

QTC

A remarkable
new material to
control electricity



Innovations in
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SEP
Science Enhancement Programme

QTC

A REMARKABLE NEW MATERIAL TO CONTROL ELECTRICITY

The Science Enhancement Programme is a part of Gatsby Technical Education Projects. It is developing curriculum resources to support effective learning in science, and providing courses and professional development opportunities for science teachers. This booklet is part of the series 'Innovations in practical work', exploring ways in which low-cost and novel resources can be used in secondary science.



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HEALTH AND SAFETY

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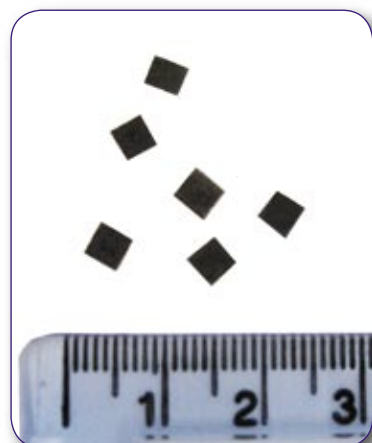
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INTRODUCTION

What is QTC?

QTC (Quantum Tunnelling Composite) looks rather ordinary, but this black, rubbery material is actually quite extraordinary. When it is squeezed its electrical resistance drops. This unique property opens up a vast range of domestic and industrial applications - finger sensors for robots to give them touch-sensitivity, a musical keyboard that you can fold up, switches with no moving parts, clothing with electrical controls made of fabric, and amazingly sensitive 'electronic noses' are just a few.

Just as remarkable as its versatility is the low cost of the material, which means that whole class practical work on QTC is easily affordable.



Practical activities using QTC

There is a wide range of possibilities for using QTC in practical activities for 11 to 16-year-old students. It is simple and safe to use, and so it is suitable for KS3 pupils in lessons on conductors, insulators and electrical circuits. There are opportunities for using QTC in work on electricity at KS4, and its complex and subtle behaviour make it a fascinating material for investigation at KS4 and above.

What's in this booklet?

This booklet provides a source of information about QTC, as well as suggestions for classroom activities and materials that can be used in existing schemes of work. The booklet includes the following:

- *Using QTC in the classroom* An introduction to QTC, along with ideas and suggestions for how it could be used in teaching about electricity and scientific enquiry.
- *Activities A Teaching and learning about electricity* Teachers' notes and student resources for a range of activities on electrical circuits across KS3 and KS4.
- *Activities B Scientific enquiry* Teachers' notes and student resources for a KS4 enquiry on making a tactile sensor, focusing on concepts of accuracy and reliability.
- *Background science* Further information for teachers who wish to know more about how QTC was discovered and how it works.

At the back of the booklet, there are references to useful websites, and information on how to obtain the practical resources. In addition, you can find further resources on the SEP website (www.sep.org.uk/practical), including PowerPoint slides and Word worksheets that you can adapt for your own use.

CURRICULUM LINKS

Activities A Teaching and learning about electricity: circuits, switches and QTC

These activities are concerned with using QTC to support the teaching of conceptual aspects of electricity across KS3 and KS4. These include concepts of conductors and insulators, series and parallel circuits, current, voltage, resistance and power.

Activity	KS3 QCA Schemes of Work	KS4 National Curriculum Sc4
A1 Conductors and insulators ... and QTC	make and test predictions about circuits (7J/1)	
A2 Switches everywhere	use ideas about complete circuits to describe how a switch works (7J/1)	
A3 Making a panel of switches	construct parallel circuits (7J/3)	
A4 Using QTC to control electrical currents	predict the current in branches of a parallel circuit (7J/3) how current behaves in electrical circuits (9I/1)	the qualitative effect of changing resistance on the current in a circuit (1b)
A5 How do the current and voltage change?	how to measure voltage in a circuit (9I/2)	the quantitative relationship between resistance, voltage and current (1c) the quantitative relationship between power, voltage and current (1f)

Activities B Scientific enquiry: making a tactile sensor using QTC

This series of investigative activities looks at whether QTC would make a suitable material for a tactile sensor in an artificial hand. Students need to decide whether it is good at distinguishing between different forces, which involves applying the concepts of *accuracy* and *reliability*.

Activity	KS4 National Curriculum Sc1	KS4 National Curriculum Sc4
B1 Setting the scene		the qualitative effect of changing resistance on the current in a circuit (1b)
B2 Making the sensor		the qualitative effect of changing resistance on the current in a circuit (1b)
B3 Testing the sensor	make sufficient measurements to obtain reliable evidence (2h) judge the level of uncertainty in measurements (2i) represent data using charts (2j)	
B4 Writing the report	use charts to identify patterns (2k) use measurements to draw conclusions (2m) explain to what extent conclusions enable further predictions to be made (2n)	
B5 What else could QTC be used for?		considering ways in which science is applied in technological developments (Breadth of Study 1b).
BX1 Further investigations	turn ideas into a form that can be investigated (2a) make sufficient measurements to obtain reliable evidence (2h) represent data using tables, charts and graphs (2j)	how current varies with voltage in a range of devices (1d)
BX2 What makes a good material for a tactile sensor?	use graphs to identify patterns and relationships in data (2k)	

USING QTC IN THE CLASSROOM: IDEAS AND SUGGESTIONS

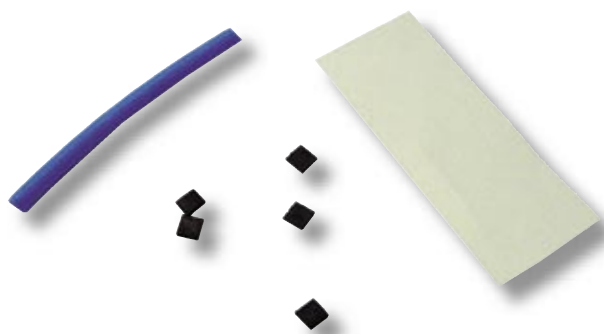
QTC has only recently been invented, and most of its applications are still in the development stage. This means that students are able to use it in schools before it has found its way into many commercial products. The behaviour of QTC is not yet fully understood, and the investigations that students can perform reflect the kind of research that is now being done in laboratories around the world. Students who have worked with QTC have been excited that they are dealing with a material that is at the cutting edge of science and technology.

This section gives an 'illustrated overview' of QTC and how it could be used in the classroom. In the margin, references are given to student activities - these resources and the accompanying teachers' notes can be found later in this booklet.

WHAT IS QTC?

QTC stands for Quantum Tunnelling Composite. Its name may sound complex, but what it does is essentially quite easy to understand - when you squeeze it, its electrical resistance drops. In fact, it changes from an almost perfect electrical insulator to conducting as well as a metal when a force is applied.

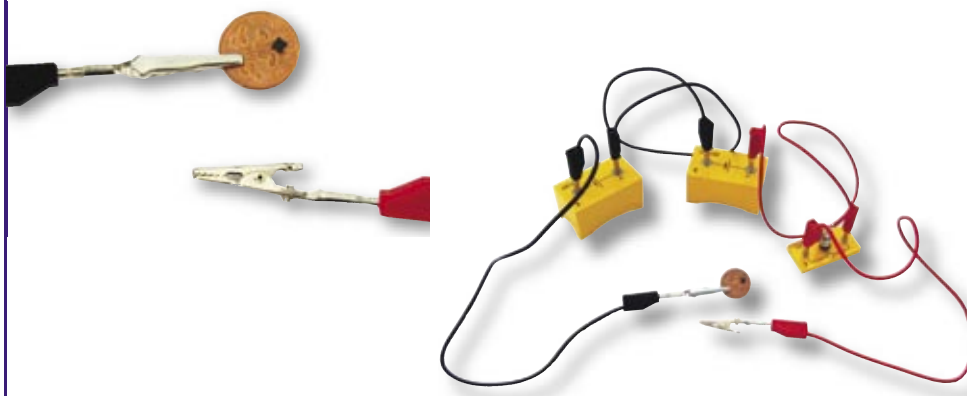
QTC is a rubber-like material and is manufactured in a variety of forms - strips, sheet, cable, and so on. The rubber can be made to different specifications so that it is sensitive to a light finger-touch or to very large forces.



QTC's unique properties mean that it has an enormous number of potential applications, and has won its developers many major awards for innovation.

The change in the resistance of QTC when it is compressed means that it can be used to control an electrical current. A simple way to show this is to use a series circuit containing a battery, a bulb and a 'QTC pill' (a small square piece of QTC).

When a QTC pill is placed between two metal contacts and squeezed, its resistance drops. By pressing on the pill in this circuit, you can control the brightness of the bulb.



HOW QTC WAS DISCOVERED?

David Lussey, a research engineer in Darlington, invented QTC in 1997. It was an 'accidental' discovery as he was trying to make something quite different.



QTC was invented (or discovered) by David Lussey while he was trying to develop an adhesive that would conduct electricity. He was experimenting by mixing fine metal powders in a polymer. Metal-filled polymers have been investigated for about 100 years, so it is surprising that he should find a way of making a material that was quite unlike anything that had been known before.

The implications of the discovery were not immediately apparent.

"It happened at my home lab. The substance showed unusual electrical activities but I didn't realise what I had was special straightaway. It wasn't so much a eureka moment as a eureka fortnight."

What he had produced was not a conducting adhesive, but something with even more interesting properties.

"When I tested the sample, it had really high resistance - which was no good for my purposes. But I noticed that when I pulled at the joint, the resistance suddenly dropped to almost zero."

It is a long way, however, from a scientific discovery to commercial applications. Lussey set up a company, Peratech, which undertook research into the development and manufacture of QTC. To demonstrate to potential customers what QTC could do, one of the first things the company did was to make a prototype power drill.

In this prototype drill, the surface of the handle contains QTC. By squeezing it, the speed of the drill can be controlled.



At first, it was not obvious how many applications there were for this new material. It was when designers began to work with Lussey that the true potential of the material became apparent, with many new ideas being proposed that were not thought of at the beginning. Since then a huge range of potential applications has been identified and many patents have been taken out.

CONDUCTORS AND INSULATORS: EXPLORING THE PROPERTIES OF QTC

See Activity A1
'Conductors, insulators
...and QTC' (page 23)

QTC can be used in lots of different ways in science lessons. Whatever the age of the students, the first thing is to do some simple experiments to explore the behaviour of the material. For example, if a QTC pill is put in a circuit with a bulb or a motor it can be used to control the brightness of the bulb or the speed of the motor.

Classroom activities

QTC can be used with students when looking at the differences between conductors and insulators. Using the circuit described earlier, students can compare QTC with a number of other materials, such as aluminium, paper, plastic and copper. QTC shows a very different behaviour.

A simple series circuit that can be used to test the electrical conductivity of a range of materials including QTC.



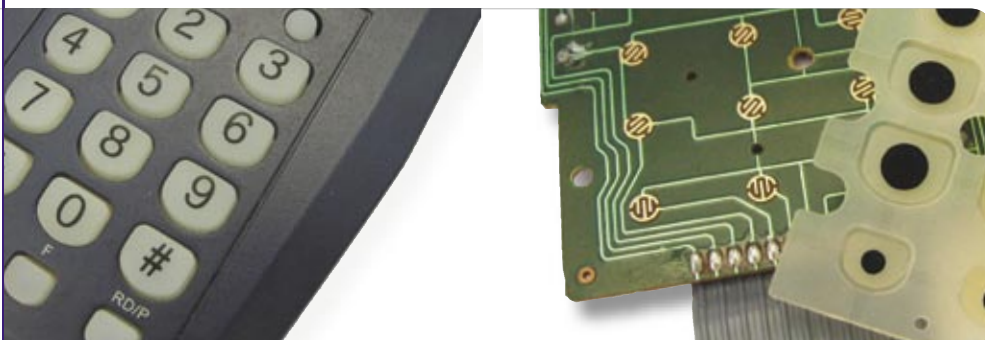
Students tend to think of materials as being either conductors or insulators. In fact, no material is a perfect conductor or insulator, but what makes QTC quite unusual is that what it is depends strongly on the external conditions.

