Episode 53: Consistent Variables with Brent Knopf and Matt Sheehy

Physicists: Ben Tippett, Fiona Burnell, Brian Sullivan

The Titanium Physicists Podcast

www.titaniumphysics.com

Transcribed By William Blewitt

Ben: Oh hello old friend. It's good to see you. Let's talk about this word "fascination". It describes an unquenchable urge which compels our hearts to quest and be captivated. As long as there are elegant explanations to complicated phenomena science will never lose its romance. Over the years I've traveled the world indulging in my fascination of physics and now I find that a new hunger has woken within me – a fiery need to share these great ideas with the people around me. And so I have assembled a team of some of the greatest, most lucid, most creative minds I've encountered in my travels. And I call them my titanium physicists. You're listening to the *Titanium Physicists* podcast and I'm Ben Tippett. And now allez! physique!

[1:49]

Ben: In 2010 a band called the Insane Clown Posse produced a music video presenting a song of theirs called miracles. The song itself was uncharacteristically earnest. The two clowns, Violent J, and Shaggy 2 Dope listed the wonders and mysteries of everyday life. The music video was so visually dissident and the lyrics were so ignorant that the video quickly went viral. Lyrics like, and pardon the language, "water, fire, air, and dirt, fucking magnets how do they work?" Generating popular memes ridiculing the ignorance of the two clowns. But here's the thing, magnets are strange and it's not absurd that a person should wonder about them. The first and most common example of an invisible force that people encounter in their regular life. And certainly isn't strange that we should wonder at them. Opposite poles attract each other. And it seems that magnets mostly only affect metals. But some metals aren't magnetic at all. The Earth produces a magnetic field, so does the sun, and so does all those weird car lifting magnets out of the dump, and so do the floppy magnets on my fridge. It's not clear what these four things have in common and yet they're all generating and interacting with this mysterious invisible field. How do they work indeed Shaggy 2 Dope? It's a question which motivated some of the greatest scientists in history. And so today on the Titanium Physicists podcast we'll be talking about magnets. So I was sitting around minding my own business when I got an email from a musician in Portland who said he liked the show. His name is Brent Knoft and he's got an indie rock band called Romona Falls out of Portland. They sound so great. So great that I was like yeah this is really good indie rock. I should have them on the show. But then before I could put any plans in motion Brent asked a favor. It's his birthday he says and he wants me to phone his friend Matt Sheehy from the indie rock band Lost Lander to talk to him about physics. And Lost Lander is a tight indie rock group as well. And they just put out an album called Dirt and they're close to finishing a second record which will be announced soon. So good. Good I said. It's been a while since we've had two people on the show, let's do it again. So I invited them then and there to come on the next episode Matt Sheehy of Lost Lander and Brent Knopf of Romona Falls welcome to the Titanium Physicists podcast!

Brent: Thanks for having us.

Ben: So Matt, Brent, for you today I've assembled two of my most powerful titanium physicists. Two friends who haven't been on the show in a dog's age. Arise Dr. Fiona Burnell. Dr. Fiona did her undergraduate at UBC her PhD at Princeton. She is now faculty in the physics department at the University of Minnesota where she's a specialist in condensed matter. Now arise Dr. Brian Sullivan. Dr. Brian did his PhD at Dartmouth College and he's currently the physics teacher at the Maine School of Science and Mathematics. He's an expert on magnetohydrodynamics in the sun. Alright everybody let's start talking about magnets.

[4:45]

Brent: Are photons a form of electromagnetism? And if so is the magnet magnetic force that gets like put out or whatever, is that electromagnetism and if so is it photons that's being transmitted? What's being transmitted? Or is it a warping of that field?

Brian: It's not the only way of understanding interactions in physics but one way that not only physicists but also popular culture is very captivated by is by encapsulating the interactions we see in virtual particles called gauge bosons and the same way in which the Higgs Boson is the one to which we attribute the mechanism for mass. The photon is the gauge boson for electromagnetic interactions. Suppose you're standing on roller-skates and you have a friend and he's standing on roller-skates. And you toss a massive object to your friend. So when you do that you're going to roll backwards because you threw an object forwards. And then your friend catches it and that pushes them back, the act of catching it. And then if they throw it back to you they go even further back. So if you can imagine tossing something back and forth but instead of drifting apart due to the tossing back and forth, you were pulled together. That's kind of an idea of a gauge boson causing the interaction between the two of you on the roller-skates.

Matt: So is there a gauge boson in a magnetic interaction? Is there a similar particle like the photon between two magnets?

Fiona: The photon is both actually.

Matt: Oh it is?

Fiona: So the photon, essentially it's the same thing as saying I have some electric signal that's propagating through the air kind of like a wave in the water. And it comes from my antenna and my antenna vibrates. Now along with that electric signal you always get also a magnetic wave. So whenever you have waves, the electric waves and the magnetic waves always travel together. And so in a sense, the photon is both the gauge boson and so that kind of mediator behind electric and magnetic forces.

Brent: Wow.

Brian: So electric and magnetic interactions are completely tied to each other when you talk about light. We call them electromagnetic and they come from that hyphenated combination of the two effects because our historical understanding of the two grew together after a time of understanding the two separately. So there are interactions that are magnetic that do not have a very noticeable electric component and there are electric interactions like if you rub a balloon on your hair and then your hair stands up, that's electric but not magnetic.

Brent: So like two magnets interacting they're not emitting light necessarily? They have the magnetism part but not the photon part? Like why aren't magnets glowing? It's not that they're emitting photons beyond the range of human eyesight right? There's something else going on?

