than the other. I can't fool it! It's just automatic. This guy pulls on this guy just as hard as this guy pulls back. There's nothing I can do to avoid it.

Likewise, here. These carts are going to push on each other equally hard. But they're not going to respond the same way. The forces are the same, but because the masses are different the change of speeds will be different. Let's see. *[Carts push off from one another and the heavier cart rolls away more slowly.]* Yeah, this guy accelerated less. It changed its speed less than the light guy. This is like you, perhaps, and a child going ice skating. You push the child away from you—you're not a good parent *[laughter]—*you push the child away and that child goes flying off while you recoil at slow speed. But the force the child applied to you was just as great as the force you applied to the child, even though you're doing the pushing. The forces are equal, but the masses aren't, so the speed changes aren't.

Let's add another half kilogram to the cart. Now this cart is three times as massive as the first cart. Same plunger, same force, three times as much mass. I imagine you know what's going to happen. *[Carts push off from one another and the heavier cart rolls away even more slowly.]* Now this guy just lumbers along. The force only acted while the plunger came out—during that time there was just as big a force as ever but much more mass. I've been using the word *inertia*. The words *mass* and *inertia* are synonymous.

So one final point here before the break. What if we keep piling mass on here, and what if I could afford a stronger track, and a stronger cart. Would we ever reach a point where this cart wouldn't move at all?

Attendees: Sure we would…

Hiatt: You think? I've got, let's say, ten newtons of force exerted by the plunger. So in this equation, f is 10 newtons. And you might say, well that's not the net force, what about gravity? Again, gravity is being cancelled by the support force of the track. So the only horizontal force is the force of the plunger, 10 newtons. So what value of mass here in this equation ($a = f/m$) is going to make the acceleration equal zero?

Attendees: Are you assuming a truly frictionless track?

Hiatt: Yes, it's an ideal track, thank you.

Attendees: I think it would have to be infinite.

Hiatt: Yeah, the only way a is going to be zero here, is if m is infinitely large. If the mass is infinite! This is the case of the modest force meeting a truly immovable object. Immovable because it has infinite mass. Now, there's nothing with infinite mass that we know of. So what about the earth? If I now use *my* pair of plungers here *[indicates legs]* to push on the earth *[jumps],* I am exerting a force on the earth, and the earth exerted a force on me. In fact, that's why I rose, because the earth pushed me upward. That's the only way we can make sense of it. I push on the earth, the earth pushes on me, but notice: *I* accelerated. I went up briefly and then gravity brought me back down. *So did the earth.* Did you feel it? *[Laughter]* The earth's acceleration is so small, it's so subtle, that no instrument can measure it. But that little prince in the fabled story, on his little asteroid—if *he* were to jump, the asteroid would clearly recoil a little bit. The more massive the world, the less its recoil. But in fact, every step you take, horizontal or vertical, affects the earth. It's one of the most basic laws of physics, Newton's third law. And a nice place to stop. *[Applause]*

Gallin: We'll try to make it kind of a quick break, and then we'll get back to it. So save all your great questions! Also, if you want to be on the Ask a Scientist mailing list and you're not on it already, there's a sign-up sheet being passed around.

------------BREAK------------

Gallin: Ok everybody, we're going to get started again. Recess is over. Thanks for staying, everyone! Tucker…

Hiatt: Yes, thanks for staying, indeed. All right. Newton's laws give us a certain cockiness, a certain arrogance, about our ability to predict the future. At least for very simple things, like carts on aluminum tracks. I think we could maybe step up the problem a little, to maybe two dimensions. I had a one-dimensional track there before, and I think you know that if I knew how many newtons of force I applied to the cart, and I knew let's say I could take friction into account, I could predict pretty well where that cart would be, at least a few seconds down the road.