SERIES AND PARALLEL CIRCUITS: USING QTC SWITCHES

If you take an old telephone keypad apart, you can see how pressing on each of the keys makes an electrical connection. It completes a circuit between two electrical contacts on the printed circuit board. There are literally billions of these kinds of switches in existence - on telephones, mobiles, remote controls, and other consumer goods. Because they have moving parts and are used repeatedly, they are liable to wear out.

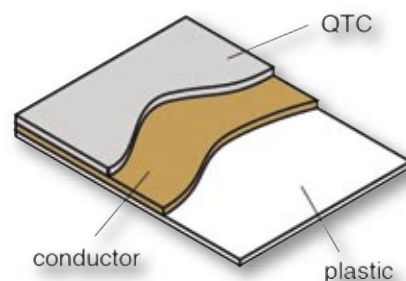
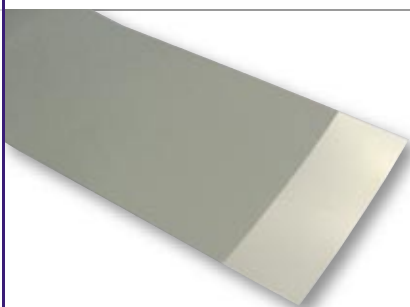
QTC can change from an almost perfect insulator to an almost perfect conductor when it is squeezed - effectively acting as a switch. This means that traditional switches could be replaced with more reliable QTC switches that have no moving parts.

When a key is pressed it completes a circuit. The constant movement means that it is the switches on these kinds of devices that often fail first.



QTC sheet has been manufactured to be used in simple switching devices for low currents. QTC sheet consists of three layers. The first is made of white plastic to give the sheet strength. Next is a thin layer of aluminium that acts as a conductor. Finally there is a thin layer of QTC.

QTC sheet has a layer of QTC on a conducting base. When it is pressed, current can pass through the QTC, and then along the conducting layer.



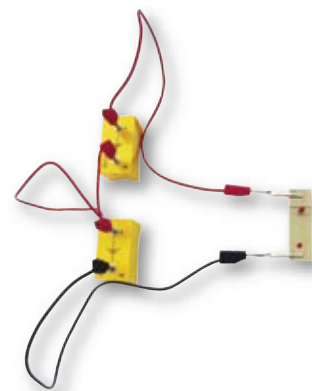
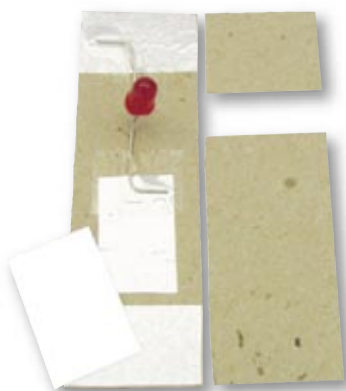
A piece of QTC sheet placed face down on two electrical contacts can form a conducting bridge between them when pressed. This cheap and reliable switch has huge potential for commercial products.

Classroom activities

See Activity A2 'Switches everywhere' (page 24)

Using QTC sheet students can make a model of a new kind of switch that could be used to replace the traditional switches in a keypad. The basic ingredients are some cardboard and aluminium foil, a glue stick, a piece of QTC sheet, and a battery and LED. Because QTC sheet can only carry a small current, you need to use an LED rather than a filament bulb.

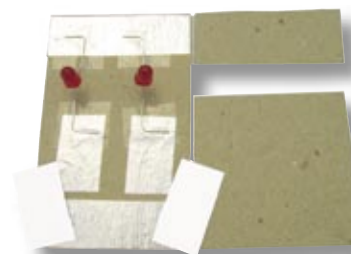
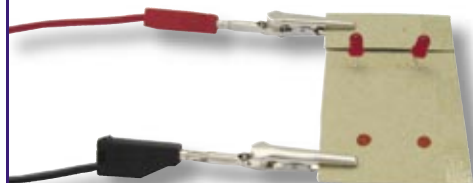
The QTC sheet is in contact with two strips of aluminium in a 'cardboard sandwich'. When it is pressed, it completes the circuit and the LED lights up.



The strips of aluminium are glued onto a piece of cardboard, and the strip at each end is folded over and tucked down underneath (this gives two robust electrical contacts on the bottom surface of the cardboard). Across one gap is stuck an LED using clear sticky tape. Across the other is placed a piece of QTC sheet (QTC side down). When the cardboard covers are put on top and the whole thing is connected to a battery, the students have then constructed a series circuit. The LED can now be switched on by pressing on the switch to complete the circuit. Making a switch like this and explaining how it works involves students in applying concepts of conductors and insulators and the conditions needed for an electrical circuit.

See Activity A3 'Making a panel of switches' (page 26)

This panel of switches uses two pieces of QTC sheet to control two LEDs independently in a parallel circuit.



This idea could be extended to any number of switches and LEDs, thus mimicking the behaviour of a real keypad. A lot of keys means a lot of branches, as can be seen by looking at the printed circuit board from an old telephone.

CURRENT AND RESISTANCE: DIMMER SWITCHES

A typical domestic light switch contains two metal contacts that come into contact when the switch is turned on. QTC allows improved switches to be designed. By putting it between two such contacts, the switch can be given a smoother operation with the current slowly increasing to its maximum. In addition, when using switches with a high voltage across the contacts, there may be a tendency for 'arcing' when the current jumps across the gap before the contact is fully made. This can lead to damage and wear of the switch. This is also an important safety feature in situations when there are flammable vapours that could be ignited by a spark from a switch.

Conventional switches can 'arc' when switched on. With high voltages, this is hazardous in environments with flammable vapours such as oil rigs. QTC switches could avoid these problems



However, QTC can act as more than simply an on/off switch. Because its resistance changes as it is squeezed, it can be used as a dimmer switch. The more force that is applied, the lower its resistance and the more current there will be in the circuit. Students often have particular difficulties in understanding the effect of resistance on current in a circuit, and need to explore what happens through experiments. Though these can be done with conventional variable resistors, 'QTC dimmer switches' can provide a fresh approach, using technology that is at the cutting edge of research and development.

A dimmer switch can control electrical current by changing the resistance in a circuit.



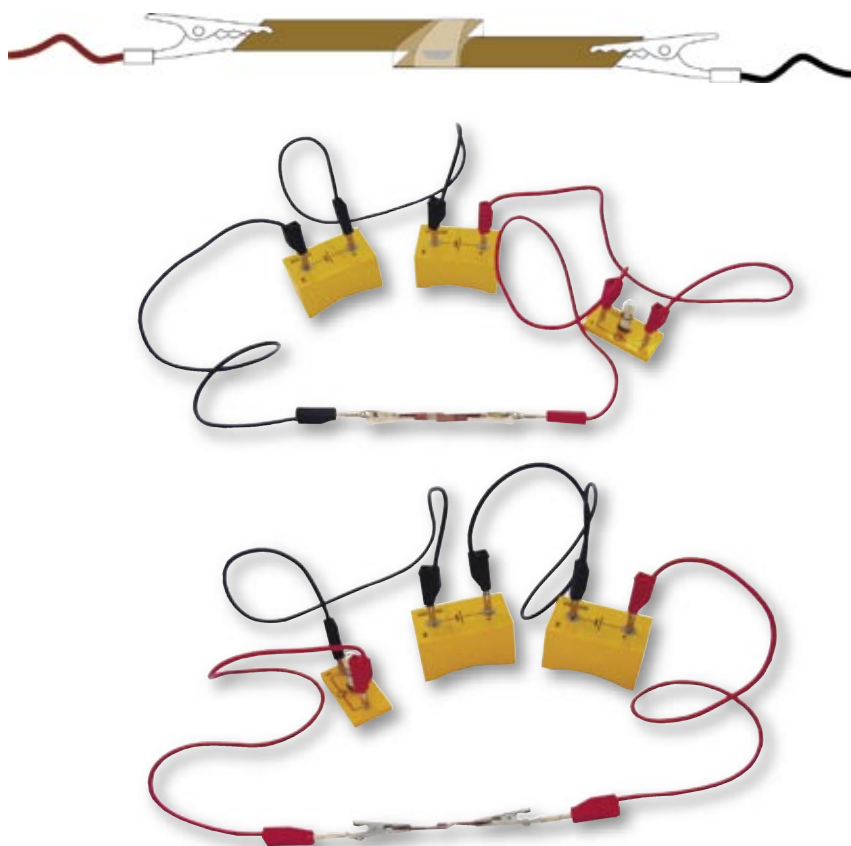
See Activity A4 'Using QTC to control electrical currents' (page 27)

Classroom activities

Many students have a sequential view of an electric current in a circuit. The way they reason about its behaviour is to consider what happens to the current as it leaves the battery, travels through each of the components in turn and then returns to the battery. Using this model, students may predict that changing the resistance of a component affects the current after it in the circuit but not before it. This idea is easily proved to be incorrect experimentally. To understand the behaviour of the circuit, students need to see the circuit as a system - changing any component will affect the behaviour of the circuit as a whole.

A 'QTC dimmer switch' can be made by putting a QTC pill between two strips of copper and taping them together. Students can test their predictions of the effect of putting this dimmer switch in different places in a circuit.

The QTC dimmer switch controls the brightness of the bulb in both of these circuits. Many students may have the misconception that the switch in the second circuit has no effect.



After trying a series circuit with just one bulb, students could look at series circuit with more than one bulb, or at the effects of putting a dimmer switch into different branches in a parallel circuit.

Alternatively, students could be challenged to construct circuits which behave in different ways (for example, how to make a circuit with two bulbs, both of which can be controlled by a single QTC switch, or a circuit with two bulbs which can be independently controlled by two QTC switches).

In all of these activities, the focus for students should be on using their scientific knowledge of current and resistance to explain the behaviour of the circuits.

VOLTAGE, CURRENT, RESISTANCE, POWER

To develop their understanding of electricity further, students can use ammeters and voltmeters for quantitative work on circuits containing a QTC dimmer switch. Many students have their existing ideas challenged when confronted by measurements of the current in a circuit or the voltage across components. For example, students may believe that a battery always gives out the same current in every circuit, or that current is used up as it travels around a circuit. Students also have difficulties in differentiating between concepts, in particular between voltage and current.

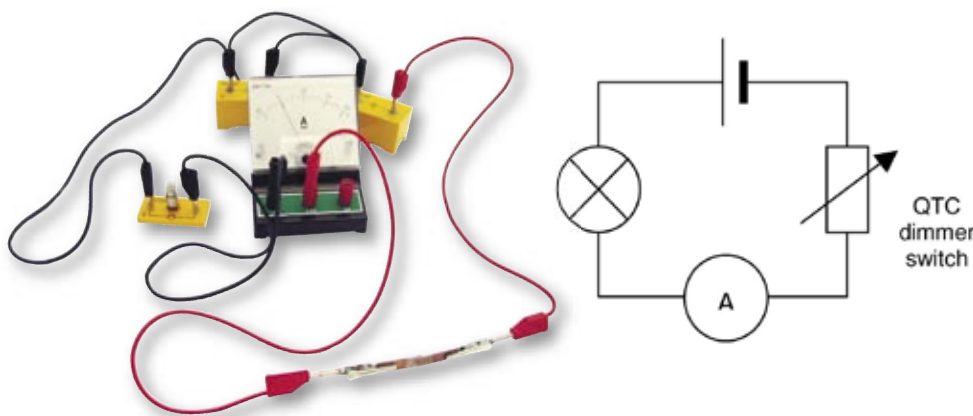
As with earlier activities, although students could test their ideas experimentally using conventional components, using QTC provides a novel and interesting context.

