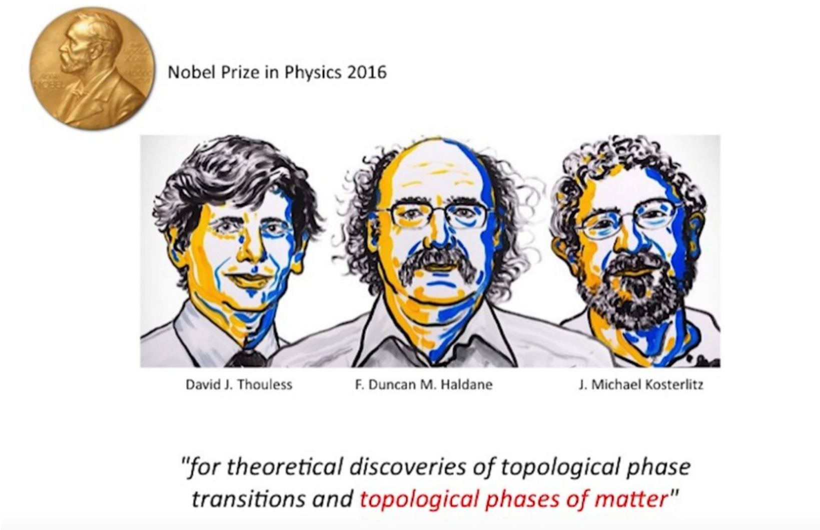
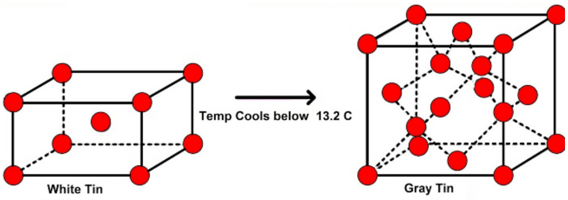
Hi my name is Michael Fuhrer I'm a physicist here at Monash University in the school of physics and astronomy and I'm going to tell you about a discovery of a whole new class of materials that can help us make better computers.

So first why would we care? one reason that everyone here probably has a device like this (cellular phone) in their pocket. We rely on these devices to do lots of things so they can listen to our voice and find information from all around the world and deliver it to us. They entertain us, they predict the weather, they predict the traffic and we want them to do even more, right? so I'd like my phone to be able to translate languages in real-time or drive my car, and those things are coming. So, we demand a lot to these devices and it turns out that the computation that they're doing actually requires an awful lot of energy. That's in some sense hidden from us because most of the computations are actually not going on inside our phone or and even in our desktop but often they're going on in a server somewhere. They're going on in the cloud and those server farms use incredible amounts of energy. These days they use about 10% of the electricity in first world countries and that's a number that's growing. It's a doubling about every decade so that's a problem and it's a growing problem. We want more from our computers but they're using energy. At the same time, in the devices that we're using, the transistors are the actual computer chips that are doing the computing and they are made of silicon. Now silicon has had this huge revolution that's made the information technology revolution possible. The gains in silicon every year are what's powered this revolution in technology but that those gains are coming to an end. We're reaching the point where we can't make silicon transistors any better. That'll happen in the next few years and, at that point, we'll stop having it gains in efficiency in silicon and so this problem will become even worse. So, we need new materials, we need to come up with a new way to make computers which are more efficient and new materials is part of that solution.



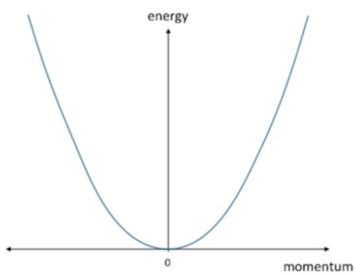
The thing I'm going to tell you about today has to do with the Nobel Prize that was given in physics last year in 2016 to Michael Koster, Duncan Haldane and David Thewlis. This prize was given for theoretical discoveries of topological phase transitions and topological phases of matter so that may be something that you might not be on the tip of your tongue I think this is something that maybe the general public isn't quite familiar with yet. So, I'm gonna try to explain a little bit about what this means, what topological phases of matter are and why it's important.

This has to do with electronic properties of materials and for many many years or for almost a hundred years physicists thought of electronic properties of materials as falling into classes. They're really two types of materials according to their electronic properties and those types are metals and insulators so metals are things that conduct electricity. There's material like copper or silver or aluminum that they are conductors they also tend to be ductile, so there are other properties associated with metals. Insulators are materials like quartz or silicon dioxide which is the basic component of glass or diamond or Teflon. Those are things that don't conduct electricity, they tend to be also brittle materials so one of the great triumphs in the 20th century of quantum mechanics was to understand why it is exactly that some materials are metals and some materials are insulators, not totally obvious when you look at them. In fact, this problem is actually quite deep and I'll give you an example of why or just how deep it is. The element tin, for an example, can actually form two different crystal structures so the atoms and tin can be arranged in one of two different ways and we call them white tin and gray tin.