Let's make the problem more complicated. I want to pose the question, "Where will this mass, *m,* be at time *t,* where *t* is any time in the future. And *m,* you might think of as being a billiard ball. In the game of billiards there are no holes in the table. There's just a rectangular table with felt on it, a lot of friction, but I want to imagine that this is an ideal billiard table, where the ball experiences no friction, where it will never slow down, and where the collisions with the cushions are—the term is—*perfectly elastic.* You know, perfectly bouncy. So the ball doesn't lose any of its speed upon each collision. Kind of like how air hockey has this property of *almost* being frictionless and *almost* having perfectly elastic collisions. So we have this mass *m* here, it's a billiard ball, or a hockey puck. And it has this initial velocity, v_0. The subscript zero just means "at the start," when we start our clock at time t = 0. We would say this is one of the *initial conditions* of this system, this very simple system of an ideal billiard table and one mass, the billiard ball. The initial conditions are, again: v_0, and the two coordinates *[referring to a Cartesian graph drawn on the board]*, x_0 along the x axis, and y_0 along the y axis; the zero, again, indicating the initial situation. So we have v_0, x_0, and y_0. Those three numbers could constitute the so-called *initial conditions* of this system. You've got a ball on the table, it's in some position to start with, and you're giving it some initial velocity.

Now, I think you can see that the equation that describes what this ball does would be pretty complicated. But I think we'd still say that we could do it. We could figure out where this ball will be at any time *t* in the future (x_t, y_t)—assuming we know certain things, and assuming these special conditions of no friction and perfectly elastic collisions with the sides of the table. So here the ball would bounce, it bounces down something like this, bounces here—it might be quite complicated, but I think we could predict where the ball would go. It wouldn't take a terribly advanced understanding of physics to be able to answer this question pretty accurately, for quite a bit of time into the future.

Let's imagine making it more complicated. What if the table is no longer frictionless? It's a real billiard table now. The collisions with the sides are no longer perfectly elastic, and there's friction. Clearly this makes the problem harder, but I don't think it makes it intractable. I think we would just need a more powerful computer into which to feed the equations in order to predict where the ball will be. You'd have to have really good knowledge of what the forces were: the force of each impact with the cushions and the force of friction with the felt on the surface of the table. But I think we'd still say that this ball's path was predictable. A better way of saying it, since we might not have a computer that could do this problem—you know, I'm a high school teacher, our funds are limited! *[Laughter]* But I would say that the future of this fairly simple system—one billiard ball on a table—is *determined* by the initial conditions and the laws of physics.

What if we make it *more* complicated? Let's put a second ball on the table and give *it* another initial position, and let's give it some other initial velocity. So this ball's going to bounce around according to some equations that are well understood and very difficult for us to solve, and occasionally the balls will collide. This makes the system quite a bit more complicated. But I still think you would say that if we had a powerful enough computer we could predict the future of these balls, the future of this system. And I don't think we would shy away from saying that this system of a billiard table and two balls has a future that's determined, it's a *deterministic* system. As we add more balls, it's hard to see how the system would ever make a magical break away from this notion of being a determined system described by the initial conditions, position and velocity, and the laws of physics.

You might say: well, what if somebody from the outside comes and puts their hand in? Let's draw a bigger box around the table. Let's include intervening hands, not as outside forces, but as *inside* forces that affect the ball. We might be able to write an equation that would describe the hand. And perhaps you see where I'm going…what if we no longer talk about billiard balls on tables, but talk about atoms? Atoms that make up human beings! You and I are collections of around 10^{30} atoms, subject to complicated laws—but as far as we know, all those laws are manifestations of Newton's laws. The forces at work are very complicated, but they are still forces that play into that big equation $a = f/m$. If I know all the forces that act on that carbon atom here in my hand—if I know all the forces, and I know its mass, I can predict how its motion will change. It's in the cards; in the initial conditions and the laws of physics.

What classical mechanics—what Newtonian mechanics—seems to indicate is that any collection of particles, however complicated, is a determined system. Its future is—in principle, not in fact—knowable from those initial conditions and the laws of physics. This is a philosophy called *determinism,* and it was something discussed by a French physicist, about fifty years or so after Newton, named LaPlace. Pierre Simon de LaPlace said that if there were a God who had knowledge of all the forces that act on all the particles in the universe, that God could look into the future and compute the paths of all of the particles in the universe and would know the future. He said that the entire future of the universe would be visible to such a "superbeing." Now again, doing this calculation is absurdly difficult. But it is very hard to see how collections of particles, if that is in fact what we are, are *not* deterministic systems. It must be that the words I'm saying right now are the product of the actions of forces on my atoms, no? And what I'm to say in the future is, in principle, predictable, based on the current positions of my atoms and the forces acting on them! This deterministic view is most distressing to many people, and it's worth considering some counter arguments.