Classroom activities

Students can use an ammeter to measure the current at different places in a circuit. A circuit containing a battery, a bulb and a QTC dimmer switch behaves the same way regardless of the order of the components. An ammeter placed anywhere in the circuit will give the same reading. A student with a sequential model may think that the ammeter reading will go down as the current goes round the circuit.

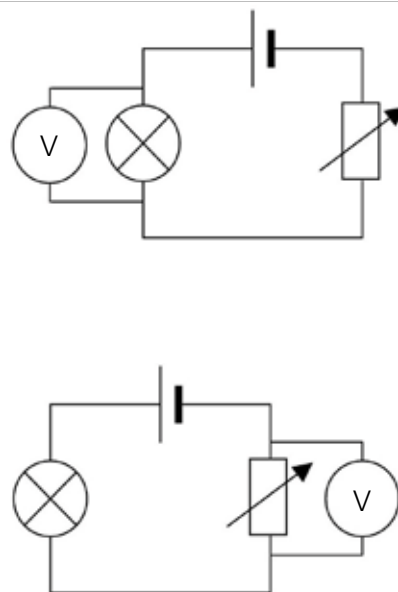
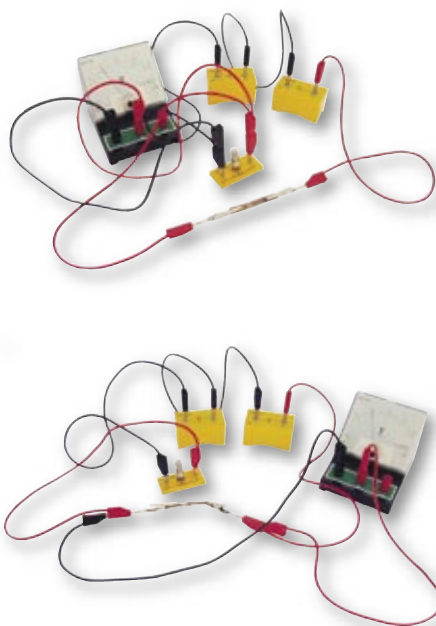
See Activity A5 'How do the current and voltage change?' (page 28)

In this series circuit, the sequence of the components does not affect the brightness of the bulb or the reading on the ammeter.



Measuring the voltages in the same circuit may also challenge students' conceptions. When the switch is squeezed, the voltage across the bulb increases and the bulb gets brighter - an intuitive relationship. But the voltage across the switch decreases as the bulb gets brighter, and this may be more difficult for students to believe. In its rest state, QTC is an almost perfect insulator, so that the voltage across it is almost the same as the voltage across the battery. When it is squeezed, it is an almost perfect conductor, and the voltage drops to about zero - similar to measuring the voltage across a piece of conducting wire.

When the QTC dimmer switch is pressed, the voltage across the switch increases, and the voltage across the bulb decreases.



From their measurements of current through and voltage across the bulb at its maximum brightness, students can use the standard quantitative relationships to calculate its resistance and its power output. They can also extend their measurements to parallel circuits containing QTC switches.

ACCURACY AND RELIABILITY: AN INVESTIGATION OF TACTILE SENSORS

When someone picks up an object, they can judge how much force to use, because the brain gets feedback from the touch receptors in their hand. Artificial hands (e.g. for robots or for prosthetic limbs) also need a sensing system if they are to use the correct force. Researchers are developing tactile sensors for the fingertips of mechanical hands.

A human can sense how much force needs to be exerted by the hand on an apple to stop it slipping when it is picked up. A mechanical hand could squeeze too hard and crush the apple if it does not have tactile sensors to judge the force needed.



One of the first organisations that took an interest in QTC was NASA. They had been working on a project to develop a robot (the Robonaut) that could work in space alongside human astronauts; the robot could undertake tasks in situations that were too risky for humans. One problem they were tackling was how to construct a hand that could give feedback to the robot about the force the hand was using to grasp things.

NASA is researching the use of QTC in developing tactile sensors for robotic hands as part of their 'Robonaut' project.



Being a material whose resistance increases when it is squeezed, it is possible to use QTC as a force sensor. NASA had already developed a first version of the robotic hand, but when QTC became available, they incorporated this into a new design. The Robonaut was given touch sensitivity by building QTC into the finger sensors of a tactile glove. NASA's first test was to see if this glove could tell the difference between the forces needed to hold a plastic cup and a spacecraft. Work is continuing on this project.

This tactile glove has QTC sensors built into the fingertips. It can then be placed over Robonaut's mechanical hand.



See Activity B1 'Making a tactile sensor using QTC: setting the scene' (page 37)

Classroom activities

Students can be asked to investigate the suitability of QTC for making a tactile sensor, and to write a 'technical report' summarising their findings and making recommendations. An essential thing to find out is whether the results are *reproducible*. In order to distinguish between different magnitudes of forces *reliably*, the QTC's measured resistance needs to be similar each time the same force is applied. An interesting aspect of QTC is that it shows some *variability* in the measurements of its resistance.

The central question then is, *how big is this variability compared to the differences it is trying to detect?* This is a key idea in science, and occurs in many different contexts. Many scientific issues subject to public debate concern levels of uncertainty about the sizes of errors and whether reported effects are real or illusory.

The focus then of this enquiry is on concepts of *accuracy*, *precision*, *errors*, *reliability* and *reproducibility*.

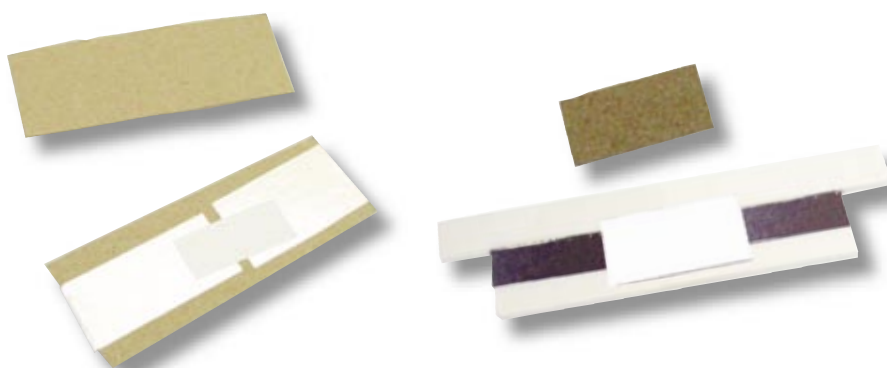
Before starting any systematic investigation of QTC, students should familiarise themselves with the operation of a resistance meter.



See Activity B2 'Making the sensor' (page 39)

After a preliminary exploration of QTC, and practising how to use a multimeter to measure resistance, students are ready for the investigation. QTC sheet is an easier material to start with than the pill (investigating QTC pills is better for students to do as an extension activity). The first thing for students to do is secure a piece of QTC sheet between two metal contacts, so that an electrical connection is made when it is pressed. They can make this 'test sensor' using cardboard, aluminium foil and QTC sheet. Alternatively, they can be supplied with a pre-made QTC sheet holder.

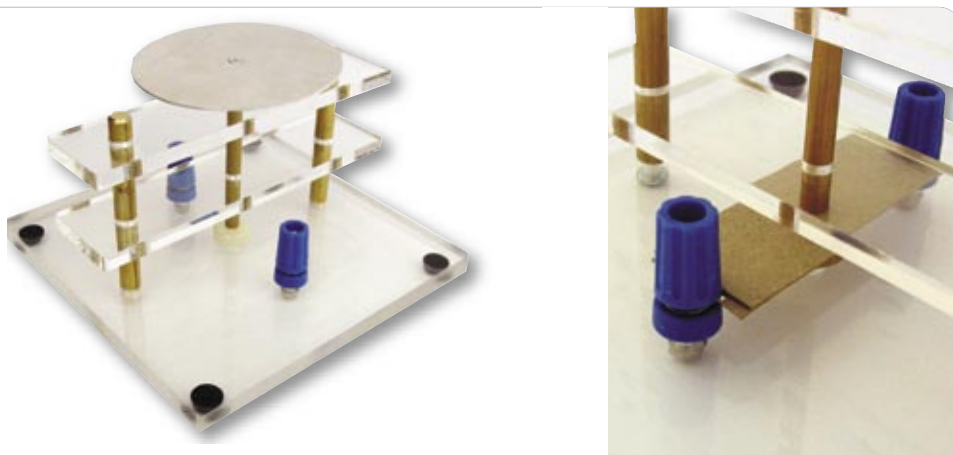
Two 'models' of a tactile sensor with covers removed to show QTC sheet. The first can be made by students, the second is supplied with the QTC testing kit.



See Activity B3 'Testing the sensor' (page 41)

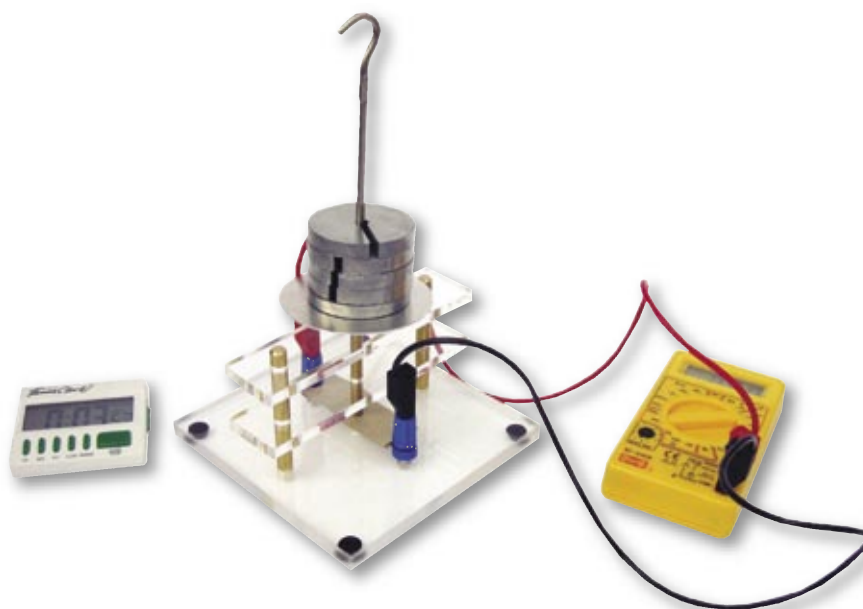
To measure how the resistance varies with the force exerted, students can use a commercially available QTC testing kit. This allows the 'test sensor' to be firmly secured and different forces applied. The kit has been designed so that unwanted movement is minimized as much as possible. The measured resistance is very sensitive to small changes in the position of the sensor or the load. Although looking at variability is the key idea in this investigation, too much variability masks any patterns, and simply leads to frustration.

The QTC testing kit allows the test sensor to be held securely between two terminal posts. Slotted masses can be put on the loading pan to apply a force on the sensor.



The kit is ready to be used. It can be connected to a digital multimeter to measure the resistance. When a load is applied, the resistance decreases, though it takes a little while before it reaches a steady value. This is due to 'creep' in the rubbery material, which is where the compression of the material continues after the load has been applied. To obtain repeated results that can be compared, a fixed stabilising time needs to be chosen (for example, 15 seconds).