Ben: Yeah, when Brian was saying that the photons mediate the force. That's a really quantum mechanically way to imagine it. Because in quantum mechanics, little packets of force are exchanged between two electrons say, as they fly around and do their thing. In our macroscopic world we're use to thinking about our magnetic and electric forces in terms of a field. So there's the magnetic field and the electric field. And Maxwell said these two things, magnetic and electric, are two different parts of a whole. But take a step back. The deal with an electric field is that if you have a positive electric charge, say you rub your head on a balloon, get it all positively charged, if you bring another positive charge around it, they'll both be emitting electric fields and then they push off of each other's electric fields and that pushes them apart or if one is positive and the other is negative, it pulls them together. Similarly, if you have two magnets, like fridge magnets, just normal magnets, they're emitting a field. Their field is polar; there's a north and a south pole. And the deal is that if you try to bring a north pole to the south pole of another magnet they'll stick together; they'll attract. And if you try to bring the north pole to the north pole of another magnet they'll repel. That's the old opposites attract thing. So the deal is that we were studying these things because magnetism, this magnetic field is what causes compasses to align north-south. Electric fields, you can use van de graph generators and stuff to make strong electric fields. But it wasn't until the late 1800s that this Maxwell guy took a look at the equations describing electric fields and how they change and magnetic fields and how they change. And how they're related to each other. And he came up with essentially they're called the Maxwell equations. It's a description of how electric fields and magnetic fields are two sides of the same coin. So there's a rule of thumb when it comes to electric fields and magnetic fields. So you can imagine both of them having sources right. So the source of a magnetic field is a magnet something with a north pole and a south pole. And the magnetic field looks kind of like, I'm sure you've seen drawings of the earth's magnetic field. It kind of blooms outwards in rings and the rings go from the north pole of the magnet to the south pole of another magnet. And the thing that creates electric fields are electric charges so electrons, protons, stuff like that. So if you have a changing electric field. So if you have a bunch of electric charges and you wiggle them around, you make the electric field that they're emitting change, by moving them around in space. That change will generate a magnetic field that a magnet can respond to. Or conversely if you have a magnetic field, electric charges that are moving near a magnetic field will respond to the existence of the magnetic field. They'll feel a force from the magnetic field in a particular way. So specifically what happens is if you have an electric charge near a magnetic field line, if the electric charge is moving, it only feels this if it's moving, if it's moving near a magnetic field line it will feel a force that will kind of move it around in a circle around the magnetic field line. And one of the really fun explanations involving this is you know the northern lights? So the Earth has a big magnetic field that it blooms out the south pole goes up to the north pole, great big magnetic field. If charged particles fly in from the sun, there's always this space radiation coming off the sun, these charged particles – electrons, protons, flying off from the sun. When they try to hit the earth, to get to the surface of the earth they have to get past all these magnetic fields and because they have electric charges they feel a force that kind of make them spin around, circle around the magnetic field. So what happens is when they try to hit the earth they get caught in the magnetic field. And they end up spirially around the shape of the magnetic field and they'll either end up going north or south and so all these charged particles instead of hitting the earth irradiating us from space, they end up following the magnetic field and hitting the atmosphere around the north pole or around the southern hemisphere around the south pole. And that radiation hitting the atmosphere is what we see as northern lights.

[11:46]

Brian: So the property that says whether you interact electromagnetically or not is charge. And we can divide whether it's electric or whether it's magnetic in a very simple way. If charge is not moving, the interaction it undergoes simply due to having charge is electric. But if the charge is moving, either individual moving charges, or a collection of them which we call an electric current, named by analogy to a current of water, then that interaction caused by the moving charges is magnetic.

Fiona: I guess the other thing that I wanted to add also is that the intimate connection between electricity and magnetism…so Ben was talking about a situation earlier that if you rub the balloon on your head and your hair sticks to it; so your hair is being pulled up by the balloon. And in that case you can think of that as just a sort of force that the balloon is exerting on your hair, but there is nothing sort of propagating. Whereas a photon or a signal you pick up with an antenna, this is due to some kind of propagating wave. And it's the propagating waves that require both electricity and magnetism together. So anytime you're sort of sitting still and all you see is a static force, that needn't necessarily have both electric and magnetic properties. But if you send light or you send radio waves or what's going on in your microwaves, that's actually both electricity and magnetism at the same time.

Matt: Because they're moving? Is that the reason why?

Fiona: Yeah basically, because you have sort of propagating waves. It's very similar to waves in water, that if it wants to propagate it has to have both.

Brian: One thing that's a little bit complicated, I think, is that if charge is completely not moving the interaction is electric and we call it electrostatic because the charge isn't moving. If charge is moving in a particular pattern but suppose that pattern is fixed, that steady motion of charge would cause a static magnetic field – we call that magnetostatic. And so we can have moving charge that doesn't cause waves, electromagnetic waves or light or radiation. And you can have static charge not moving at all that causes electric fields. But if you have a pattern that is moving in time, that is when you start getting the waves involved and it becomes completely electromagnetic.

[14:08]

Matt: What would be a catalyst to put it over that threshold? Are you just talking about a material in general will have a magnetic property or an electromagnetic property.

Brian: I think that's a good direction to go.

Fiona: Yeah because then we can talk about levitating frogs…which I think should be a central focus.

Brian: So there are sort of two kinds of motion of charge that are fundamentally what's behind magnetism. And one we call spin and has to do with an inherent apparent spinning of the fundamental charges, primarily electrons. And the other is the motion of charge, like we've been talking about. So maybe in elementary school we might have wound coil of wire around a nail. So you have like an old fashion phone cord helix winding around the nail and if you attach that wire to a battery, you'll find that the nail has become a magnet and can pick up paper clips and can pick up other magnets and all the great things magnets do. And that twistiness of that wire pattern is very important for getting magnetic field to be generated. And you don't actually need the nail there but for reasons having to do with spin, the nail will make the effect much smaller. And my background is actually kind of related to the motion of charge in plasmas where Fiona's background is in the spin end of things in condensed matter.

[15:35]

Ben: I mentioned earlier that if you have an electron and it tries to hit the Earth and it gets caught in the magnetic field it kind of moves in a circle or a spiral… it kind of gets pulled in a circle shape.

Brian: It gyrates.

Ben: It gyrates. There's kind of a connection here between the motion of an electron and the magnetic field that it generates. The idea here is if you take a ring and you make electrons march, say counter clockwise around the ring, so you have a whole bunch of electrons moving all in a circle, what that will do is it will generate a magnetic field equivalent to the magnetic field that would cause them to march in a circle if they were passing through. So motion, circular motion or rotation of electric charges generates magnetic fields. And there's an interesting thing about magnets which is that electric fields are generated by static charges. There's electrons and protons or positive charges and negative charges. And you say that the electric field is kind of emitted by one and kind of absorbed by the other. The straight lines come out of one charge and they enter another. And you never see that with magnets. With magnets there's always these two poles or where the magnetic field always goes out of one poll and enters the other.

Fiona: It's basically saying you can't have a magnet with only a north pole.

Ben: Yeah.

Fiona: They always have north and south. You take your bar magnet and you cut and cut and cut it. But no matter how far you cut it it's always going to have a north and a south pole.