I want to show you a toy, a simple toy that many of you have seen before. It sometimes goes by the name of Newton's cradle. Here are five steel balls lined up, hanging from strings like pendulums, so that when I pull one back there is a collision here that is nearly elastic. The reason steel is used, even preferable, say, to superball rubber, is that steel-on-steel is very nearly an elastic collision—meaning very little heat is generated. So when I pull one back *[demonstrates the Newton's cradle effect by pulling first ball back, letting it swing back in and collide with the line-up, and watching the fifth ball fly out]* the motion is preserved. The balls' motion, of course, will eventually die out. But this is a system, as systems go (in physics anyway), that is pretty simple.

I have another story to tell you that goes hand-in-hand with the story of deterministic arrogance, the notion that physics allows us to predict the future, at least in principle. And that is the reminder of how we've come to know these so-called laws of physics. I need to make a distinction here—let's use the board—I need to make a distinction between two kinds of inferences, two ways of understanding. One is *deduction*—this is what Sherlock Holmes was famous for—as opposed to *induction.* Deduction is inference from self-evident axioms. Induction is inference from particular instances—and repetition. These are the two principal ways that we come to understand things: by deduction and by induction. Which of these two strikes you as the way that physics, and in fact all of science, proceeds? Would you say that the laws of physics are understood by deduction or induction?

Attendees: Induction.

Hiatt: Yeah, I think scientists around the world would say that we discover things by induction. We see something happening in the world that interests us, we see it happening again in the same circumstances—if we really think we understand it, based on enough observations, and it's a reliable occurrence, we say that it becomes a law. For instance, the law of momentum conservation. Here's a law in physics that I won't explain in depth here, but when this ball comes down *[indicates Newton's cradle]* it transfers its momentum to this ball, which pops out on the side here. By repeated viewings of pool tables, of balls colliding like this, of car crashes, and all sorts of collisions—physicists are convinced that momentum is always conserved in any collision. *Conserved* means that the same amount of momentum that goes in to an event, the collision, is the momentum that comes out. You've also heard of the law of energy conservation. It is also an inductively understood law. We observe that the energy that goes into any event is equal to the energy that comes out.

I want to ask you something though. Let's suppose I were to pull *three* balls back, here. What do you think will happen? If I pull three back and let them go, what's the immediate response going to be on the other side of Newton's cradle?

Attendees: Three balls.

Hiatt: So these three come in, and these three will come out on the side?

Attendees: One! Two! *[Laughter]*

Hiatt: Maybe… Maybe if I drop three, one ball will pop out, but three times as fast. That would seem to conserve momentum, for those of you who know the strict definition of momentum: mass times speed. Three balls going in slowly might turn into one ball coming out three times as fast. That would conserve momentum. Let's try it. But I want you to appreciate that unless you've seen this particular event before, it's just got to be surprising! *[Pulls three balls back, lets them swing back in and collide with the remaining two, yet three balls fly out on the other end.]* Yeah, so three balls come in and three balls go out. The middle ball is involved in both actions, the downward action *and* the upward action. It's kind of nice. Newton's cradle is a great tool for demonstrating both momentum and energy conservation. And yet everything that we know about Newton's cradle, based on the laws of physics, has been arrived at by induction: inference from particular instances and repetition. There's a deep problem with this, induction. Before I point out the problem, maybe we should make sure we see what *deduction* is.

Let's suppose we talk about bachelors. An inductive inference about bachelors is that all bachelors are well-dressed. *[Laughter]* Now it may be false, but let's say that all bachelors dress well. Because they're in the market, you know, that's the idea. So all bachelors dress well. That might be something you've observed—you don't get out a lot, you've seen three bachelors in your life, and sure enough all three were well-dressed. You see a fourth bachelor, he's well-dressed, you're really getting cocky now. *[Laughter]* By the time you see that fifth well-dressed bachelor, you're sure it's true. By *induction,* you see that all bachelors are well-dressed. Maybe it should take a hundred to convince you, but pretty soon you're a scientist. You're saying, I have this law of science that says all bachelors are well-dressed. That's induction.