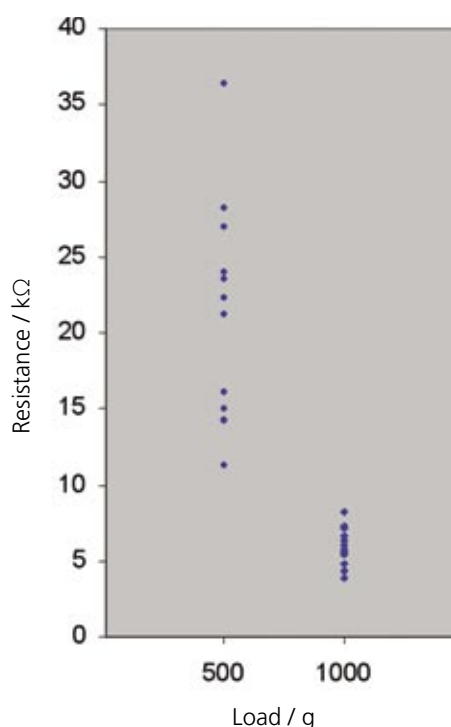
A set of repeated resistance readings can be obtained, by adding and removing a load with a fixed interval between each operation.



The following chart shows the results of a set of measurements of resistance with two different loads using this testing kit. Although there is a good deal of variability in the two sets of readings, there is no overlap between the two sets.

Thus, using this technique, it is possible to distinguish reliably between these two loads. The accuracy is sufficient in this case, because the variability in each set of readings is smaller than the difference between the two sets. For a 500 g and a 600 g load, however, the difference may be more difficult to detect reliably. Students can do further tests to find out whether this is the case.

This dotplot compares the resistances of QTC sheet when loaded with 500 g and 1000 g loads respectively. Repeated measurements were taken using a stabilising time of 15 seconds, with a rest time between loading of 15 seconds.



See Activity BX1 'Further investigations' (page 46)

There are many possibilities for further investigations. Students can carry out similar tests using a QTC pill and compare the results. They can look at which specimen has a faster response time - also an important requirement for a tactile sensor. Being thinner and subject to less creep, the sheet is in fact a better material for a sensor.

See Activity BX2 'What makes a good material for a tactile sensor?' (page 48)

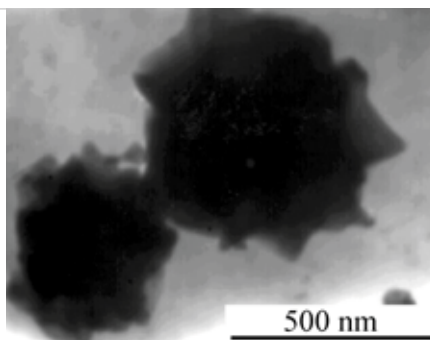
Instead of using the testing kit, students could be asked to devise their own experimental procedure for measuring how resistance changes with force. It is not easy to get reliable results, and so an investigation that focuses on experimental design is more suited to advanced work.

Finally, students could be given data that has already been collected and be asked to interpret it, thinking about the properties that would be required in designing a tactile sensor.

HOW DOES QTC WORK?

QTC consists of tiny nickel particles embedded in a rubbery polymer material. When QTC is deformed in some way - by squeezing, stretching or twisting - the nickel particles get closer to each other and the material becomes a conductor. The more it is deformed, the closer the particles get and the better the material is at conducting electricity. By using electron microscopy to see the structure of the material, researchers have been able to get a better understanding of its behaviour.

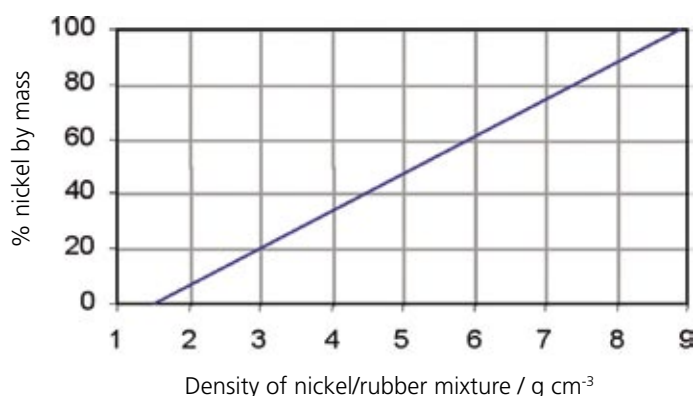
This electron microscope image of QTC shows the tiny nickel particles embedded in it.



Composites already exist which consist of polymers containing carbon particles. However, these work in a very different way. The carbon particles are sufficiently close to each other that when the material is deformed the particles of carbon touch each other. This allows it to conduct electricity. In QTC, although the metal particles are close together, they do not touch each other even when the material is fully compressed. In simple terms, when the metal particles become closer to each other, electrons are able to 'jump' from one metal particle to another. This process is called 'quantum tunnelling', and hence the material is called Quantum Tunnelling Composite. You can find out more about quantum tunnelling in the 'Background science' section at the end of this booklet.

Classroom activities

A single QTC pill just feels like a piece of rubber. But if you have a longer strip of them, it feels noticeably 'heavy'. Students can try to estimate QTC's nickel content by measuring the mass and dimensions of a pill, and calculating its density. The density of rubber is about 1.5 g cm^{-3} and the density of nickel is about 8.9 g cm^{-3} , so the density of QTC will be somewhere in between. Calculating its composition from these values will need some algebra. An easier method is to use the graph below:



An electron microscope image of QTC could be used for a class discussion with students on how QTC conducts electricity. With advanced students, understanding how QTC works through quantum tunnelling allows them to apply their knowledge of quantum theory in an interesting and novel context.

FUTURE DEVELOPMENTS

The earlier sections have looked at just a handful of possible applications of QTC. Because QTC is so new, only a few products have come to market, but many are under development. It is very likely that in the next few years we will see many products appearing that use materials like QTC.

One major area of current research is the development and application of 'smart' fabrics. One aspect of this is the development of textiles that include electrical and electronic components. QTC is finding a place in this research. By coating fibres with QTC, soft flexible fabrics can be made that act as switches, and that can be incorporated into clothing and other products.

Using QTC coated fibres, it has been possible to produce textile switches. There are many potential applications, for example, 'dance mats' and clothing that contains controls for built-in audio players.



In addition to these leisure and novelty products, QTC is finding medical uses. For a bandage, it is very important to get the tension right - too little and it may slip, and too much may prevent blood flow. Being flexible, QTC can be incorporated into a bandage, and connected to a monitoring system.

A bandage containing QTC can measure the pressure on the body and give a warning signal if the bandage is too tight.



QTC can also be used in many other kinds of sensors. On cars, bumper sensors made from QTC can be used, so that if a pedestrian is hit, the bonnet rises up slightly cushioning the impact. QTC sensors can be used in industry to measure the pressure at critical interfaces, such as valves and seals. Other sensors can detect the angle of a joint or measure the tightness of a bolt. In addition, since its properties are temperature dependent, it can be used as a temperature sensor.

One exciting development is the 'electronic nose'. The conductivity of QTC is very sensitive to the presence of certain gases and vapours and so can be used as a detector for volatile organic compounds. When exposed to such vapours, the polymer material expands and the resistance increases. Different vapours have differing effects on different polymers, and so by using an array of sensors (an 'electronic nose'), specific vapours can be identified. The inventor of QTC, David Lussey, reports that the test rig they built was sensitive enough to detect the difference between the front and the back of his hand!

Research continues on developing a new forms of QTC. When David Lussey originally invented QTC, he was using nickel powder that was commercially available. By creating new kinds of these tiny nickel particles with particular characteristics, it is possible to design materials with different properties. This takes QTC research into the realms of nanotechnology.

Classroom activities

Once students have explored QTC, they could try inventing their own applications for it. This work is just beginning. They may come up with an idea that no one has ever thought of before.

See Activity B5 'What else could QTC be used for?' (page 45)

Activities A

TEACHING AND LEARNING ABOUT ELECTRICITY: CIRCUITS, SWITCHES AND QTC

Teachers' notes

Teaching and learning about electricity: circuits, switches and QTC

The activities in this section give students an opportunity to apply key ideas about electricity across KS3 and KS4 in a novel context. These ideas are:

- A circuit is needed for an electrical current
- Conductors and insulators
- Series and parallel circuits
- Effects on current of changing resistance
- Measurement of voltage and current
- Calculating the resistance of a component from the voltage across it and the current through it
- Calculating the power dissipated by a component from the voltage across it and the current through it.

For supporting resources, including image files and editable versions of the student sheets, visit www.sep.org.uk/practical.

See page 62 for information on obtaining the practical resources.

Health and safety

QTC contains a high proportion of nickel embedded in a polymer material. Some people experience allergic reactions to nickel. However, the particles of nickel in QTC are intimately coated by the polymer, and susceptibility to allergic reactions is very much less than for pure nickel, or for alloys containing a high proportion of nickel (e.g. as found in cupro-nickel coins or in some jewellery). See the section 'Health and Safety' on page 61 for further details.

An overview of the activities

The activities are:

- Activity A1 Conductors and insulators ... and QTC
- Activity A2 Switches everywhere
- Activity A3 Making a panel of switches
- Activity A4 Using QTC to control electrical currents
- Activity A5 How do the current and voltage change?

Notes on the activities

Activity A1: Conductors and insulators ... and QTC

Students test the conductivity of a QTC pill in a series circuit (see also page 5 of this booklet, 'Conductors and insulators: exploring the properties of QTC').

LEARNING OBJECTIVE Students will: • apply the concepts of electrical circuit, conductor and insulator in order to interpret the behaviour of QTC. NOTES Before doing this activity, students should already have done work on classifying materials as electrical conductors or insulators. Students should be encouraged to handle QTC with forceps - it does not in fact suffer too badly from contamination of surfaces when handled, but this encourages them to treat the samples with care. By testing other conductors and insulators (e.g. aluminium foil, paper) in the same way, students can see that QTC has a very different behaviour. It is neither a conductor nor an insulator, but its property depends on the force applied.	RESOURCES NEEDED Each group needs: • 2 batteries (1.5 V) in holders • Bulb in holder • 4 plug-plug leads (2 red, 2 black) • 2 croc clips • QTC pill in a labelled plastic bag • Forceps • Metal disc or 2p coin • Small sheets of aluminium, paper, plastic, and other conductors and insulators
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Activity A2: Switches everywhere

Students make a series circuit containing a battery, an LED and a QTC sheet switch (see also page 5 of this booklet, 'Series and parallel circuits: using QTC switches').

LEARNING OBJECTIVE Students will: • learn how an electrical current can be controlled using a QTC sheet switch. NOTES Students should handle the QTC sheet carefully and avoid contamination of the QTC surface. In particular they need to take care not to get glue on the surfaces in electrical contact.	RESOURCES NEEDED Each group needs: • 2 batteries (1.5 V) in holders • 3 plug-plug leads (2 red, 1 black) • 2 croc clips • LED • QTC sheet (approx 25 mm x 15 mm) in a labelled plastic bag • Access to cardboard, aluminium foil, clear sticky tape, scissors, glue stick
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CIRCUITS, SWITCHES AND QTC

Activity A3: Making a panel of switches

Students make a model keypad with a 'panel' of two switches to control two LEDs in a parallel circuit (see also page 5 of this booklet, 'Series and parallel circuits: using QTC switches').

LEARNING OBJECTIVE

Students will:

- learn how two QTC sheet switches can control the current in the branches of a parallel circuit.

NOTES

An old telephone keypad could be taken apart to show how each key presses down on two electrical contacts. Students can be shown a completed QTC panel and be asked to think about what might be inside.

This is quite challenging, but the layout of the switch has been designed so that, when opened, it is clear that it consists of two switches and two LEDs in a parallel circuit.

