STEM *Talks*

Presenter: Professor Michael Fuhrer - *2017*

Title: Topological Insulators and how they might change the world - (17:34)

Time	***Dialogue***
00:12 00:40	Hi my name is Michael Fuhrer and 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 is that everyone here probably has a device like this in their pocket. We rely on these devises 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 would like my phone to be able to translate languages in real time, drive my car and those things are coming.
01:08	So we demand a lot from these devices and it turns out the computation they are doing actually requires an awful lot of energy. So that is in some sense is hidden from us because most of the computations are actually not going on inside our phone or even in our desktop, but often they are 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 is growing and it's doubling about every decade. So that's a problem and it's a growing problem.
01:31	We want more from our computers but they are using energy. At the same time the devices that we are using, the transistors or the actual computer chips that are doing the computing are made of silicon. Now silicon has had this huge revolution that has made the information technology revolution possible. The gains in silicon every year are what have powered this revolution in technology but those gains are coming to an end. We are reaching the point where we can't make silicon transistors any better. So that will happen in the next few years and at that point we will stop having the gains in efficiency of silicon and so this problem will become even worse.
02:18	So we need new materials. We need to come up with a new way to make computers which are more efficient and new materials are part of that solution. So the thing I'm going to tell you about today has to do with the Nobel prize that was given in physics last year, 2016, to Michael Kosterlitz, Duncan Haldane and David Thouless. So this prize was given "for theoretical discoveries of topological phase transitions and topological phases of matter". That maybe something that 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 going to try to explain a little bit about what this means and what Topological phases of matter are and why it is important.
03:08 03:59	So this has to do with electronic properties of materials and for many, many years, for almost 100 years physicists thought of the electronic properties of materials as falling into two classes. So there are really two types of materials according to their electronic properties and those types are metals and insulators. Metals are things that conduct electricity. They are materials like copper, silver and aluminium. They are conductors. They also tend to be ductile so there are other properties associated with metals. And 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 and they tend to be also brittle materials.

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04:01	One of the great triumphs of the twentieth century of quantum mechanics was to understand why it is exactly that some materials are metals and some materials are insulators. It's not totally obvious when you look at them. In fact this problem is quite deep and I'll give you an example of why or just how deep it is. The element Tin for example can actually form two different crystal structures, so the atoms of Tin can be arranged in one of two different ways. We call them White Tin and Grey Tin.
04:33	It turns out that White Tin is the one you are most familiar with if you melt Tin and cast an object that form of Tin is White Tin. It's a metal, ductile but it's not the only phase of Tin and in fact if you take White Tin and you cool it down to a very low temperature it will spontaneously transform into Grey Tin which is an insulator and it's actually brittle. So this can have major consequences.
05:01	There's a story, it's possibly apocryphal that when Napoleons army marched into Russia the buttons on the uniforms of the jackets were made of Tin and in the very very cold Russian winter that Tin actually transformed from White Tin into Grey Tin, became brittle and fell apart and so the army was in tatters and that possibly is partially due to the fact that the buttons were made of Tin and they transformed. So we want to understand why it is that the crystal structure actually determines or helps to determine whether something is a metal or an insulator.
05:39	So to understand that we need to talk a little bit about what electrons are doing in the material. So what I'm going to talk about is the energy of an electron and its momentum. So momentum is a vector. It has a direction, so it can be either, forwards or backwards, positive or negative and the energy the electron gets is a scalar and it is always positive. So more momentum means more energy whether it is forward or backwards so we have a relationship between energy and momentum which look something like this curve.
06:12	OK so 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 the 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 and the shorter the wavelength gets. So the wavelength of the electron depends on the momentum. So why does that matter?
06:50	Well … these electrons ….we are talking about electrons that are inside a crystal, inside a solid. And inside a crystal there is a periodic arrangement of atoms. So there are actually special wavelengths when the electron wavelength is equal to that atomic spacing and it's in step with the atoms in the crystal and in that case there are actually two states that the electron can be in. So the crest of the wave can be right on top of the atom and the electrons like to be on top of the atoms and so that lowers the energy. The electrons are happy there.
07:30	Or the crest of the waves can occur in the spaces between the atoms and the electrons are not as happy between the atoms and that raises the energy a bit. And so because these electrons are in a crystal and this crystal has evenly spaced atoms then things happen when that momentum as such that 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 certain energies that are not allowed in these gaps.
08:05	So the picture we develop is something like this. There're bands of allowed energies and there are gaps between those bands and so 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 know about this band theory determines the properties of the solids is that 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 have a certain number of electrons to put into these bands and what we do is put them in at the lowest energy and they kind of fill things up, up to some energy where we have all the electrons.