An example of *deductive* inference would be that all bachelors are men. That's a deduction based on the definition—you might say "an axiom"—of the meaning of the word bachelor. All bachelors are men, there's just no arguing about that. It is an inference, but it's not a particularly deep one, because if you understand what bachelor means, you see it. But here is the key thing. Induction is inherently uncertain. Maybe that 101st bachelor is a slob! And you just haven't discovered him yet. What we forget is that all of science is inductive in nature, and so it could be that tomorrow, when I pull these three balls back, just one ball squirts out at three times the speed. I'm not going to count on it, but I don't know why! I cannot use the argument, "because it's a law of physics," because that begs the question. I'm trying to understand why I can claim that a law of physics will be true tomorrow. I can't say, well, it will be true tomorrow because the laws of physics are always true. That's called begging the question. I live my life supposing that the laws of physics will be true only because they *have* been true. And I don't know if tomorrow will, in fact, be the same as today. And I don't mean, you know, that I'll meet nicer people than you tomorrow. I mean that the universe will be fundamentally different tomorrow than it is today. Every law of physics, every particle that makes up the universe, could be so vastly different tomorrow than it is today—I'm going to get up tomorrow, of course, supposing that it won't be different, but fundamentally *I don't know why.* Why is there this continuity in nature? Why is today like yesterday, and why will tomorrow be like today? There is no physicist that I'm aware of, no scientist, no philosopher even, that has any inkling of why that's true. There are religious answers—that God makes each day the same as an encore, that he or she is so pleased with himself that he does it again. Unfortunately, that's as good an explanation as any. But I think it's wonderful to remember that, that if you need some promise of spice in your day tomorrow, just remember that you don't know if the laws of physics are still going to be working tomorrow! *[Laughter]* We've spent a long time developing them, and we think they're true; we think they *have* been true, and we think they *are* true. Will they be true tomorrow? This is the poverty of induction. That 101st bachelor might be a slob. *[Laughter]* We just don't know. And yet, all the time, physicists get cocky and say, oh, the laws of physics are the same always and everywhere. We may quibble about whether the speed of light might change by a few meters per second over a billion years—well the speed of light might change any second now! Because we don't know why the speed has the value it has! We don't know the gravitational constant has the value it has. We don't know why any of these deep physical laws are true. That they *have* been true seems valid, you know, I hope I'm not being deluded about that, I hope you're real. *[Laughter]* But there is something glorious about looking at tomorrow as really being something wonderful. Again, I wouldn't bank on the laws of physics not holding, but I cannot tell you why.

So on the one hand, we have this deterministic universe, which even quantum mechanics doesn't help. And I'll try to make this point and then open it to questions, where we can talk about determinism and free will and also about the uncertainty of tomorrow. So we have this billiard table, and it seems that if Newton and LaPlace are right, that human beings are gloriously complex billiard tables—subjected to outside forces, but we just need to draw a bigger box, to imagine a bigger billiard table to understand how all the masses interplay, and yet in a deterministic way nonetheless.

What about quantum mechanics? You've heard that there is randomness in the quantum world, an irreducible randomness—something that irritated Einstein to no end apparently, but that really does seem to be there. In a hundred years since this quantum mechanics was first being discovered and investigated, it seems like there's no way out of this. There really is some fundamental indeterminacy at the quantum level—*quantum* meaning the smallest amount of something. This is ironic because companies talk about their "quantum leap" in such-and-such technology, which in fact is the smallest amount of change they could possibly imagine. *[Laughter]*

The quantum world does have profound elements of randomness about it. On the other hand, quantum mechanics guarantees that every hydrogen atom is precisely the same as every other one. Snowflakes may all be different, but every hydrogen atom is exactly like every other one, as far as we can tell. So while quantum mechanics does have some randomness—some indeterminacy—about it, that doesn't mean that everything is up for grabs in the quantum world. Some things in the quantum world are exquisitely measurable and persistent and certain like the likeness of all hydrogen atoms.