Ben: Yeah and so what this is an indication of is that magnetic fields aren't generated by a source. Magnetic fields in our universe are always generated by moving charges or charges moving in a circle. That's pretty fun, the deal is just like Brian's electromagnet you get the electrons marching in a circle as they spiral around your nail and that generates a magnetic field down through the nail. The neat thing is that quantum mechanically we say that electrons have spin which means that mathematically it's like they're spinning. Electrons are point particles so it's not clear what we mean by them spinning because they don't have an edge to go around the middle the way the earth spins or the way a basketball spins. But mathematically it's like they have a spin and because they have charge and a spin, individual electrons even the ones that aren't moving anywhere have a little magnetic field. So when Brian was saying that when you talk about say Fiona who works with things that are really really really cold, when they're really really cold the electrons stop moving around but they'll always have this spin. So they'll always have this tiny little magnetic filed. So if you get something cool enough these magnetic fields emitted by the little individual electrons all start interacting. And that's the difference between something hot and something cold.

Fiona: Sort of. Sort of

[18:11]

Ben: So I want you to imagine an atom. So it's just this clump of protons and neutrons around which are spinning a whole bunch of elections. And there's usually the same amount of electrons as protons. So when we want to make a solid, like a metal, what happens is you'll have two say iron atoms right next to each other and they're so close together that what they'll do is say, "Hey we're right next to each other why don't we share some electrons. You can take a couple of my electrons when you need them and I can take a couple of yours." They're like neighbors with cups of flour of something. So you got these electrons moving back and forth and that kind of sticks to two adjacent atoms together.

Brian: And that's called a covalent bond.

Ben: So if you want to create essentially a big lattice, a big crystal structure, a big chunk of metal, you take a gabillion of these little iron atoms and you stick them all together – chunk chunk chunk. So they're all sharing stuff with their neighbors and if you move one neighbor the other neighbor is like "Hey you can't move that far away from me." And so you get a nice rigid structure. Kind of independent that each atom, with its electrons, has its own magnetic properties because each of the electron in the thing has its own spin so it has its own magnetic field. But each electron is also spinning around the nucleus. So that's another little circle it's making. So each individual atom itself will have an overall magnetic field depending on the details – how the electrons are spinning around it, how many electrons there are. Are there the same number of electrons spinning up as spinning down. It's complicated business depending on how many electrons you have per atom.

[19:50]

Brian: So what makes some metals magnetic and other metals neither magnets nor magnetically active. Their electron configurations are different for different metals and in some cases every electron has a partner and electrons play by a certain rule. Kind of like if they went to a traditional square dance, there might be some expectation that the partner you have is the opposite kind of person from you. And wears the opposite costume and all those different things.

Brent: You mean like a republican?

Brian: Exactly. So these conservative electrons play by a rule that we call Pauli exclusion and it says if you have a partner it needs to be the right kind of partner, the kind that doesn't have the kind of spin you have. So if you have a spin up electron here, you have to have a spin down electron to be partnered with that one. And many materials have electrons paired up so that every electron has a partner and the overall atom has no spin and those are called diamagnetic. And then the other possibility is that there is an electron that doesn't have a partner and that gives the entire atom overall spin and that's called paramagnetic. And certain special paramagnetic atoms are very eager to interact with neighboring atoms that also have a lone electron that isn't paired and those are called ferromagnetic and iron is the prime example. But there are basically six elements that have that property that they can become very strong magnets.

Fiona: So Brian earlier on was talking about this pairing if you like where electrons want to sort of partner up with other electrons that have the opposite little magnetic moments and then they don't contribute to this magnetic moment of the atom that Ben's alluding to. And so you can have a situation some materials where you have lots of electrons that actually are single, much like 20-somethings of the modern era, there are many men that are single. And they're all pointing the same way and they make this large magnetic moment which is what typically happens in a ferromagnetic material.

Matt: So spring break?

Fiona: Maybe spring break in the computer science department or something.

[22:04]

Ben: So say you have a ferromagnetic material like iron. You can make iron have its own magnetic field. Usually in diamagnetic materials what happens is often you can have different atoms making up your material that have different magnetic moments but they all kind of cancel out. What happens in iron, say when it has a magnetic field is fascinating. So imagine you've got two bar magnets – two straight rectangular magnets.

Fiona: Yeah we're with ya.

Ben: And imagine they can swivel around their middle, kind of like a compass needle in a compass. You know how it can spin? So if you have two of these magnets, north attracts south so what will happen is if they can both swivel and you bring them close to each other, they'll want to align so the north pole of one is pointing to the south pole of the other. Choosing which one is which is random. So you might do the experiment sometimes and north is facing right and south is facing left. And you might do it another time and they reorient themselves and south is facing right and north is facing left. So which one lines up with which one is kind of just a matter of chance. So what happens in these magnets is, essentially there is a little bit of thermal noise that keeps these things spinning. So imagine you set a similar experiment up in your kitchen. And you've got a whole bunch of these little magnets that you're putting on little stands and they can swivel about their little stands and you're putting them all on the kitchen floor and occasionally your dog runs through and sets everything spinning.

Brian: Right now we're talking about rotation of magnetic moment which means the direction the miniature needle on each atom points. That can indeed quote-unquote spin or rotate but that's completely different from the quantum mechanical spin we were talking about.

Ben: Yeah.

Matt: So it's the same term for something completely different?

Ben: Yes. Right.

Matt: I feel like that as a lay person who does a lot of reading about this kind of stuff I feel like from time to time I will encounter this phenomenon where two super different things are named the same thing. And I've just got to say I'm really glad that shows yours exist to help people like me figure out what the heck you guys are talking about.

[24:20]

Ben: You're right to be frustrated at the stupid books that use spin interchangeably. Alright so imagine you have your kitchen floor occasionally your dog comes in and messes thing up. But given enough time what will happen is the magnets will kind of align with their neighbors. So one of them will be like, "Hey I'm going to point this way." And then the magnets immediately adjacent to it will realign themselves in accordance to the magnetic field of the first one. So it will kind of spread out as all the other bar magnets on my kitchen floor reorient themselves. But the deal is there's nothing special about where one particular domain starts growing from. So you can get multiple domains and they'll all choose orientations in patches. And you end up with a big patchwork of orientations. Over here there's a bunch of magnets that are all pointing the same way towards the living room. Over here there's a whole bunch of magnets, they're all pointing the same way towards the kitchen sink. Over here they're all pointing the same way towards the bedroom.

Brian: And the bigger a neighborhood gets in one direction, kind of like a gerrymandered congressional district, the effect grows.