RESOURCES NEEDED

Each group needs:

- Same equipment as for Activity A2
- An additional LED.

Activity A4: Using QTC to control electrical currents

Students predict and test the effect of a QTC switch in series and parallel circuits (see also page 7 of this booklet, 'Current and resistance: dimmer switches').

LEARNING OBJECTIVE

Students will:

- use the concept of resistance to explain the behaviour of QTC in an electrical circuit.

NOTES

This activity is appropriate for KS3, but many KS4 students also have misconceptions about the behaviour of current in a circuit. Many students have a 'sequential' view of current, and believe that a dimmer switch only affects those components 'after' it in a circuit and not those 'before' it.

RESOURCES NEEDED

Each group needs:

- 2 batteries (1.5 V) in holders
- 2 bulbs in holders
- 6 plug-plug leads (3 red, 3 black)
- 2 croc clips
- QTC pill in a labelled plastic bag
- Forceps
- 2 copper foil strips (approx 5 mm x 25 mm)
- Access to clear sticky tape and scissors

N.B. The QTC dimmer switches made here are also used in Activity A5.

Activity A5: How do the current and voltage change?

Students make measurements using an ammeter and voltmeter in a circuit containing QTC (see also page 9 of this booklet, 'Voltage, current, resistance, power').

LEARNING OBJECTIVE

Students will:

- apply the concepts of current and voltage to interpret the behaviour of QTC in an electrical circuit.

NOTES

This activity could be adapted for work at KS3, but the later part of the activity is intended to give KS4 students an opportunity to use the quantitative relationships between voltage, resistance, current and power.

RESOURCES NEEDED

Each group needs:

- Same equipment as for Activity A4
- 1 ammeter and 1 voltmeter (or use digital multimeter as both ammeter and voltmeter)

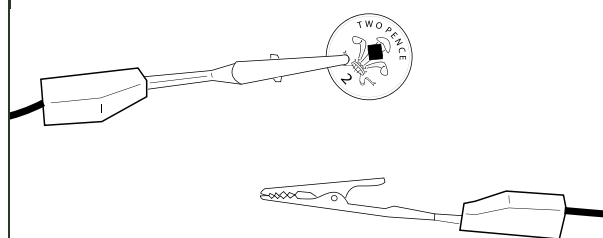
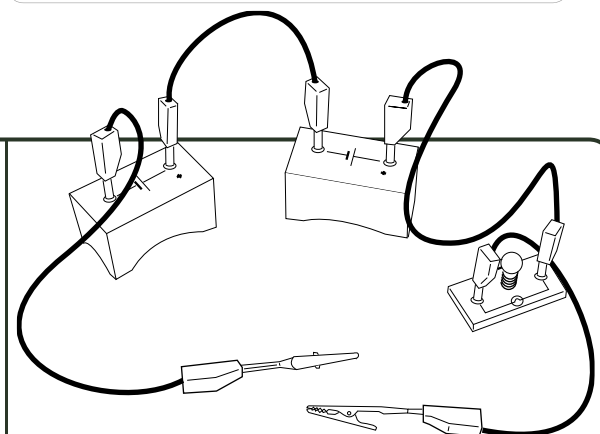
CIRCUITS, SWITCHES AND QTC: CONDUCTORS AND INSULATORS...AND QTC



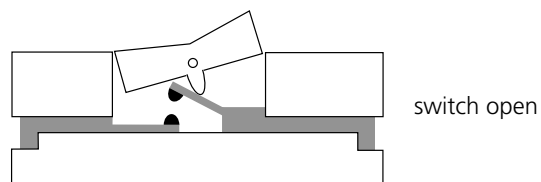
QTC is a very safe material, though it does contain the metal nickel. Some people have allergic reactions to nickel-containing items (e.g. jewellery, coins). Follow your teacher's instructions on using QTC.

Materials that allow an electrical current through them are called conductors. Materials that don't are called insulators. What kind of material is QTC?

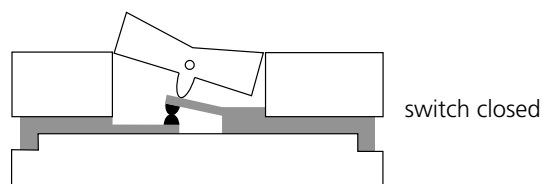
1. Connect a battery to a bulb and two croc clips as shown here.
2. Touch the croc clips together to make sure the circuit is working.
3. Now attach one clip to a metal disc (e.g. a coin) and put a QTC pill on it.
4. Press on the pill with the second croc clip. What happens to the brightness of the bulb?
5. When the QTC pill is squeezed, is it a conductor or an insulator?
6. When the QTC pill is not squeezed, is it a conductor or an insulator?
7. What would happen if you used a piece of aluminium instead of QTC? Why do you think this? Test your prediction.
8. What would happen if you used a piece of paper instead of QTC? Why do you think this? Test your prediction.
9. The diagrams show how a QTC pill can be used in the switch. What happens to the current when the switch is closed?
10. Which parts of the switch are conductors? Which parts are insulators?



QTC pill on 2p piece



switch open



switch closed

Plastic
 Metal
 QTC

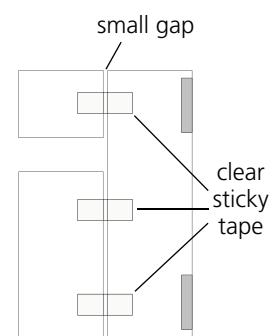
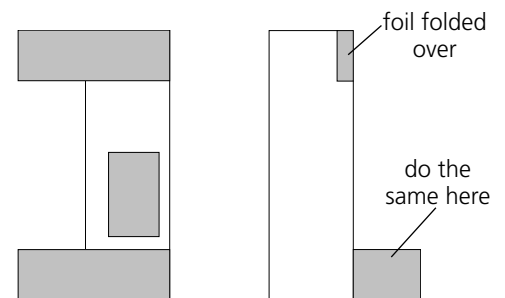
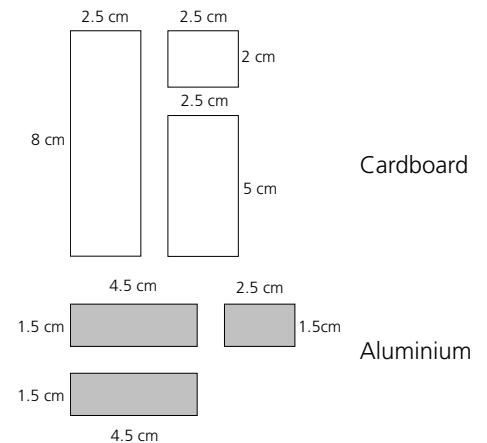
CIRCUITS, SWITCHES AND QTC: SWITCHES EVERYWHERE



QTC is a very safe material, though it does contain the metal nickel. Some people have allergic reactions to nickel-containing items (e.g. jewellery, coins). Follow your teacher's instructions on using QTC.

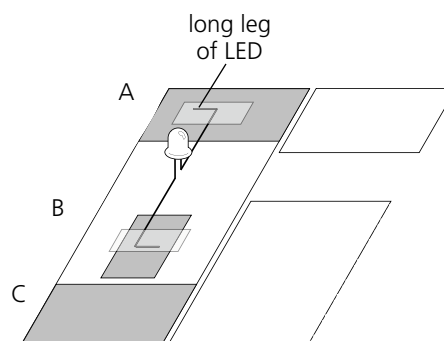
Mobile phones, TV remote controls, CD players – these are all devices that have lots of switches. Sometimes these switches wear out through constant use. Using QTC you can make a switch with no moving parts to wear out.

1. Cut out 3 pieces of cardboard and 3 pieces of aluminium as shown.
2. Stick the 3 pieces of foil to the large cardboard pieces using a glue stick.
3. Turn the cardboard over. Fold the foil over and tuck it down.
4. Stick on the other 2 cardboard pieces using sticky tape as 'hinges' – leave a small gap.
5. Turn the whole thing over and check that the 2 cardboard 'flaps' can close.

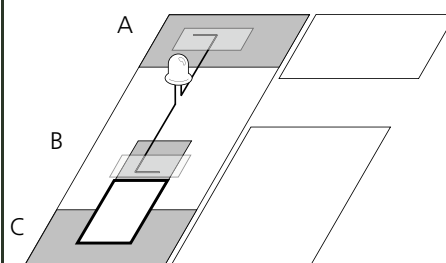


Switches Everywhere continued...

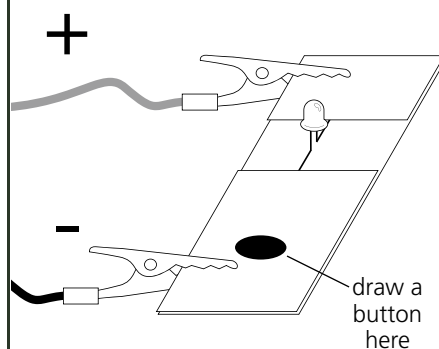
6. Bend the legs of an LED as shown.
7. Stick the LED across the aluminium contacts A and B using sticky tape - make sure the long leg is on contact A.
8. Test that the LED is working properly - touch the contacts A and B with leads from a battery.



7. Put a piece of QTC sheet across the aluminium contacts A and B.
8. Close the flaps.



9. Use a felt-tip pen to draw a 'button' on the card over the piece of QTC – this is where you will press the switch.
10. Attach the leads from the battery – make sure they are the right way round.
11. Push the switch and watch the LED.
12. What happens to the size of the current when you press the QTC switch? Why?



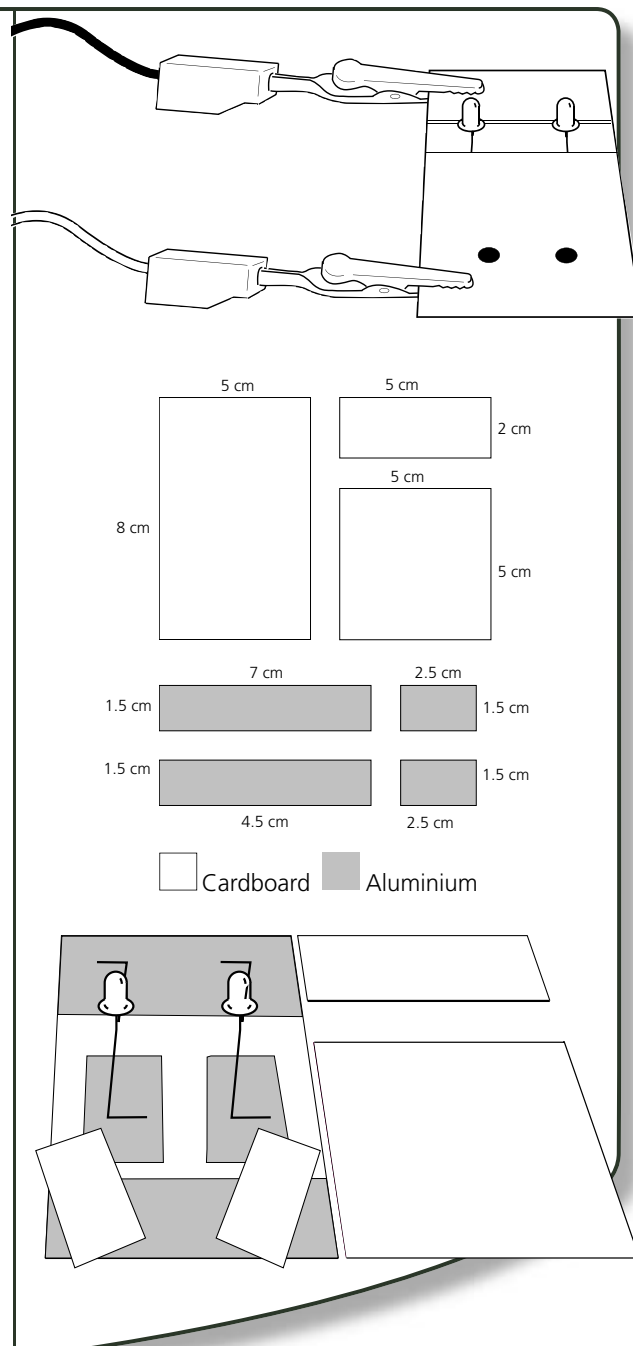
CIRCUITS, SWITCHES AND QTC: MAKING A PANEL OF SWITCHES



QTC is a very safe material, though it does contain the metal nickel. Some people have allergic reactions to nickel-containing items (e.g. jewellery, coins). Follow your teacher's instructions on using QTC.