What then can we make of adding quantum indeterminacy—quantum randomness—to this billiard ball table we call our body? Could quantum randomness inject something into our systems to make them unpredictable? To make us indeterminate? I think the answer could be yes. We don't know to what extent quantum mechanics influences human behavior. I have had a chance to talk to neuroscientists who are looking into this, and *almost* to a person they agree that the brain is not an entity affected by quantum mechanics, except to the extent that all atoms are quantum mechanical. There's no quantum randomness that makes one neuron fire in one case and not in another. But still what we want, I think, in our actions is not quantum indeterminacy anyway. We're not happy with determinism, which Newtonian physics seems to suggest is the case, but we're also not happy with quantum randomness. We want something else, which is usually called *free will.* And I don't know how to find that, except to try to exercise it every day that I live! I don't see room for it—and I'm speaking purely scientifically now—I don't see how we could have metaphysical free will, given what we know about the world. We can sure have emotional free will, that when you get up in the morning you decide what you do—you *think* you decide what you do *[laughter]*—and that's very important. You also think that the laws of physics are going to be the same that day, that's another good thing to believe.

Einstein was fond, I'm told, of quoting the philosopher Schopenhauer about free will. Einstein said this thought of Schopenhauer's gave him comfort when he contemplated the evil in the world. This is the quotation. Schopenhauer said, "We can do what we want, but we can't want what we want." That strikes me as being quite profound, that it's doing what we want that we perceive as freedom. And that's awfully good; I like to be able to do what I want. The people at Guantánamo cannot do what they want. I can do most of what I want—I can't fly, I understand there are still restrictions—but I can't *want* what I want. Nonetheless, we build a society that tries to encourage certain wants that are beneficial to the majority. So I don't claim to have an answer to the question of free will, I just think this is something worth considering.

But I promised I would shut up and listen to questions—perhaps about deduction and induction, about free will vs. determinism, or about the uncertainty of tomorrow.

Attendee: What about Einstein, didn't he work mostly deductively though? I mean he had an idea, and he had axioms, and he extrapolated from that.

Hiatt: Yes. Take, for instance the special theory of relativity. I claimed earlier that the foundation of that was this insight that the speed of light is invariant. From that axiom, all the rest of special relativity is deducible. It's remarkable. But that axiom itself is arrived at inductively. Only experiment after experiment tells us that the speed of light really is invariant. And Einstein would have been the first one to say that if experiments deny that axiom, then we'll toss it, we'll throw it out. We have a tough time, though, then explaining why so many other results of relativity are verified.

Attendee: Did he believe it before he proved it?

Hiatt: Yes—well there were other reasons, you know, we imagine what it was like for this little guy to ride on the cart that was shooting the ball upward, and how he would see the ball just going up and down whereas we saw the ball following an arc. Einstein, we are told, did something similar. Einstein imagined himself trying to ride along with a beam of light. Even as a young man he did this. But as he studied electromagnetism more and more—how these changing electric and magnetic fields made the light—he couldn't understand what the light would look like as he was riding alongside the beam unless it kept moving at the speed of light. And so this is how he arrived at this axiom, or postulate, of relativity. Today we don't think of it as a postulate or axiom because it's not self-evident. We have to do experiments to see if it's true. To Einstein it had to be true to be consistent with the rest of electromagnetic theory, which James Maxwell developed about 25 years before Einstein.

So we still use deduction in science, but fundamentally, science's so-called axioms, its deepest principles, rest on induction.

Attendee: I wonder if you could talk a little more about Schopenhauer's quote, because I'm not sure I understand. Is he saying we're not able to control our desires?

Hiatt: I guess he might argue that if you—let's say you have an urge to drink. You also have another urge to keep yourself from drinking. That amalgamation of wants—the urge to drink and the urge not to drink—and all the other urges and wants that you have—make you who you are. And that *those* are outside of your control. Look, I'm trying here. *[Laughter]*

Attendee: Well, you can change what you want by changing what goes on in your mind. For example, the guy who wants to drink. He goes into a tent, a temperance guy gets to him, and now he doesn't want to drink. Or he wants to drink but he also wants *not* to drink, which he didn't want before. So he changes his behavior and he changes what he wants.

Hiatt: But in the end he makes a decision. Whether to put that cup to his lips. And that decision event is an interplay of atoms, subject to forces—I'm not trying to denigrate human freedom, the fact that the more I believe I can control my life, the more I can.