Ben: And the deal is that the size of them depends on how often the dog runs through the kitchen or how warm the material is. So if you cool the material down or if you keep the dog out of the kitchen metaphorically long enough they'll all just kind of orient themselves in the same way. And this is essentially what happens when you magnetize a big chunk of iron. You're forcing all these domains to face the same way so that all the magnets in the kitchen are pointed the same way. All these little domains and overall you end up with a great big magnetic charge. Your nail or your screwdriver has an overall magnetic field that comes from adding up all these little magnetic fields of all the individual atoms in the thing. So all the atoms in the magnetic field are pointed in the same.

Brent: It seems kind of intuitive to me that coldness makes that happen. It seems like it would require energy to switch the gerrymandered district to the opposite party.

Brian: So what is meant by cold is all kind of relative to what you're talking about. So there's a temperature above which iron is completely not ferromagnetic. It's called a Curie temperature, named after the usual Curie. And above that temperature the spins have no preference for what their neighbors do. So if you take a block of metal and heat it up above that point then apply a magnetic field externally, keep that external field in place and cool it down to below I think it's 900 Celsius, the Curie temperature for iron, but I don't have that off the top of my head. Then you transition to a change of phase. The same way that when you take water and cool it down it turns to ice, non-ferromagnetic iron turns into ferromagnetic iron and it's the same kind of phase transition.

Fiona: I think also what Ben was alluding to was I think if you actually set this up with bar magnets on your kitchen floor you wouldn't have enough magnets to get these rigid, frozen, gerrymandered districts. But if you take a magnet even on your fridge, there are just so many more iron atoms than you could possibly put on your kitchen floor. So it's a slightly different situation. I think what Ben was alluding to is that you can demagnetize iron. You can have demagnetized iron. And that's kind of the soup of these different districts and are aligned one way or the other. If you then take your piece of iron and put it in a magnetic field this applies a strong external pressure in one direction so that those districts if you will that have the quote-unquote the wrong orientation come under a lot of pressure to line up with the ones that have the right orientation. And once their all aligned it becomes extremely difficult to change the direction that the things are going. If that makes sense.

Brent: Why don't you get the district super upset about something and tune everybody's televisions to Fox news while they cool down and they can't change the channel and everyone starts believing pretty much the same thing.

Fiona: That's right yeah.

Brian: Put some numbers into these domains or district sizes. We right now have pushing close to 10 billion people on earth. So that's 10^{10} people. And there are about 10^{10} iron atoms per domain in a block of iron, whether it's magnetized or not magnetized. And 10^{10} obviously on a human scale is a very large number. But if you consider a mole which is kind of the relevant size of number when you're talking about macroscopic groups of atoms. That's 10^{23}, so 13 orders of magnitude more than when you're talking about the domains. If you had a mole of iron you're likely to have 10^{13} domains in that or congressional districts if we want to use that analogy. So there's a huge number of atoms per domain and a huge number of domains in say a refrigerator magnet.

Brent: So there's an absolutely immense number of these iron atoms all orienting their magnetism in the same way.

Fiona: And also what Brian was emphasizing was that there are a massive massive number of these iron atoms in each congressional district. Although I really like the idea of trying to build this thing on your kitchen floor. I think it would look really cool. But you would really need a lot of fridge magnets to see multiple domains.

Brent: I don't know why the word domain is significant in terms of the quantity of iron. Maybe it's the certain threshold beyond which iron gets a charge. I don't know.

Fiona: Well a domain is the scale of which … so if you just take a piece of iron like a frying pan that you have in your kitchen. You'll notice that it doesn't stick to your fridge for example. It doesn't appear to be magnetized. And that's sort of like saying if you look at the United States as a whole and you broke up the popular vote and kind of averaged it out it's probably neither strongly democratic nor strongly republican. Let's say on average it looks pretty close to 50/50. But now if you zoom into certain areas of say San Francisco. You would find that if you polled within that area you would find a very strongly democratic orientation. So a domain is sort of the little area in which you look. So when you look locally if you'll find that everyone is thinking alike. But globally you have this pattern where some people prefer one party and other people prefer the other. So if you kind of look at the country as a whole you would say it's not particularly one side or the other. Whereas individual regions may be strongly affiliated.

Brent: Got it. So it's like an individual region with a strong affiliation.

Fiona: Yeah.

Brent: Cool.

[31:14]

Fiona: Can we also talk a little about diamagnetism also? Mostly because… So everyone listening should go out and google Andre Geim. I think he's actually the only person who has won both the Nobel and the Ig Nobel Prizes. And his Nobel Prize is for work on graphene and his Ig Nobel prize is because they levitated a frog just using a very strong magnet. And it's kind of cool. You can look at the video online of this frog suspended in a big magnetic field. But the way they did this is by using diamagnetism. So what we're talking about with iron which is the business of these electrons if you like on the individual atoms. An electron is like a bar magnet and has a little magnetic moment. And when all those magnetic moments align then each atom basically behaves like a little magnet. And that happens in some materials. In other materials, things like water, you don't have that kind of effect. And basically all the electrons are sort of partnered up. Their individual magnetic moments don't contribute. But if you put them in a magnetic field. If we were talking earlier about how a magnetic field applies a force on a charge. And we were also talking about how electrons, they're always kind of moving; they're never really still. So any time you apply a magnetic field on a material, if each atom doesn't have kind of a net magnetic moment then basically what happens is that magnetic field applies a type of force on electrons as they're running around. And then we talked about earlier that one way to make a magnet is to basically coil up a wire and have a current run through that wire. And that's called an electromagnet. So what happens as you apply a magnetic field that makes the electrons move and as they move they generate a magnetic field. And this is called diamagnetism and you can use it to levitate frogs and other objects.

Brian: Diamagnetism has another extreme case so if you have these lone singleton electrons that don't have a partner and they're roaming around the metal that's when you can potentially get ferromagnetic effects. But if every electron has a partner then the material can be a perfect diamagnet and completely reject magnetic field lines. They can just push them out. And that's how maglev trains work. There's something called the Meissner effect.

Fiona: Well that's in a superconductor.

Brian: So electrons can have a special kind of duo called a Cooper pair. Yes, that's more complicated.

[33:56]

Matt: Yeah that was going to be one of my questions actually. I grew up believing that one day I would have a hover board. It was one of the things I was really looking forward to as a kid, reading sci-fi books and movies and stuff.

Ben: Yeah me too, geez.

Matt: That if you could get superconductivity to work in warm objects then you could make a hover bored theoretically.