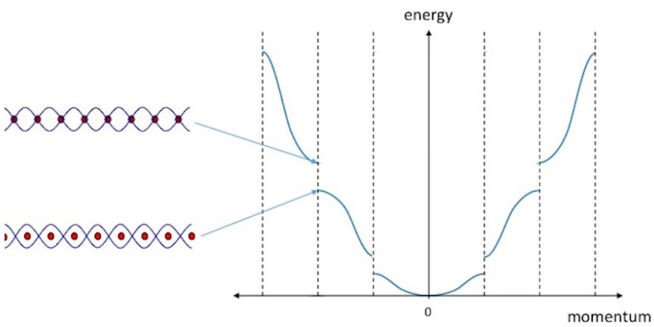
White tin is the one you're most familiar with. If you melt tin and then cast an object that form of tin is white tin it's a metal it's ductile. But it's not the only phase of tin and, in fact, if you take white tin and you cool it down a very low temperature it'll spontaneously transform into gray tin which is an insulator and it's actually brittle so this actually can have major consequences. There's a story, it's possibly apocryphal that when Napoleon's army marched into Russia the buttons on the uniforms of the of the jackets were made of tin and in a very very cold Russian winter tin actually transformed from white tin to gray in became brittle and fell apart and so the army was in tatters and that possibly that's partially due to the fact that the buttons were made of tin and they transformed.

We want to understand why it is that that crystal structure actually determines or helps determine whether something is as a metal or an insulator. To understand that we need to talk a little bit about what electrons are doing in the material. What I'm going to talk about is the energy of an electron and its momentum. Momentum is a vector it has a direction and can either be forward or backwards. It could be positive or negative and the energy that the electron gets is a scalar and it's always positive. More momentum means more energy whether it's forward or backwards and we have a relationship between energy and momentum that look something like this curve.

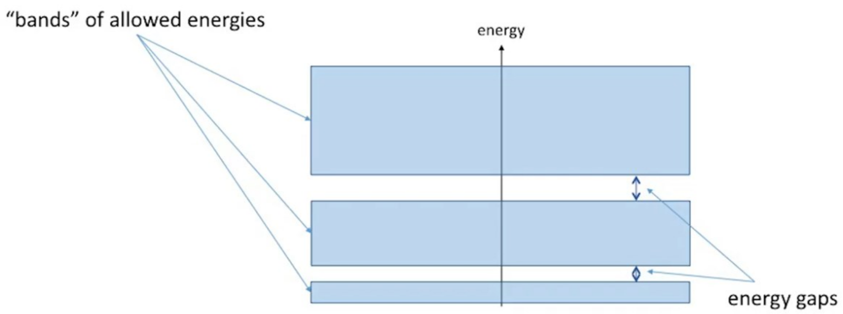


Now I need to tell you a little bit of quantum mechanics, just a little bit. The first thing that you need to know is that electrons are waves so the fact that particles behave like waves is a fundamental part of quantum mechanics. The second thing that you need to know is that the wavelength of these electron waves depends on their momentum so the larger the momentum the faster the electrons go the shorter the wavelength gets. The wavelength of the electrons depends on momentum.

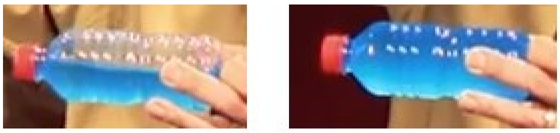
Why does that matter? well, these electrons we're talking about electrons that are inside of crystal so they're inside a solid and inside a crystal there's a periodic arrangement of atoms. So, there are actually special wavelengths when the electron wave length is equal to that atomic spacing then it's in step with the atoms in the crystal and in that case there are actually two states the electron can be in.



So, the crests of the waves then can be right on top of the atoms and the electrons like to be on top of the atoms and so that lowers the energy, electrons are happy there. Or the crests of the waves can occur and the spaces in between the atoms and that the electrons not as happy being in between the atoms and that raises the energy a bit. And so, because the electrons are in a crystal and this crystal has these evenly spaced atoms this things happen when that wavelength or that momentum is such that the wavelength is equal to that crystal spacing so what this does is it opens up these little gaps in this curve and so now there are certain energies that are allowed for electrons in the crystal and there are certain energies that are not allowed in these gaps and so the picture that we develop is something like this: there are bands of allowed energies and then there are gaps between those bands. This is the band theory of solids and it helps explain a lot about the properties of solids so the last thing we need to understand is how this band theory determines the properties of the solids.