Attendee: *[Inaudible]*

Hiatt: A *chaotic* system is sensitively dependent on its initial conditions. Now remember back here we had the initial conditions in this billiard table: the initial speed and the position of the ball. Here, I want you to consider the break, that first stroke in a game of pool or billiards—I think, well pool for sure—where the balls are set up into a triangular array and your job is to use the cue ball to send these balls flying. I think the break in pool is an example of a chaotic system. That is, if you were to make that first stroke and photograph where all the balls finally came to rest after the break, and then the balls were re-racked and you were challenged to do it again—to break the balls just the way you did the first time—you couldn't do it. The outcome of this system after the break, the result, is sensitively dependent on the force and angle of the stroke on the cue ball and the initial minute spacings of the other balls. If you change those just a little bit, then the outcome is vastly different. This is an example of a chaotic system. And it's not particularly arcane, this is an everyday example. There are systems that are chaotic like this, and those that aren't. Like a marker balanced on its end. The outcome is fairly certain. The initial conditions determine the outcome, but it's not terribly dependent on the initial conditions. There are huge ranges of angle that will result in my marker falling over this way; there are huge ranges of angle that will result in it falling over *this* way. Maybe right at the cusp—when the marker starts "perfectly" vertial—then there's sensitive dependence on initial conditions. But it's not as dramatically demonstrated as with the billiard balls.

So you, Sir, say that the brain is a chaotic system. That right now if some neuron in my brain fired a millisecond later, then there would be some drastically different outcome in my behavior?

Attendee: Yes. *[Inaudible]*

Hiatt: Well, I don't know…

Yes, a question?

Attendee: What about the Heisenberg principle? Doesn't that indicate randomness?

Hiatt: In the quantum world, the uncertainty principle describes how the position and the speed (or momentum, to be precise) of a sufficiently small particle are jointly indeterminate. You cannot specify exactly the position and speed of a particle at the same time. If the universe, at the micro level, is governed by quantum mechanics, and if there's a sensitive dependence on initial conditions, maybe the quantum uncertainty would give rise to a future that is fundamentally unpredictable. I think that's exciting. But still we know that the future is, to some extent, predictable. Maybe though, some chance events in the universe are the result of quantum indeterminacy and are active at the heart of a chaotic system. Seem plausible?

Yes, another question?

Attendee: What is the opposite of gravity?

Hiatt: Things falling up? Yeah, so is there any "anti-gravity?" Well on the local level, if I take a kilogram of something and drop it, we know of nothing like that—nothing that falls up. You might ask, "What about anti-matter?" Anti-matter has the opposite electric charge of ordinary matter. So the proton is positively charged, the anti-proton is negatively charged. But an anti-proton will still fall *down* when you release it. It still attracts every other bit of matter in the universe. Gravity seems to be a purely attractive force, unless you want to talk about this mysterious—and I think poorly named—topic of dark energy. People don't call that gravity, though—*dark energy,* or the *cosmological constant*. On a grand scale, it does seem as though matter repels other matter. And that seems to be one way of describing this hyperexpansion of the universe, that perhaps happened at the very early stages and is even happening now—not as violently though. So anti-gravity? No. Weird repulsive force on the cosmic level? Yes.

Attendee: I've never been able to understand how Einstein, when he put the two clocks—one in one airplane and one stayed behind—they came back with different times. What was going on there?

Hiatt: All right, let me describe the experiment this gentleman is talking about. It's an attempt to test a result of relativity. Before I go on here I just wanted to know, how are we doing on time?

Gallin: Let's take a couple more questions.

Hiatt: Ok. I've mentioned that the heart of relativity is this principle of the invariance of the speed of light. From that invariance of the speed of light, relativity is deduced. Parts of it are tested though, still. One of those parts is called *time dilation*—the fact that relatively moving clocks run at different rates.

And notice I said *relatively* moving—because if I had said the *moving* clock runs slowly, you'd have to say:

Attendees: "Relative to what?"

Hiatt: Right. So what I have to do is compare two clocks. I get two very accurate clocks because this effect is subtle unless speeds are very high. And by "high" I mean at least getting close to the speed of light. We can't make large clocks move at that rate. We can make small—very small—clocks move at that rate—I mean atoms, or fundamental particles that act like clocks. But let's do it with real clocks. Let's take an atomic clock, a clock with accuracy to maybe ten or twelve significant figures, and put it at SFO. And we'll put another clock in a plane that's going to fly around at five or six hundred miles per hour for a few minutes. These two clocks start perfectly synchronized, synchronized to ten or twelve significant figures. But when one clock goes off and takes a trip, the key thing is *speed*—not *where* the clock goes. It's *speed,* relative to the other clock is what matters. As long as the one clock is traveling and comes back to the other clock, and we compare them now, we find that the clocks aren't synchronized anymore! The clock that took the trip is behind; the relatively moving clock has run more slowly. And it's to the amount, rather precisely, specified in Einstein's equations. This is one of the results that's been tested again and again, to incredible accuracy.