Fiona: Well you don't need…and this is why the levitating frog is kind of cool…as you can notice as you take two fridge magnets and try to stick that two south poles together you see that they push each other apart. And you can use that force to actually levitate things. And you don't strictly speaking need a superconductor in order to do that. Although for reasons we don't need to talk about here there are numerous advantages to doing it with a superconductor. But you can actually levitate things by just applying a strong magnetic field. Now the problem is I don't know how many people with pacemakers also have this fantasy of hoverboarding. But the kind of magnetic fields you would need to levitate a person would probably have other problems. But the thing about superconductors is that this diamagnetic response, that basically the electrons move around and make their own little magnetic field and that creates a force downward basically because it creates a magnetic field going in the opposite way. That response is strongest in superconductors and so in a sense you get the maximum bang for your buck if you made a superconducting hoverboard track.

[35:33]

Matt: Cool. And Fiona you keep referring to levitating frogs because you can actually stick a frog over one of these things and it will float?

Fiona: Yeah. So what you should really do is google it and see the video. But it's kind of a joke in the community because this guy who won the noble prize from the University of Manchester, Andre Geim, prior to that he actually published a paper in which they levitated a frog. Just take a frog and stick it on top of a really big magnet. And the point is the frog is mostly water. Water is not a superconductor but the frog is mostly diamagnetic so if you put it in a large enough magnetic field you can levitate it.

Matt: No way.

Brian: The frog is just a bag for water. It's a convenient size and pretty entertaining because what a frog does while floating is entertaining.

Brent: I can't wait to see this.

[36:36]

Ben: So do you kind of get the mechanism for why things float the way they do? So the deal is if you press two north poles together they repel each other. And one way to illustrate that is in the magnetic field lines coming out of the north and south poles. So the magnetic field lines come out of a magnet and stream down, they're just like a whole bunch of party streamers, little wires coming up from the North Pole looping down through the south. And if you try to plug a North Pole into a South Pole it's very simple because the lines go straight from the north pole into the south pole of the other magnet. But if you try to push two north poles together or two south poles together what happens is all those field lines say, "I don't want to go there." And so they get really squished up together when you try to really push the north poles together. That squished up magnetic field is essentially the repulsion force that you feel. It's almost like the magnetic field as you squish it is like a spring. What happens is there are some materials that don't accept any magnetic field in them or they make their own magnetic field inside them that opposes the magnetic field that you're trying to put them in. And the net effect is that if you take one of these superconductors or frogs in this case or even just an opposite electromagnet that's punching the opposite way. The field between them gets all squished up and it supports it like a spring. And that's essentially what's going on. That's why it's levitating. The magnetic field between the two objects is getting all squished up and it pushes up the thing so it floats.

Matt: So you're saying that water just intrinsically has one of those magnetic fields that's strong enough?

Fiona: Well I think you should distinguish between water and your fridge magnet. If so water in and of itself is not magnetic. It won't stick your fridge. You can try that at home. However if you take a cube of water and you put it in a very big magnetic field basically what happens is it alters the way the electrons are spinning around and temporarily developes a magnetic moment. And that's basically because of the motion of the charges of the water. But as soon as you take it out of that magnetic field it becomes non-magnetic again. Whereas with your ferromagnet if you bring it in they have all these little domains that line up and then when you take it out it's magnetized. It'll stick to your fridge or whatever.

Ben: It's like a person who doesn't have any particular opinions but is really ornery and obnoxious. And any time you go up to them and ask "What's your opinion on global warming?" And they say "I don't care." And global warming is happening and is soon as you have an opinion that you're trying to foist on them they're like "No it's not! I don't believe you!" And that's where the pressure comes from.

Brian: But the scale of field strength that causes this affect with water is massive, like the biggest magnetic field you're likely to encounter in your life. Does anyone have a guess what that would be?

Matt: An MRI.

Brian: An MRI. So an MRI has a several tesla field which is very large. And that doesn't levitate you. If you had a much stronger field than that in principle you could levitate a person. But if you've ever received a bill for an MRI you'll see that they're extremely expensive and part of the reason for that is because it costs a lot of energy to generate extremely strong magnetic fields because we use electrical currents to generate them.

Fiona: So I once visited a place where they had a lot of these really big magnets and before going in you have to watch a safety video. And the safety video consisted mainly of footage of what would happen if you released an object that could be magnetized in the presence of this magnet. So they had like a hammer flying through these walls and break some of the magnets. So that's one of those reasons you want to be careful around really strong magnetic field.

[40:32]

Brent: The question I really want to ask but don't really know how is: Is there a magnetism equivalent to a black hole? Because I know a black hole has to do with mass and gravity and getting super big. Like could you ever have so much magnetism between two points that it creates this kind of…

Ben: One thing in relation to that there's a fundamental difference between mass and charge because there is only one type of mass but there's two types of charge. So gravitational forces between normal matter are always attractive. But electric and magnetic forces can be both attractive and repulsive. And there are two flavors of things that undergo this interaction.

Fiona: But in a sense when you think of a black hole as a breakdown in something, in a mathematical sense a black hole is something going horribly wrong with space-time. If you think about charge. If you think about lightning for example we do experience this breakdown if you like where there is so much charge accumulated in this part of the sky that you have this catastrophic event which is lightning where charge goes shooting through the air into the ground. That's in some very loose sense a little bit like a black hole. A black hole is like where you have so much mass that everything gets sucked in and lightning is like where you have so much charge that everything just explodes out.

Brian: In terms of drama the topic that's actually the focus of my PhD thesis is probably the closest thing to catastrophic behavior in terms of magnetic field and it's called magnetic reconnection. This is the mechanism behind solar flares.

Matt: That sure doesn't sound catastrophic. Reconnection sounds like a nice thing.

Brian: Right like two magnets that haven't seen each other in a long time meet up for a drink. What happens is if you take two regions of magnetic field that are oppositely directed and bring those two regions in contact with each other, and you do this in a superconducting or an extremely good conducting medium like the solar wind plasma, or the superconducting electron sea in a metal, those regions of oppositely directed field annihilate each other at the point that they meet. And in the same way magnetic field lines are frozen into or stuck to the domains, in a superconducting situation with a levitating magnet, the magnetic field lines are frozen into the plasma. And the motion of that plasma created those fields. So on the sun you get these ropes. So if you've seen Spiderman 2 where Dr. Octopus…

Ben: Oh yeah! He's got the arms and he's squishing the sun back together!