In Activity A2, you made a single switch. Mobile phones and remote controls have a panel with lots of switches on them. Each switch needs to be able to control the current in a circuit.

1. This is a simple panel with just two switches. When a 'button' is pressed the LED next to it comes on. Can you think how this might be made?
2. To make this panel, cut out 3 pieces of cardboard and 4 pieces of aluminium foil as shown.
3. Stick the aluminium to the cardboard (using glue stick). Stick on the LEDs (using sticky tape).
4. Put 2 pieces of QTC sheet across the aluminium contacts. Stick on the other 2 pieces of cardboard.
5. Attach the leads from the battery. Push the switches and watch the LEDs.
6. What kind of circuit is this - series or parallel? How can you tell?



CIRCUITS, SWITCHES AND QTC: USING QTC TO CONTROL ELECTRICAL CURRENTS



QTC is a very safe material, though it does contain the metal nickel. Some people have allergic reactions to nickel-containing items (e.g. jewellery, coins). Follow your teacher's instructions on using QTC.

How does the position of a QTC switch affect the bulbs in a circuit? In this activity, you will look at how QTC can be used to control the flow of electricity in a variety of different circuits.

You can make a simple dimmer switch using two strips of copper and a QTC pill.

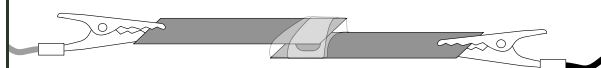
1. Put the ends of the two strips of copper above and below a QTC pill as shown.
2. Wrap a piece of sticky tape around it to hold it in place.
3. You can now use this in circuits by attaching croc clips to the copper strips.
4. Here are some circuits with batteries and bulbs. You can test the effect that the dimmer switch has on the brightness of the bulbs. The letters show the positions you can try. For each position, predict what will happen, and then test your prediction.



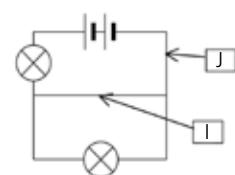
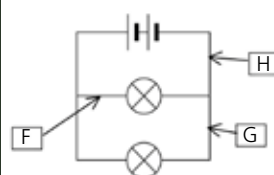
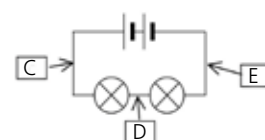
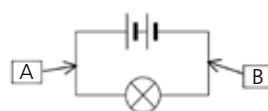
Copper strips with pill



Secure with tape



Connect to leads



CIRCUITS, SWITCHES AND QTC: HOW DO THE CURRENT AND VOLTAGE CHANGE?



QTC is a very safe material, though it does contain the metal nickel. Some people have allergic reactions to nickel-containing items (e.g. jewellery, coins). Follow your teacher's instructions on using QTC.

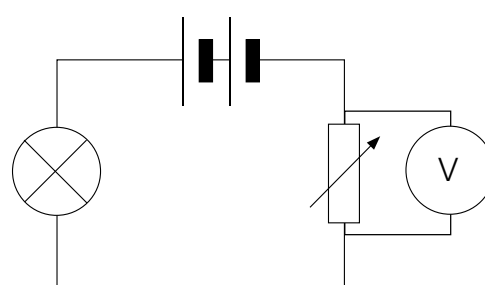
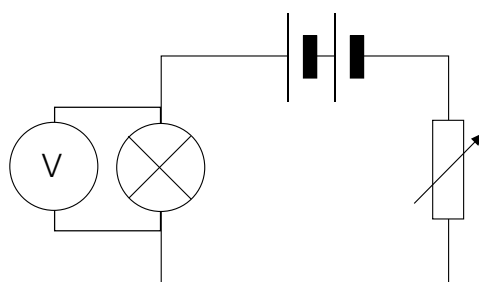
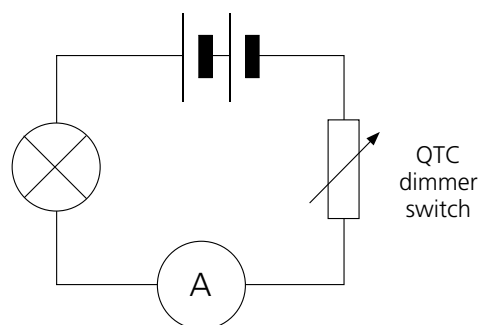
You will need the dimmer switch you made in Activity A4. To explain what happens in these circuits, you will need to use ideas about voltage, current, resistance and power.

Task A Measuring the current in the circuit

1. Set up the circuit shown here, with an ammeter to measure the current through the bulb.
2. Squeeze the QTC dimmer switch. What happens to the current? Why?
3. What is the maximum current you can get?
4. Would you get a different result if you changed the order of the bulb, the ammeter and the dimmer switch in this series circuit?

Task B Measuring the voltage across the components

5. Now use a voltmeter to measure the voltage across the bulb and across the QTC dimmer switch.
6. Predict what will happen to the voltage across the bulb when you squeeze the QTC. Try it.
7. Predict what will happen to the voltage across the QTC dimmer switch when you squeeze it. Try it.



How do the current and voltage change? continued...

Task C Resistance and power

8. What is the resistance of the bulb at its maximum brightness? Use the formula:

$$\text{resistance } (\Omega) = \frac{\text{voltage (V)}}{\text{current (A)}}$$

9. What is the maximum power output of the bulbs in this circuit? Use the formula:

$$\text{power (W)} = \text{voltage (V)} \times \text{current (A)}$$

Task D Series and parallel circuits

10. Make a series circuit with 2 lamps and a QTC switch. When you squeeze the QTC, what happens to:
- the current through each bulb?
 - the voltage across each bulb?
11. Make a parallel circuit with 2 bulbs and a QTC dimmer switch that controls one of them. When you squeeze the QTC, what happens to:
- the current through each bulb?
 - the voltage across each bulb?

Activities B

SCIENTIFIC ENQUIRY: MAKING A TACTILE SENSOR USING QTC

Teachers' notes

Scientific enquiry: making a tactile sensor using QTC

This enquiry focuses on how QTC could be used to make a tactile sensor that gives touch sensitivity in an artificial hand. The key feature that needs to be explored is whether its behaviour is sufficiently reliable. Since QTC has only been around a few years, this kind of exploratory work - characterizing the properties of QTC and identifying potential uses - is an area of much current research activity.

The unit consists of a number of short activities, some of which are practically-based, while others are paper-based. They may be used flexibly, so that individual activities may be selected and used. The enquiry would be appropriate in the context of work done at KS4 on resistance, voltage and current.

It is not easy to get consistent results with QTC and so students are provided with a good deal of guidance on how to undertake the tests. The focus of the enquiry is on the analysis of the data. (See also page 10 of this booklet, 'Accuracy and reliability: an investigation of tactile sensors').

For supporting resources, including image files and editable versions of the student sheets, visit www.sep.org.uk/practical.

See page 62 for information on obtaining the practical resources.

Health and safety

QTC contains a high proportion of nickel embedded in a polymer material. Some people experience allergic reactions to nickel. However, the particles of nickel in QTC are intimately coated by the polymer, and susceptibility to allergic reactions is very much less than for pure nickel, or for alloys containing a high proportion of nickel (e.g. as found in cupro-nickel coins or in some jewellery). See the section 'Health and Safety' on page 61 for further details.

An overview of the activities

The activities are:

- Activity B1 Setting the scene
- Activity B2 Making the sensor
- Activity B3 Testing the sensor
- Activity B4 Writing the report
- Activity B5 What else could QTC be used for?

In addition, there are resource sheets that provide information for students:

- Resource R1 What is QTC?
- Resource R2 What can QTC be used for?
- Resource R3 The development of an idea

There are two extension activities:

- Extension BX1 Further investigations
- Extension BX2 What makes a good material for a tactile sensor?

Notes on the activities

Activity B1: Setting the scene

Before starting systematic investigative work, students carry out a preliminary exploration of the properties of QTC. They are introduced to the focus of the enquiry.

LEARNING OBJECTIVE

Students will:

- recognise the properties of QTC
- operate a digital multimeter in order to measure a range of resistances.

NOTES

Students should be encouraged to handle QTC with forceps - it does not in fact suffer too badly from contamination of surfaces when handled, but this encourages them to treat the samples with care. They do however need to take care not to contaminate surfaces in electrical contact with glue.

After students have become familiar with the properties of a QTC pill, a class discussion to set the scene of the enquiry would be useful. The work of NASA, who are currently using QTC to develop tactile sensors for a robot, could be mentioned here or left until students have explored their own sensors.

(See Resource R2 for information about NASA's 'Robonaut'. There is also a lot of information on NASA's website - see the list of websites at the end of this booklet.)

RESOURCES NEEDED

Each group needs:

- 1 QTC pill in a labelled plastic bag
- Forceps
- Metal disc or 2p coin
- 2 batteries (1.5v) in holders
- Bulb in holder
- 2 red plug-plug leads
- 2 black plug-plug leads
- 6 croc clips
- Resistance substitution box or known resistors
- Digital multimeter

Activity B2: Making the sensor

Students make their own tactile sensor needed for activity B3 using QTC sheet, cardboard and aluminium foil. This activity is optional, as students can be given pre-made tactile sensors that are included as part of the 'QTC testing kit'.

LEARNING OBJECTIVE

Students will:

- construct a tactile sensor that can be used to test the properties of QTC
- compare the properties of QTC sheet and pills.

NOTES

Students should be made aware that the QTC sheet consists of three layers (see Resource R1), in order for them to understand how they can use it - it may not be obvious to them. QTC sheet is manufactured in rolls about 30 cm wide. The strips of QTC sheet that you can buy have been cut from this roll (about 30 cm x 5 cm). You can see the aluminium layer at each of the edges where there is no QTC coating. It is also possible to scrape the QTC layer off to reveal the aluminium layer.

In Activity B3, the 'sensors' will be secured between two terminal posts, and need to be cut to the correct length. If they have the kit then they could test that they will fit.

Note that the resistance of the pill can drop down lower than the sheet. Thus, in task B activity B3, the dimmer switch with the sheet can control the brightness of an LED, but not a bulb, which requires a bigger current.

RESOURCES NEEDED

Each group needs:

- 1 piece of QTC sheet (approx 25 mm x 15 mm) in a labelled plastic bag (also students can put their sensors in here when made)
- Forceps
- Scissors
- Glue stick
- Access to cardboard
- Access to aluminium foil or tape
- 2 batteries (1.5v) in holders
- LED
- 2 red plug-plug leads
- 2 black plug-plug leads
- 6 croc clips
- Digital multimeter
- Resource R1 What is QTC?

MAKING A TACTILE SENSOR USING QTC

Activity B3: Testing the sensor

Students undertake a systematic investigation to find out how the resistance of QTC changes with applied force.