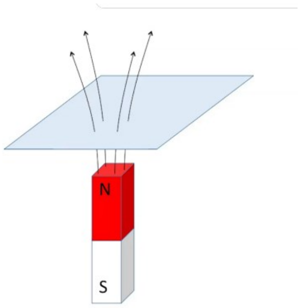


Quantum mechanics tells us that for any given state of momentum and energy there can only be one electron in that state and so we've got a certain number of electrons to put into these bands and what we do is we put them in at the lowest energy and then they kind of fill things up to some energy where we've got all the electrons. And when we do that there's two possible results: once we've put all the electrons in, we can have a half-full and those are our metals or we can have a band that's completely full and those are the insulators. That explains why there's two different kinds of materials and I can also try to give you a picture of why a half-full band would be a metal and a full band would be an insulator.



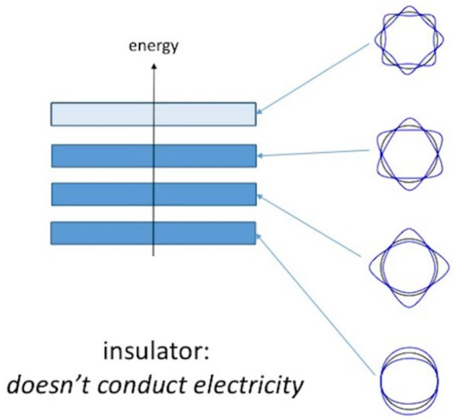
If I have this half full bottle of water. This represents this half full band it's fairly easy to slosh the fluid around the water in this bottle and what I'm doing then if these are the electrons in the band that you can imagine that it's fairly easy to create a state where there are more electrons over here in a state that's positive momentum than electrons over here in a state negative momentum and so that means that those electrons are moving forward and they're carrying a current so it's easy to create different kinds of states carrying different amounts of current by sloshing the electrons around or the fluid around. That's the half full band which would be a metal. In a full band no amount of sloshing creates any state that carries current because I can't make the positive momentum States any more populated than the negative momentum States and so there's really no way to get current to flow here so there's an energy gap in the way and you have to give the electrons that extra energy to get over the gap and it's very difficult to do and so the insulator doesn't carry any current. It's interesting to think about this full band because what this full band is its electrons in different states of different energy and different momentum and so the electrons are actually moving around some of them are moving to the right some of them are moving to the left but net there's no current flowing and so even in an insulator we think of as electrons is actually moving around in some sense but they're not carrying any net current.

This is our picture of the electronic properties of metals and insulators. It explains everything, at least that's what we thought until around 30 years ago or so, physicists started looking at a very special system. That special system is a very very thin metal it's thin enough that the electrons are really confined to only move in two dimensions only move in a plane in a in a magnetic field.

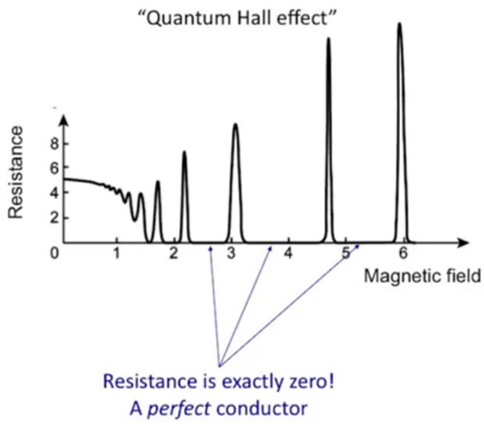


It turns out to be interesting: what does the magnetic field do? A magnetic field causes the electrons to bend in their trajectories so electron moving along will curve if we have a really strong magnetic field what that does is it makes the electrons tend to go around in little loops,

so we picture the electrons are sitting in this this plane of this material and they're making little loops but again quantum mechanics tells us as these electrons must be waves so this picture of little billiard balls going in loops isn't quite right we need to convert those two waves and so these waves are kind of curled up on each other and they come back around to meet each other head to tail. There are different ways that waves can do that. We can have different number of wavelengths going around that loop but it should be an integer because they should come back and meet each other and so physicists thought about this particular system and they said well, aha this is going to give us new energy bands and that's what it does. There's a new energy band now associated with every integer number of wavelengths around that loop so in a really high magnetic field what we expect is that we'll get an insulator, we'll get a material that has these energy bands it has gaps between them and well at least if we get it full right up to the next energy gap it should be an insulator.