Brian: …miniature sun. It's got these ropes of fire coming out. So those ropes are contained by magnetic field on the sun and that was really painful to watch in the movie. But it is also what really happens on the sun. You get these structures that have a lot of vorticity in them so there's twistiness in the magnetic field. And if you've ever taken a yo-yo string and gotten it way too, twisted, you'll see that it kinks up. The string has two strands that are twisted around each other but if you twist those enough it will kink and start to twist a supercoil around itself. And magnetic fields do those same things for the same reasons in these very good conducting environments such as high temperature plasma. And you can get where the kinked part of the yo-yo string in this analogy pinches off. And if you have a highly kinked, tensile structure and you suddenly snap it a lot of energy is released from the energy that was stored in the field configuration. And that goes into kinetic energy of the particles if the plasma. So you can have a big bubble and you can cause a solar flare or another event called a coronal mass ejection. Magnetic reconnection is an important mechanism in the release of energy in both of those cases.

[44:48]

Brent: Is the release of that energy is that a significant cause of the northern or southern lights?

Brian: It is the main cause. So we haven't talked at about the earth's magnetic field and how it comes about. But on the earth and the sun there's a stirring of a highly conductive fluid in the mantle of the earth and throughout the internal workings of the sun. And since the motion of charge is an electric current, and electric currents, like we said with a nail example, cause magnetic fields, you can have the motion of a fluid cause a magnetic field. And in certain situations that motion can evolve so as to cause the field that causes the motion that caused the field. And that circular process causes a stable field to exist for a long time. So the sun is stirring itself using its magnetic field and that stirring is causing the magnetic field that causes the stirring. However, that is not permanent and the sun basically every 11 years, for the history of our ability to observe the magnetic field of the sun, reverses. And there's a sunspot cycle so lots of sunspots and then almost no sunspots then lots of sunspots and then almost no sunspots. And that's been extremely regular every 11 years for about 400 years. Until the last 20 years and we're expecting to see an oscillation and everything is all kind of screwed up. And the last time that happened was around Shakespeare's lifetime, when there was a mini ice age around northern Europe.

Brent: Oh no should we be completely terrified right now?

Brian: A cause for concern is if the mini ice age is linked to the magnetic anomaly that happened then. Suppose you have anthropogenic global warming and you have solar induced global cooling, it might cause you to misinformation about both of those things because they're happening at a time that they partially cancel each other out.

Brent: Does the earth's magnetic north-south orientation switch ever?

Brian: It also does and it does so on about 100 thousand year timescale. And the reason we know that is because magma oozes out of a crack along the center of several oceans where either tectonic plates are moving towards each other or moving away. And since the earth has a relatively large magnetic field, when that rock which contains a lot of iron goes from being above that Curie temperature we talked about to below it, the magnetic field record at the time it became rock and no longer magma is sealed in. So if we take a slice of the rock going from the center of the subduction zone outward we can see it pointing north and then pointing what we currently call south and then pointing north and then pointing south. And by looking at the rate at which the plates move in terms of centimeters per year and the thickness of each of those pointing directions we can deduce the duration of each orientation and the time in between the flips.

Brent: How near are we to the next flip?

Brian: I think it's just about time to somewhat overdue or something like that. And since the time of Carl Friedrich Gauss in the 19th century, I believe the overall magnetic field strength of the earth has decreased something like 20-25%. But you think you'd hear a lot more about doomsday.

Ben: Oh no you do. You hear about it all the time on doomsday things. Everybody's like the magnetic field is going to go away and we're all going to die.

Brian: But speaking of the earth and bar magnets, we have compasses and we have a north end on the compass and it points a certain direction. But what direction are north ends of magnets attracted towards?

Matt: Oh right the opposite one, south.

Brian: So before we understood this we named the North Pole "north". However, it's a magnetic south pole.

Matt: Whoa.

Brian: Mind blowing.

[49:12]

Brent: But why aren't the magnetic and geographic poles aligned?

Brian: Well the geographic North Pole is the center of the spin axis of the earth; the earth is rotating. And the magnetic north pole and South Pole coincide with the ends of the axis of the magnetic field. And those happen to not be aligned, and need not be even closely aligned. They're more misaligned for some planets than ours, and they're not statically misaligned to each other. So that axis is not only tilted relative to the earth's spin axis, it's also offset.

Matt: So it's sounds to me like the churning inside the earth, like the mantle of the earth is unrelated to the spin of the earth itself.

Brian: It's not unrelated to the spin of the earth. We believe that it's necessary to have a spinning body and even differential spinning. Meaning for example, we believe the earth has a solid iron and nickel alloy core and outside of that a liquid metal core. And the two are not spinning at the same rate as each other. So if you have say a ball spinning inside a ball. But the inner ball is spinning faster than the outer ball. There's a shear spinning at the boundary of those two balls. And that shear is an important ingredient in general, generating a magnetic dynamo. Which is what we call this mechanism for generating permanent magnetic field.

Matt: Got ya. But what is causing that spinning?

Brian: The most honest answer is we don't know. In general in physics things continue to do what they're doing unless something stops them from doing so. So that's one thing that goes on. But the earth condensed from a cloud of gas and already had angular momentum and just like when an ice skater pulls in his or her arms the rate of spin increases, when the earth condensed out of that gas everything kind of spun up from condensing since it already had some angular momentum and the center is spinning even more because it's more condensed. There are some thoughts of importance of having a moon or moons for tidal squeezing that causes the core to stay molten or might play some role in developing vorticity or little whirlpools inside the liquid metal inside the planet. But exactly how that happens is not totally understood.

[51:55]

Brian: I think we should talk about how guitar pickups work since you guys are both musicians.

Brent: Hell yeah.

Brian: Somehow we didn’t get to that. So those involve both copper coils and permanent magnets inside the coil and there’s typically one coil under each string. And the way that works is because the strings are made of magnetically active metal, ferromagnetic metal – you can magnetize them. So when they get closer to the string they’re more magnetized and when they’re further away they’re less magnetized. They move back and forth over the magnet and that causes a wobble in the magnetic field and part of the electromagnetic interaction we talked a little bit early on is when you have a changing magnetic field string that causes a twisty electric field around that region. And in this case since there’s coiled wire there that causes a voltage. When you think about pickups, do you know single coil vs. humbucker?

Brent: I’ve heard about them both but I don’t know exactly how they’re different.

Brian: So if the narrow pickups that you usually see under strings are called single coil and there’s one coil under each string. But the problem with that is that all of the power in North America involves a 60Hz AC current. So what you hear if you grab the end of a mic cable is [humming noise]. And that’s always the same note. And the reason for that is that your body is basically a sack filled with water and electrolytes. So your body is acting as an antenna for that 60 Hz signal and that’s what you pick up. And magnetic pickups are also very good antennas but what you can do is take two of them, wind one of the coils left handed and the other right handed and put them right next to each other. So a humbucker pickup is twice as wide and its purpose is to buck the hum. So because coils are oppositely wound, the noise component which comes from far away is canceled out from the voltages but the vibration of the string causes a voltage of the same kind in both coils. So you get a better signal-to-noise response from the humbucker.