LEARNING OBJECTIVE

Students will:

- select appropriate values and ranges to use, and the number of readings collected
- analyse and present data using appropriate graphs
- recognise patterns in data that show variability.

NOTES

QTC is not an easy material to investigate because of the variability in the measurements. This is an interesting phenomenon in the context of looking at accuracy and reliability, though only if the variation is not too large and unpredictable. For this reason, students are given detailed instructions on how they should set up the testing kit, in order that they can obtain reasonable results. The activity thus focuses on the appropriate collection of data rather than on experimental design.

The resistance of QTC is very susceptible to anything that affects the electrical contacts. The main thing is to ensure that *everything is secured firmly and that movements on the QTC are kept to a minimum.*

For example:

- The experiments should be carried out on a steady table or bench, avoiding movements caused by walking past or carrying out other activities on the bench.
- The switch should be held securely in place.
- Rotation of the loading pan should be avoided and the weights should be placed carefully and slowly on the pan.

Being thinner and subject to less creep, the resistance of the sheet reaches a steady value faster than the pill - this is the reason that students are asked to investigate this. In fact the sheet is what the manufacturers use in their force sensors; the pill was developed for switching functions as it is able to carry a much larger current than the sheet.

RESOURCES NEEDED

Each group needs:

- 'Sensor' made by students in activity B2, or pre-made sensor included with the QTC testing kit
- 1 QTC testing kit
- Holder with 10 x 100 g slotted masses
- Stop clock
- Digital multimeter
- 1 red plug-plug lead
- 1 black plug-plug lead

Activity B4: Writing the report

Students write a brief report to summarise the key points from their investigation and make a recommendation about the suitability of QTC for a tactile sensor.

LEARNING OBJECTIVE Students will: • interpret results in terms of accuracy, variability, error, and reliability • select relevant evidence from experimental results and from given information • present the evidence taking into account the audience. NOTES When writing the report, students should be encouraged to use appropriate scientific terminology when interpreting their results. Some simple definitions of relevant terms that could be used with students are given below. <i>Accuracy</i> The accuracy of a measurement is how close it is to the true value. <i>Error</i> The difference between the true value and the measured value. <i>Precision</i> The similarity of a set of readings of the same thing. <i>Random error</i> These errors can make a reading higher or lower than the actual value. <i>Reliability</i> The reliability of an instrument or an experimental procedure is the extent to which it gives similar results each time.	<i>Repeated measurements</i> A set of measurements of the same thing designed to reduce the effects of random error. <i>Spread</i> The spread of a set of values is the extent to which they differ from an average value. <i>Sensitivity</i> The sensitivity of a measuring instrument is how many figures it gives in its readings. <i>Systematic error</i> These errors make a reading systematically different from the actual value. <i>Variability</i> A set of measurements of the same thing show ‘Error’ is a word that can cause difficulties for students because it may imply ‘things that they have done wrong’ in carrying out the experiment. The scientific term for this is human error, but in this investigation they are paying attention to random errors. A word whose everyday usage reflects better the meaning of this kind of error is uncertainty. This may be a useful term to discuss in helping students to understand the scientific meaning of the word error. RESOURCES NEEDED None
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Activity B5: What else could QTC be used for?

Students write a brief report to summarise the key points from their investigation and make a recommendation about the suitability of QTC for a tactile sensor.

LEARNING OBJECTIVE Students will: • describe some applications of QTC and identify the properties that make it suitable • devise ideas for new potential applications of QTC.	RESOURCES NEEDED Resource R2 What can QTC be used for?
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MAKING A TACTILE SENSOR USING QTC

Notes on the extension activities

Extension BX1 Further investigations

This activity includes suggestions for more open-ended investigation building on students' work from Activity B3

LEARNING OBJECTIVE

Students will:

- recognise patterns in data that show variability
- select appropriate values and ranges to use, and the number of readings collected
- formulate a question that can be investigated experimentally
- plan an experiment and collect appropriate data
- analyse and present data using appropriate representations.

NOTES

In Tasks A and B, students should try to choose a load of a suitable size. It is best to have one so that they can measure the resistance readings over time without needing to change the scale on the meter.

The data they collect give students an opportunity to use ideas that they may have encountered in higher level GCSE mathematics. With a large batch of values, a stem-and-leaf diagram is a useful way of quickly organising them. From a stem-and-leaf diagram, the median and the quartiles can be found. These values can be used to draw a boxplot that summarises the distribution of values visually.

To compare two sets of data (e.g. for the sheet and the pill), and the overlap between them, drawing two boxplots side-by-side can be very useful.

RESOURCES NEEDED

TASK A - same equipment as for Activity B3.

TASK B - in addition to equipment from Activity B3:

- QTC pill

TASK C - in addition to equipment from Activity B3:

- 1 G-clamp

TASK D - in addition to equipment from Activity B3:

- 1 variable power pack
- 2 red plug-plug leads
- 2 black plug-plug leads
- 1 ammeter and 1 voltmeter (or a second digital multimeter)

Extension BX2 What makes a good material for a tactile sensor?

Students look at a variety of graphs to consider the properties needed for an effective tactile sensor.

LEARNING OBJECTIVE

Students will:

- interpret graphs showing relationships between the properties of materials
- select materials with required properties and identify the criteria for selecting them.

NOTES

The answers to this activity are: 1 B, 2 A, 3 A, 4 B, 5 B, 6 A.

The key ideas here are that for a tactile sensor the material should show:

- a large variation of resistance with force (1, 2), with a single value (3)
- small variability (4) and a fast response time (5)
- small effects from other environmental factors (6).

RESOURCES NEEDED

None

MAKING A TACTILE SENSOR USING QTC: SETTING THE SCENE



QTC is a very safe material, though it does contain the metal nickel. Some people have allergic reactions to nickel-containing items (e.g. jewellery, coins). Follow your teacher's instructions on using QTC.

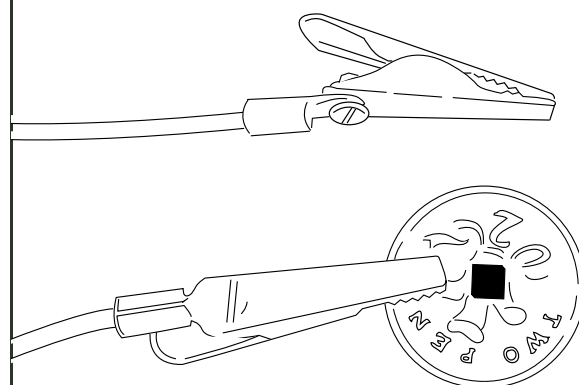
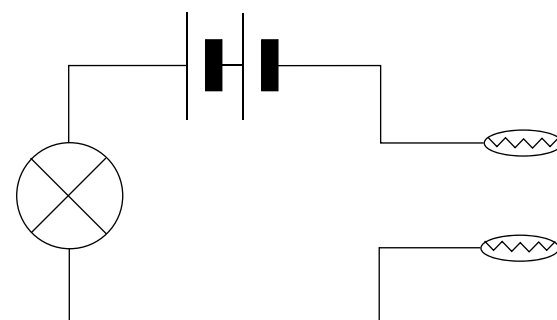
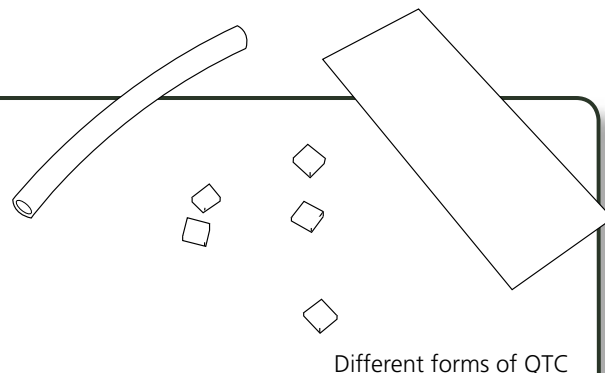
What is QTC?

QTC has only recently been invented. It is a rubber-like material containing tiny metal particles. QTC stands for 'Quantum Tunnelling Composite'. Its name sounds complex, but what it does is easy to understand. When you squeeze it, its electrical resistance drops. A lot of research is now being done on how it could be used. Its behaviour is not yet well understood, and there is much to learn about how it works.

Task A Exploring the behaviour of QTC

A 'QTC pill' is a tiny square piece of the material. You can explore its behaviour by putting it in a simple circuit. (Note: to avoid surface contamination, handle QTC using forceps.)

1. Connect a battery to a bulb, and two croc clips as shown in the circuit diagram.
2. Touch the croc clips together to make sure the circuit is working.
3. Now attach one clip to a metal disc (e.g. a coin) and put a QTC pill on it.
4. Press on the pill with the second croc clip. What happens to the brightness of the bulb?



Setting the Scene continued...

Task C Measuring resistance of the pill

You can measure how the resistance of a QTC pill changes using a digital multimeter.

5. To practice using the meter, start with a resistor of known resistance (e.g. 10 k Ω). Use the selector switch on the meter to find the right range. Check that your meter reading agrees with the known value. Choose some other resistances to check.
6. Now use the multimeter to look at how the resistance of the QTC pill changes as you press on it. What is the minimum resistance you can get? What is the maximum?

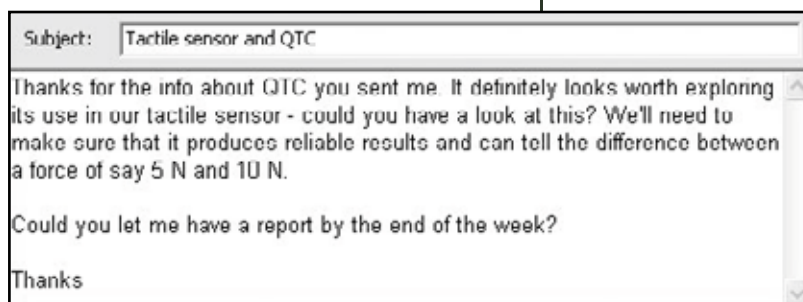
What is a tactile sensor?

When you grip an object, like an apple, you can judge how much force you need. You can do this because your brain gets feedback from your fingers about how hard you are pressing. Researchers are trying to make mechanical hands that can do the same thing. These would be useful for a robot or for a person whose hand has been amputated. The problem is how to get feedback about the forces used. Without this, an apple could be squeezed too hard and crushed.

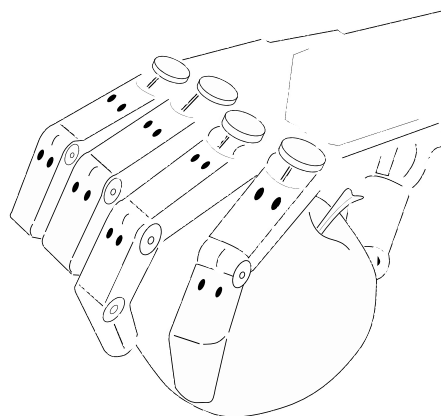
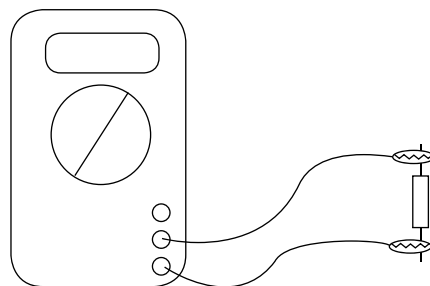
To solve this problem, sensors can be put on the fingertips to measure the forces. These devices are called tactile sensors.

The Enquiry

You are going to investigate whether you could use QTC to make a tactile sensor. Imagine that you are researching into mechanical hands and you have been sent this email:



You will need to carry out some tests and write the report.