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08:44	And when we do that there are two possible results. So we can have, once we have put all the electrons in we can have a band that is half full and they are our metals or we can have a band that is completely full and those are the insulators. This explains why there are two different types 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 fairly easy to slosh the fluid around; the water in this bottle.
09:20	And what I'm doing then if these are the electrons in the band, then you can imagine that it's fairly easy to create a state where there are more electrons over here in a state of positive momentum than electrons over here in a state of negative momentum and so that means that those electrons are moving forward and they are carrying a current. So it's easy to create different types of states carrying different amounts of current by sloshing the electrons or the fluid around.
09:46	So 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 is really no way to get current to flow here. There is an energy gap in the way so you have to give the electrons that extra energy to get over the gap and that's very difficult to do so the insulator doesn't carry any current.
10:14	It's interesting to think about this full band because what this full band is, is its electrons in different states of different energy and different momentum. So the electrons are actually moving around. Some of them are moving to the right and some are moving to the left but in net there is no current flowing so even in an insulator we think of electrons as moving around in some sense but they are not carrying any net current.
10:42	Ok … alright … so that's good and this is our picture of the electronic properties of metals and insulators that explains everything. So that is at least what we thought until around 30 years ago until physicists started looking at a very special system … so that special system is a very very thin metal. It's thin enough that the electrons are confined to only move in two dimensions, so only move in a plane … in a magnetic field … OK. Well that is what they were looking at.
11:20	It turns out to be interesting. So what does the magnetic field do? The magnetic field causes the electrons to bend in their trajectories so an electron moving along will curve. If we have a really strong magnetic field … what that does is it tends to make the electrons tend to go around in little loops. So we picture the electrons are sitting in this plane in this material making little loops but again quantum mechanics tells us that electrons must be waves so this picture of little billiard balls going in loops isn't quite right so we need to convert that those waves.
11:54	And so these waves are kind of curled up on each other and they come back to meet each other head to tail. There are different ways that waves can do that. We can have a different number of wavelengths going around that loop but it should be an integer so it should come back to meet each other. So physicists thought about this particular system and they said well 'Ar-har' this is going to give us new energy bands and that's what it does. So there is a new energy band now associated with every integer number of wavelengths around that loop.
12:24	So in a really high magnetic field, what we expect is that we will get an insulator. We get a material that has these energy bands with gaps between them; well at least if we get them full right up to the energy gap it should be an insulator. Ok so far so good, but … well you always have to do the experiment and it turned out that when people actually measured the electrical properties of this very thin metal in a magnetic field they found something rather different.
13:00	So when you measure the resistance of this very thin metal and you turn up the magnetic field you get something like this. So the resistance starts out at some finite number and it maybe oscillates around a bit but eventually it starts dropping around to zero periodically. Now if the material is becoming an insulator then you 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 zero.

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13:29	This means it is not an insulator it's a conductor and not only that it's a perfect conductor. No resistance at all. So this is very surprising but … this is a discovery that is now famous that's called the Quantum Hall Effect and this effect is now well known by physicist and it was recognised in 1985 by the Nobel Prize for Klaus von Klitzing who is the experimentalist who discovered this effect. So what's happened recently is that we have 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 conceptualised this material is that we didn't think what was happening on the edges.
14:18	The electrons inside this material in 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 they keep bouncing around the edge and actually go just one way around the edge of the material. It's these electrons on the edge that have additional momentum and energy states that are inside the gap so these lines inside the gap represent the electrons along the edge.
14:48	That means that we can never have the system filled up until it is filled up to a gap and then there are no states above because there are some extra states always in 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 and they never turn around and go in the other direction.
15:06	So this is now what we 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 is a bit complicated but now it is understood. So understanding that is what lead to the Nobel prize in 2016 and what's more is it has led to the discovery that you don't actually need a magnet field.
15:34	In fact there are lots of materials out there that are topological insulators and we just didn't know it. For instance Bismuth and Mercury Telluride. There are several materials actually that don't fall into that category of insulator and metal in fact that are topological insulators and if you make them very thin they can have these conducting edges that can conduct perfectly.
15:58	So that's really amazing so these materials were always out there we just didn't know it. Ok so I told you I was going to tell you about why this can help us make better computers. So what we are doing here at Monash we have an ARC funded centre of excellence, the Future Low Energy Electronics Technology. What we are trying to do is make new kinds of transistors, the basic elements of computing and instead of using silicon, which is an insulator … it's a semi-conductor, … an insulator with a small band gap, we are going to use topological insulators,
16:32	So what we want to do is … A transistor is something that uses a gate to control a current that flows from source to drain. Our vision is to take that gate and we are going to use it to turn a material from a conventional insulator to a topological insulator. So what that will do then is it will now have these edges that will conduct once it is a topological insulator it will have these conducting edges and those edges will current perfectly from source to drain.
16:58	Because that's a perfect conducting channel it won't have any resistance and we won't be wasting any heat through resistance as those electrons are doing the conducting. This is a way to make a transistor which works with really low energy consumption and that should make our computing devices work better and better farther into the future. So thank-you for listening and I hope you have enjoyed that story.