Matt: Awesome.

Brent: Don’t like loudspeakers behave the reverse where you send electric charge and it meets a magnet and that pushes and contracts against the diaphragm.

Brian: That’s right.

Matt: Maybe Brian and Brent and I should start a band and we just write a song that's like in response to that Insane Clown Posse song call "Magnets, This Is How They Work".

Brian: We can release a clean-lyrics version.

[54:36]

Ben: Well that was pretty crazy. Okay thank you Brian. Thank you Fiona. You've pleased me. Your efforts have borne fruit and that fruit is sweet. Here is some fruit. Brian you get a donut peach. Good, sweet. And Fiona you get a pumpkin.

Fiona: You want me to eat a whole pumpkin?

Ben: Well just a part of it. Ah, good. Good pumpkin. Alright I'd like to thank my guests Matt Sheehy of Lost Lander and Brent Knopf of Romona Falls. I hope you guys had fun. Please look up their albums on the internet. There will be links to their bands on our website.

Hey Tiphyters listen. There are four things you need to know. Firstly, please leave us an itunes review. Whenever I feel sad or tired I check the itunes store. And I read your reviews and they make me feel better. Your nice words are giving me power! Second, there's a podcast app called Podiversity for the Android phone. It's a subscription for content-based app and it's nearly like Netflix but it's for podcasts and they pay us money for each downloaded episode. So if you get the app listen to our show on it. Good work. Now t-shirts. Go to our store off the Ti-Φ website and buy a sweet shirt. Some of them were designed by brilliant designer Chelsea Anderson from Calgary. They're wonderful shirts! They don't even wear out. You can wear them for years and they won't wear out. And they're gorgeous. People will talk to you on the streets if you're wearing them. Fourth thing, if you'd like to contact us you can send us an email, my address is Barn@titaniumphysics.com. I forward people their fan mail so if you want to tell Jocelyn how great she was and if you want to tell Dave how good his jokes were you can do that and I'll pass them on. Also we're on Twitter and Facebook and Tumblr, if you can find me on Tumblr good for you. Okay that's it for the main part of today's show. Remember if you like to listen to scientists talk about science in their own words you might also like to listen to other shows on the Brachiolope Media Network. I'm going to talk about *Astrarium*. *Astrarium* is about astronomy and my good friend James is on it. Or you can listen to *Science…sort of*, that's pretty fun. There are other ones *Technically Speaking*, *The Collapsed Wavefunction* is about chemistry. Hey guys we need other shows on science – a biology show; that would be good. A show on birds. I don't know, a medicine show? Okay, cool. So the intro song for our show is by Ted Leo and the Pharmacists and the end song is by John Vanderslice. Until next time my friends, good day. And remember to keep science in your hearts.

[57:40]

Matt: When that happens, when the radiation hits the earth and people in the north start seeing the northern lights are people in the south also seeing the northern lights or does that radiation just usually pick a pole to go to?

Brian: Both happen at the same time. At the same time there's activity in the northern, we call it auroral oval. There's also comparable activity in general in the southern aurroral oval. And we call the northern lights the Aurora Borealis and the southern lights the Aurora Australis. You can actually see the same thing on every planet that has a magnetic field. So there are aurora on Jupiter. There are aurora on Saturn. But not all of them involve visible light, some of them are ultraviolet aurora. So it's like if you were at a rave and you had ultraviolet lights on, you could put on your rave gear and go under the aurora on Saturn or Jupiter and bask in the auroral glow with your glowing party gear.

Brent: That's awesome. How politically incorrect is it to refer to the northern lights when you're down at Antarctica? Like when you're south of the equator do people say, "Oh do you have the southern lights?" Is it the same thing?

Brian: Probably. They might just call them the Aurora. I think most of the people in Antarctica are scientists and they're more likely to say aurora than the northern lights.

Brent: I don't know how many listeners are south of the equator but I just want to be sensitive to those people.

[59:05]

Brent: So would an MRI magnetize the iron in my blood?

Brian: There's an interaction between all the atoms in your body and the permanent field in the MRI. The way the MRI works is it creates a very strong background field that orients the spins of atoms in your body. And then there's a jiggling field added on top of that very strong field. And we can see different responses from different kinds of atoms in response to that jiggling field once it's superimposed on top of a very strong uniform background field. So it does magnetize the blood but not in an "X-men pulls the blood out of your body Magneto" sort of way.

[59:50]

Brian: Does anyone have fridge magnets handy?

Fiona: I own about 5.

Brian: If you have the business card size and thickness, if you take those and put them magnet size to magnet size, you'll notice that when you drag them across each other they go "clack clack clack clack clack" in one direction but they slide smoothly in the other direction. This is called a…an array that maybe we can edit me knowing the name. This is stripes of spin. So there's stripes of north poles and a stripe of south poles and a stripe of actually pointing horizontal. So the North Pole nor the South Pole is pointing out of the magnet. And this allows us to make magnets that very strong stick to the refrigerator but only when they get very close to the refrigerator. If you don't have a magnet handy you should definitely grab two of those business card type magnets and put them back to back, sticky side to sticky side and drag them across each other. It's really fun.

Brent: That's awesome.

[1:00:07]

Brian: Another neat thing about metals is that the reason they're shiny, the reason they feel cold when you touch them, the reason they're typically strong, all of that is because of the way they share these electrons. And it's kind of just mind blowing. It's beautiful. Up to a certain energy the electrons belong to a certain host nucleus and above that energy all bets are off and they can at any instant in time anywhere in the whole big block of metal. We call it a Fermi sea. Is that right Fiona? That's still the current term?

Fiona: Yep.

Brian: Not the Dirac Sea?

Fiona: Dirac is reserved for relativistic. Which is not typically the case in metals. You have a Fermi circus. Yeah.

Brian: So at that energy they're just wandering around. And they can conduct heat very well because they have very low mass. And that means metals are very good conductors not only have electricity but have heat and that makes them feel cold when you touch them because they conduct the heat away from your hand. And they're shiny because of the way incoming light interacts with the charges it encounters when it hits the surface of a metal.

Matt: Does that mean that material has an electric current running through it all the time, just with those electrons jumping around from nuclei to nuclei.

Fiona: Yeah so the usual situation, if you just have the metal sitting there in your room, the electrons are all running around but. I went to this seminar recently and someone shared these great picture of people crossing the street in Tokyo.