Now, *why?* Why do clocks not run at the same rate when they're moving relative to each other? I think you have to say it's because of special relativity. Because the speed of light is invariant. That's as deep an explanation as you can get. Will it ever be the case that people have a deeper feeling for the truth of relative clock rates? Yes, when we all have grown up around very fast moving clocks. Then it'll be common knowledge that you'd better check your clock when you've come back from your trip, because it's not going to be synchronized with the clock back home. But until that day comes, until our spaceships are traveling at 20%, 30%, 40% of the speed of light, we're just going to feel that this is not the way nature works.

But it's not strange that relative seems strange! Our intuition developed at speeds of a hundred miles per hour. Why should that intuition apply at speeds of half the speed of light? It's not surprising. It's our tendency toward induction to say that because clocks stay synchronized at relative speeds of a hundred miles an hour, that they must also stay synchronized at half the speed of light. But experiment says they don't, and deductive inferences from the invariance of the speed of light say they shouldn't.

Attendee: Just a question on that then, if we're talking about the time reference of those clocks as relative to each other, why is it that one goes slower than the other?

Hiatt: D'oh!! *[Laughter]*

Attendee: I could go back to a Newtonian question if you'd like! *[Laughter]*

Hiatt: No, no! I can give you the essence of the answer to this. I have seen the explanation in detail, and it's gnarly. But here's the essence of the question. One of these clocks sits there at SFO and the other takes a ride in a plane. And I said it was the one that took the ride in the plane that is the slower of the two clocks. But you're saying, wait a minute…couldn't we put ourselves in the frame of reference of the plane, and then the clock at SFO was the one that took the trip? Relative to us in the plane, it's the SFO clock that's "flying around" somewhere.

The trouble is that, in fact, only one of the two clocks did change space-time reference frames. Or better said, only one of the two clocks did accelerate. And remember, while speeds are relative, accelerations aren't. So only one of the two clocks actually took a trip. In the ideal case of space flight, there are twins instead of clocks—this is called the *twin paradox.* (But it's not a paradox anymore. It was at first, but people resolved it upon deeper understanding of relativity.) The twin paradox says that Moe and Joe are identical twins; they have the same age. Moe is a space cadet and Joe is a stick in the mud, stay-at-home kind of guy. So Joe is on earth and Moe takes a high-speed space trip out to Alpha Centauri and comes back. And when he gets back Moe has aged maybe a year, while Joe has aged twenty years. But couldn't we say that from Moe's point of view, Joe climbed onto Spaceship Earth? And Joe blasted off the other way and then took a trip and came back and landed next to Moe's spaceship? No. Only one person, only Moe, really did change space-time reference frames by accelerating. That's the key to the resolution of the twin paradox.

Attendee: And negative acceleration going the other way doesn't count? *[Laughter]*

Hiatt: No. For instance, Joe on his Spaceship Earth, will never feel the so-called *inertial effects* of acceleration. You know, when you're in your car and somebody punches the accelerator, you feel it! The seat pushes against you, you're thrown back. Even turning—when you turn, which is a form of acceleration—not changing speed but just the act of turning—when you turn it's a kind of acceleration. And you feel thrown inside the car—like the woman's pigtails, in the box. That turning is also an acceleration, and accelerations are absolute.

Attendee: Well it would change the mass, so wouldn't it move slower? If the acceleration gets bigger, then so the mass… I'm just thinking about how the acceleration would affect the mass.

Hiatt: Oh ok, you're alluding to the fact that not only does high speed play tricks on time, you've heard that it also plays tricks on mass. My understanding here is hazy—you'll notice how the title of this talk was *Classical* Physics 101. *[Laughter]* So, would the person, say in this high speed spaceship, perceive him or herself to be more massive? No. No more than any person looking at his or her own clock would perceive time to be running differently. It's only when we on earth see the high speed spaceship go by, that we would say, look, that person's clock runs more slowly or that person's mass is extra large. Now, how do we see their extra mass? We wouldn't see them as getting fatter. We would see it in their attempts to accelerate. When they try to accelerate, to go faster and faster, there would be more inertia, and that's what you're saying. Yes, it would be harder to turn them or to speed them up or slow them down.