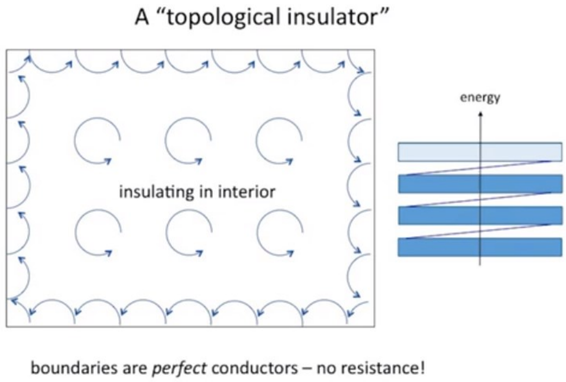


So far so good but well you always have to do the experiment and it turned out when people actually measured the electrical properties of this very thin metal in a magnetic field they found something rather different so when you measure the resistance of this very thin metal and you turn up the magnetic field you get something like this:



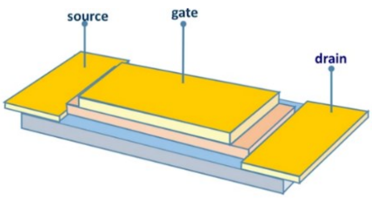
The resistance starts out at some finite number and then it maybe oscillates around a bit but then eventually it starts dropping down to zero periodically. Now if the material is becoming an insulator you'd expect the resistance to go up to infinity, it becomes very resistive to electrical current. This is a material that's resistance is going not to infinity but to zero that means it's not an insulator it's a conductor not only that it's a perfect conductor. No resistance at all so this is very surprising but this is this is a discovery that's now famous it's called the quantum Hall effect that so this this effect is now well known by physicists and it was recognized in 1985 with a Nobel Prize for Klaus von Singh who is the experimentalist who discovered this effect.

What's happened recently is that we've had now a mathematical description of exactly what it is that's going on inside these materials. So the thing that we forgot, the thing that we left out, when we conceptualize this material is that we didn't think about what's happening on the edges. The electrons inside this material on a high magnetic field are going in these little loops but there are some extra electrons that live near the edge and when they try to make a loop they hit the edge and then they keep bouncing around along the edge and they actually just go one way around the edge of the material.

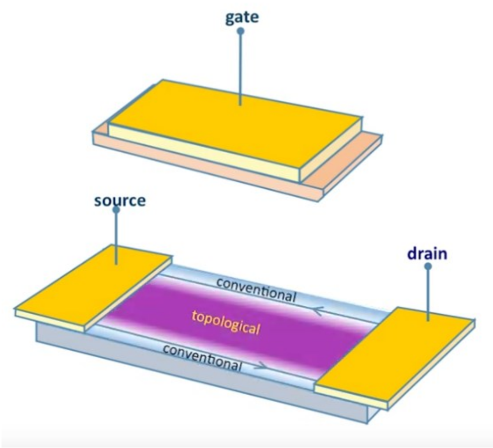


And it's these electrons on the edge they have additional energy and momentum states that are inside the gap, so these lines inside the gap represent the electrons inside the edge and that means we can never have the system filled up to where it's filled up right to a gap and then there are no states above because there's some extra states always on the gap and those extra states turn out to be these states that go around the edge and they can conduct perfectly because they just go one way around the edge they never turn around and go the other direction. So, this is what we now know as a topological insulator and the advance was to understand the structure mathematically of what the electrons are doing in this material and it has to do with topology and it's a bit complicated but now it's understood and so understanding that is what was what led to the Nobel Prize in 2016 and what's more is that it's led to the discovery that you don't actually need a magnetic field. In fact, there are lots of materials out there that are topological insulators we just didn't know it. For instance, bismuth, mercury telluride there are several materials actually that are not they don't fall into this category of insulator or metal. They're in fact topological insulators and if you make them very thin they can have these conducting edges that can conduct perfectly. So that's really amazing these materials are always out there we just didn't know it.

Okay. I told you I was going to tell you about why this can help us make better computers so what we're doing here at Monash we have an ARC funded Center of Excellence in future Low Energy electronics technologies and what we're trying to do is to make new kinds of transistors so the basic elements are computing and instead of using silicon which is an insulator, it's a semiconductor, it's an insulator with a small band gap, we're going to use topological insulators so what we want to do a transistor (it is something that uses a gate to control the current that flows from source to drain)



Our envision is to take that gate we're gonna use it to turn a material from a conventional insulator into a topological insulator so what that'll do then is now we'll have these edges that will conduct once it's a topological insulator.



It'll have these conducting edges and those edges will conduct current perfectly from source to drain because that's a perfect conducting channel it won't have any resistance and we won't be wasting any heat to resistance as those electrons are doing the conducting. So, this is a way to make a transistor that works with really low energy consumption and that should make our computing devices work better and better and farther into the future.

Thank you for listening and I hope you enjoyed that story.

https://www.youtube.com/watch?v=jQ_ihxXcqpg&t=791s