Brent: So it's like a bit chaotic?

Fiona: Well there's people moving around but they're all going in different directions so you don't see net motion of people. And that's the situation for electrons in a metal typically. But then if you connect your metal to a battery. Then that's kind of like introducing a…

Brian: It's like putting a pressure on one end like you attached it to a pump if it were a hose

Fiona: I was going to say like putting a dragon on the road but I was trying to think of something more creative than a dragon. But ok, so you put a dragon in the middle of New York or Tokyo and suddenly everyone wants to go away from that and so you're going to get this motion. So people are basically still running around and it's not like and army all marching together, they're still all kind of running around frantically. But on balance you're going to see people going away from this dragon.

Brent: Can I put forth a really bad analogy any have you guys correct it? So let's say you're at a metal show and there's like a mosh pit where all the electrons are dancing around chaotically and the bouncer comes in and all the electrons start going away from the bouncer. Is that kind of what's going on?

Fiona: Yeah so that would be like if you took like a local electric field and put it on your metal. So that would be like the bouncer and the current would go away. Or the bouncer comes in and everyone's trying to get out the other side.

Matt: Or like a fire breaks out in the theater and everyone wants to get out of the theater. Is that a terrible analogy? Sorry.

Brent: No, I'm just thinking, what was that band that that happened in Boston?

Matt: It was like Whitesnake.

Brent: So sad. But if only they had been electrons and not people they would have been able to flow right out.

Brian: The problem I think was that the doors opened the wrong direction. So when people were crushed against the door they couldn't open it. And that's actually like a diode. So current could go one direction but not the other direction. That's what the diode is. Like you hear about light emitting diodes. They're just one kind of a device that's basically the electrical equivalent of a valve.

Matt: When you say that those electrons or those moshers or those people walking around in New York City are electrons are they really just jumping around from atom to atom? Like are they physically moving through the material? Is there actual motion happening?

Brian: Yes.

Fiona: For an individual electron very much so. And the reason we don't see it is that what we're able to measure if you take your metal and just kind of put a voltmeter to it what you're able to measure is a flow of large numbers of electrons all together. And so these fluctuations in the position of an individual electron is something that you would not typically be sensitive to really.

Brent: Does that have to do with the quantum nature of electrons and their tendency to maybe exist in one little region inside a locality with a particular speed where it gets really blurry like that? Is it connected to that?

Fiona: I think there's a couple of things. One thing is that nothing we encounter in the regular world is sensitive to the charge of a single electron. So when you kind of use your intuition about what happens in a metal, well nothing happens until you connected to a battery. You're just not sensitive to anything that has to do with small numbers of electrons. But also the uncertainty principle is very important in understanding how an individual atom works. But when you glue many of them together it also has to do with the energetics. So you can think about your individual atom is kind of like... think about like a really deep well. If you only had one really deep well and to get anywhere else in the world you had to go way uphill and you dropped a ball down. It's basically going to be similar near the bottom of the well. Now what happens in many materials is that now you have lots and lots of these little wells. And they kind of make this egg carton shape. But the hill that you have to go over to get to the next dip in the egg carton is not all that tall. And some now if you imagine you had some balls in the egg carton then you shook them up a bit you would see them bouncing around between the different wells. And that's I think in a sense a picture you can have in your head when you think about an electron that's in a material. That you have lots of these little wells but it's not that hard to get from one to the other.

Brent: If I understand you right, the electron will want to stay in the local minimum or stay in like the puddle of the egg carton. But it doesn't require that much energy to jump over to the next puddle or jump over the hill to the next zone. Is that what you mean?

Fiona: Yeah. And that's where this uncertainty business comes in because if the barrier is very large you might not know exactly where your electron is. You know that it's somewhere close to your atom, the nucleus on your atom. Whereas when you have lots of atoms and your barrier to get from one to the other is small, kind of this fact that you can't pinpoint your electron exactly is sufficient to mean it's kind of impossible to know which atom it's committed to because the barrier to get from one to the other is so small

Brian: Small barrier is synonymous with what's being metal.

[1:08:57]

Brent: I have a question. Fire, air, and dirt, how do magnets work? With gravity, doesn't it warp or bend space-time and that's why things go towards it. Does magnetism work the same way? Why do things go toward or away from magnets? Is it altering the fabric of space at all?

Brian: That is actually something really interesting about space-time and magnetism. There's something called frame drag. The earth is spinning in its dent in space-time. So as earth rotates it's actually pulling on the space-time around it. Not only making a dent in it but twisting that dent. And this causes something called a gravitomagnetism which is actually a communication of the gravitational force via the warping of space-time but via vorticity in space-time rather than the "denting" of it. It's a pretty small effect and doesn't usually matter. But if you're using GPS to fire a missile down a chimney it's actually a big enough effect.

Ben: It's actually funny that you start with that question because magnetism at its deep horrible mathematical heart is a space-time effect. It comes about as a result of space-time being one big continuous sheet rather than just three dimensions of space and one dimension of time in a complicated way. But the crazy thing about it, there were some dudes about 100 years ago named Kaluza and Klein, they had a guess and their guess was that magnetism came about as a result of things moving around in higher dimensions, like a fourth spatial dimension that we couldn't see. And so it was kind of a precursor to some of the ideas they use in string theory, where they said what if this fourth space dimension is really small. It kind of fizzled. It wasn't a great theory but mathematically it explained magnetism in this one really specific way. It's archaic. No one really believes it anymore.

Fiona: Except that guy that the turning on the LHC was going to destroy the universe. People still talk about this, about large extra dimensions and gravity. And I think one of the consequences if the extra dimensions were approximately the scale of energies they produce at the LHC was the potential for generating black holes. Did you see this? This guy got a lot of press saying that turning on the accelerator was going to destroy the world.

Matt: But did that have to do with magnets? Did he say it was going to create some giant electromagnet that was going to destroy itself?

Fiona: No, sorry that was a total tangent.

Brian: So the original question was whether magnetism warps space-time in sort of the same way gravity does. And it's different.

Fiona: It's different. Well, in a sense when we say "warping of space-time" that's almost the definition of gravitational force so both electricity and magnetism are a warping in a sense. But they're not what we would call a warping of space-time. They're a warping of if you like a different fabric. But it's the same general idea that you have this distortion of some kind of fabric which is in a sense like space-time, that means things feel forces. Except when you say space-time that means anything that has mass. And in this case it's anything that has charge or magnetic moment that feels this distortion.