Attendee: So wouldn't the clock get slower because of the inertia?

Hiatt: No, I think those are both effects of relativity, but one does not depend on the other. It's not a *because.*

Attendee: Could I ask a classical question? Can you explain the difference between centripetal and centrifugal force?

Hiatt: Yes. "Center-seeking" and "center-fleeing" forces. These are two aspects of the same force, but seen from different reference frames.

All right. You're in the car. You're on your first date, you're a little shy, you're the driver—don't think this has happened to me! *[Laughter]* Ok, ok, *I'm* the driver. And I have my true love-to-be on the seat near me, and it's one of those old fashioned cars with bench seats—*very* low friction. *[Laughter]* So we're driving along and she, of course, is clinging to the door handle. She wants no part of me, but I would like…a part of her. *[Laughter]* No, no *all* of her, of course. So you know what I do. I see the opportunity—a turn coming up. And I can turn to the left or I can turn to the right. Which way should I turn?

Attendees: Right! Right!

Attendee: Wait, are you driving in the US or the UK? *[Laughter]*

Hiatt: Ok, here's the car *[drawing],* here's the top of my head, there's the part in my hair, there's the steering wheel. It's a very ugly car. And here she is over here clinging to the handle. *[Laughter]* But I've greased up the handle, she doesn't have a prayer. And here's the road. And I want her *to come towards me! [Laughter]* So you see what I do. I turn right. Now, what *we* see is that I turn right and the side of the car pushes to the right on me, and allows me to make this turn. That's a *centripetal* force. And in fact, a similar force acts on the car, namely the friction on the wheels, pushing the car sideways to allow the car to make the turn. If there's no such centripetal force then this car's going straight into the divider here. I rely on the friction of the road, by turning the wheel, to allow me to turn to the right.

All right, but what about *her.* Poor Susie. Susie here is not wearing her seat belt, I've greased up the seat, I've greased up the door handle, the car follows this curved path to the right *[indicates drawing]* and poor Susie, obeying Newton's first law of motion, goes in a straight line at constant speed. There's no door to push on her. So she goes straight, while the car and I turn into her. But what does she perceive, before she files her lawsuit? *[Laughter]* She perceives some magical force pulling her over towards me, as if she *is* subject to a force—a force that seems to push her to the outside, when in fact she's really just going in a straight line. Now why do I say *really?* Because we have this bird's eye view *[indicates drawing],* which is called an *inertial frame of reference*—a frame of reference that's not accelerated. In our frame of reference we are not accelerating, but here, in Susie's frame of reference, since the car is turning, it is accelerating. It's a special reference frame. And she will perceive this pseudo-force, pulling her to the outside, called the *centrifugal* force, a "center-fleeing" force. But it's an artifact of her being in this weird turning reference frame. Centrifugal forces arise in turning reference frames. Whereas centripetal forces, from our non-accelerated point of view, *cause* circular motions.

In the washing machine, when the clothes are spinning to get the water out of them, the walls of the washer push inward on the clothes to make them go in a circle—otherwise the clothes would go flying out just as the water does. So there's a centrifugal force on the clothes, making them go in a circle. There's no force on the water, because the water squeezes through the holes, so it goes off in straight lines, flying out of the drum. But the clothes, all bunched up, have an inward force acting on them—a centripetal force. The water droplets in this spinning reference frame would say, oh no! A centrifugal force is pushing us out! But we know that the water droplets are really just going in a straight line, not constrained by the walls of the washing machine.

So centripetal is "center-seeking" and centrifugal is "center-fleeing." Centripetal force is a real force, from our non-accelerated point of view, making things go in a circle. Centrifugal force is an apparent force, in this weird reference frame that is rotating.

Gallin: I think on that note—that was a great question—we got to learn Tucker's dating tips! *[Laughter]* Shall we call it a night?

Hiatt: Let's call it a night. *[Applause]*

Gallin: Thank you so much for coming!