MAKING A TACTILE SENSOR USING QTC: MAKING THE SENSOR



QTC is a very safe material, though it does contain the metal nickel. Some people have allergic reactions to nickel-containing items (e.g. jewellery, coins). Follow your teacher's instructions on using QTC.

In this activity, you will use QTC sheet to make a simple tactile sensor. QTC sheet consists of a thin layer of QTC on a plastic and metal sheet. You can find out more about QTC sheet in Resource R1 (What is QTC?).

Using QTC sheet you can quickly make a simple dimmer switch. You will need:

- some cardboard
- some aluminium foil
- a glue stick
- a piece of QTC sheet

The QTC sheet acts as a 'bridge' between two aluminium strips in a 'cardboard sandwich'.

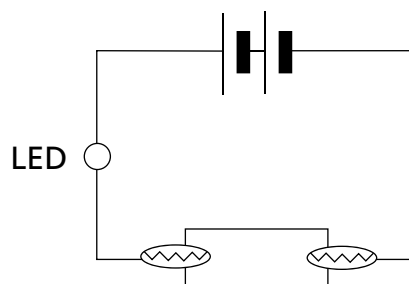
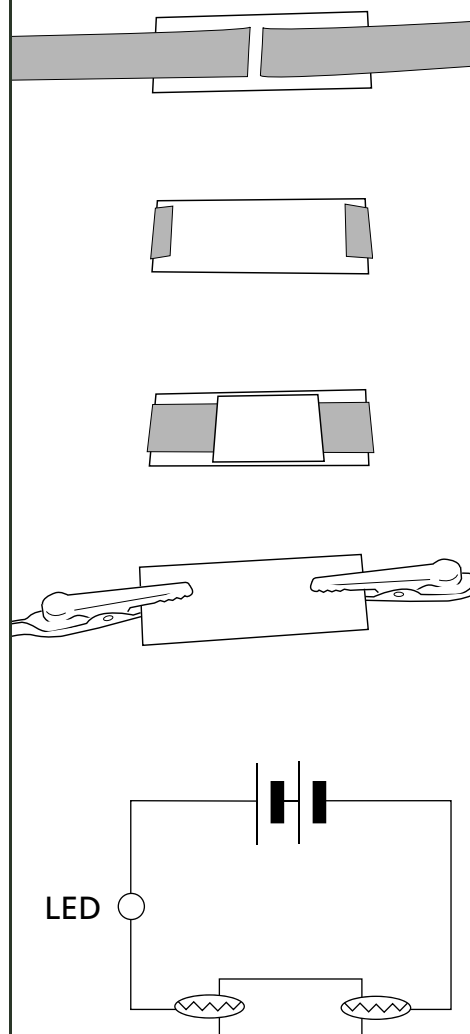


☐ Cardboard
 ☐ Aluminium
 ☐ QTC sheet

This cross-section shows what the finished switch looks like.

Making the Sensor continued...

1. Cut out two pieces of cardboard 6.5 cm x 2.5 cm. (You need to get the exact length, so that it will fit in the testing kit later.)
2. Glue two strips of aluminium onto a piece of cardboard, leaving a small gap between them.
3. Turn the cardboard strip over. Fold over the ends of the aluminium and tuck them down.
4. Place the QTC sheet (grey side *down*) on top of the gap between the aluminium strips.
5. Place the other piece of cardboard on top. Attach the two croc clips.
6. It is now ready to test. Put it in a circuit with a battery and an LED. Watch what happens when you squeeze the middle of the sensor.
7. Connect the sensor to a multimeter. What is the minimum resistance you can get? How does this compare with the QTC pill?



MAKING A TACTILE SENSOR USING QTC: TESTING THE SENSOR



QTC is a very safe material, though it does contain the metal nickel. Some people have allergic reactions to nickel-containing items (e.g. jewellery, coins). Follow your teacher's instructions on using QTC.

A good tactile sensor needs to be reliable. You need to be able to tell the difference between forces of different sizes. In this activity, you will do some tests to see if QTC would make a good tactile sensor.

When QTC is squeezed, its resistance drops. If it works well as a sensor, you should be able to distinguish between different forces. This means that:

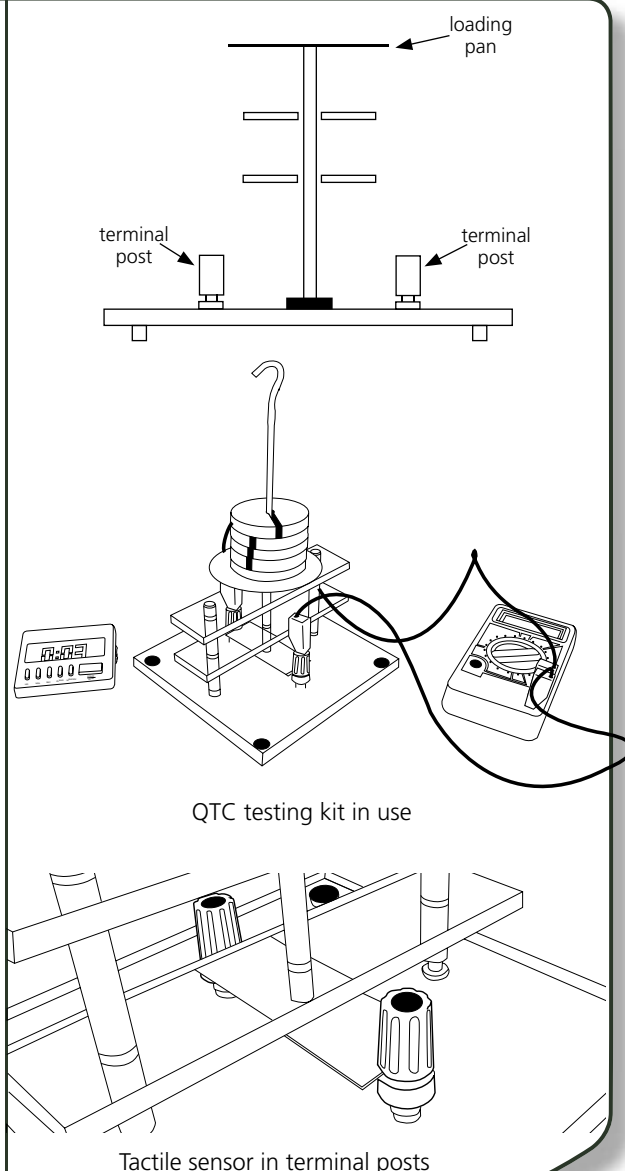
- the same force always gives similar resistance readings;
- different forces always give different resistance readings.

The diagram shows the testing kit you will use to see if QTC is a good sensor.

Task A Setting up the testing kit

You can measure how the resistance of a QTC pill changes using a digital multimeter.

1. On the testing kit, unscrew the knobs on the terminal posts. Put your sensor between them. Screw down the knobs, so that the sensor is held securely with good electrical contact.
2. Connect the terminals to the digital multimeter.
3. Turn the selector knob on the meter to a resistance scale. Push down on the pan – you should get a reading on the meter. (If not, try using another resistance scale, or check all the electrical connections.)
4. Put a load on the pan (start with a large load – say 1000 g). What happens to the resistance? Try with a smaller load.



Testing the Sensor continued...

You may notice that when the load is put on, the resistance takes time to settle. Being a rubbery material, the QTC continues to get squeezed with the load on it. Eventually the resistance reaches a minimum value.

Task B Can you tell the difference between loads?

In this test, you will compare the effects of two different loads. You can record your results in the table on the worksheet. Because the resistance changes over time, make sure the readings are all done in the same way. Use a fixed 'stabilising time' of 15 seconds for every reading.

5. Start with a large mass. Put a 1000 g load on the pan and wait 15 seconds. Record the resistance and take the load off. Wait 15 seconds.
6. Put the load back on and keep repeating this process. (Because of the variability in the readings, the more measurements you make, the more accurate the average will be.)
7. Now do the same tests with a load of 500 g.

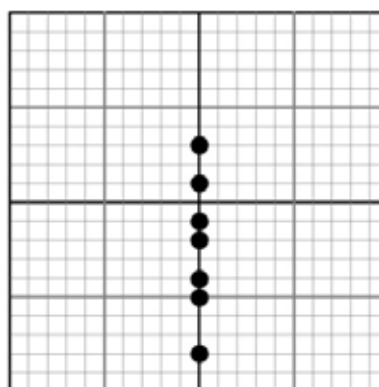
Task C Analysing the results

A good way of showing the variability in a set of readings is to use a dotplot.

8. Plot your set of repeat readings for the 1000 g load in a vertical line on your graph. Plot your readings for the 500 g load.
9. Is this set of readings different from that for the large load? Is there any overlap?
10. Can you use the resistance readings to tell the difference between the two loads?

Task D Doing further tests

11. Repeat with another load (say 600 g). Plot your data on the graph.
12. How easy is it to tell the difference between two similar loads?



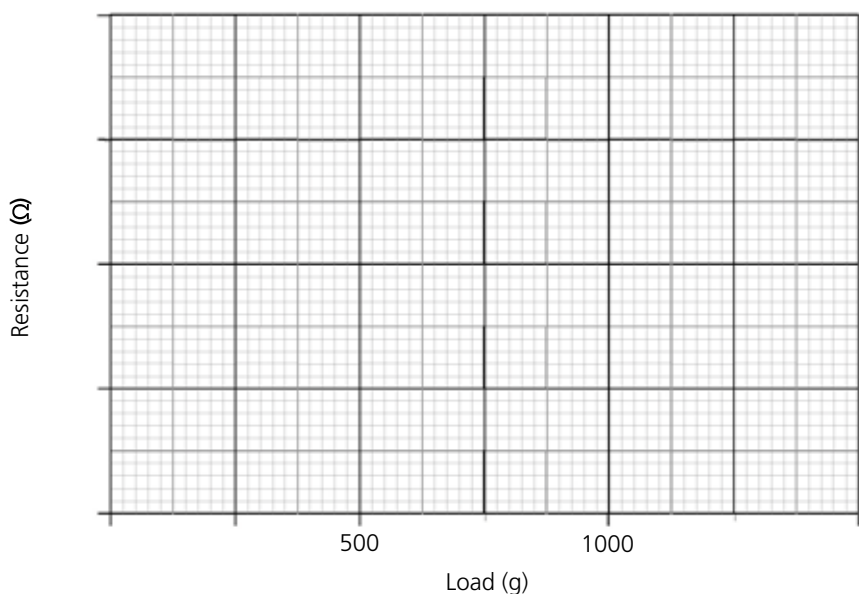
A dotplot shows a set of values plotted vertically

Testing the Sensor continued...

Results

Record your readings in this table for loads of 1000 g and 500 g. (Or, if you want to do more than 12 readings, draw your own table.) Then draw dotplots on the graph below. You can use the two blank columns for other loads that you choose.

Reading number	Resistance (Ω)			
	Load = 1000 g	Load = 500 g		
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12				



MAKING A TACTILE SENSOR USING QTC: WRITING THE REPORT

Now you have collected some evidence you should be in a position to make a recommendation: would QTC be a suitable material for a tactile sensor? Now is the time to write your report.

1. Read the email from Activity B1 again.
2. Think about the scientific terms you will use in your report. For example, accuracy, error, variability, reliability.
3. Now write your report. Bear in mind the following points:
 - *Before you start, make a bullet point list of key points.*
What do you want to say? What order will you present them in?
 - *Make your report brief and simple.*
The reader needs to read it quickly and pick out your key points.
 - *Put your recommendation at the beginning.*
Use the rest of the report to justify your recommendation. This helps the reader make sense of it.
 - *Use a new paragraph for each key point.*
It is easier to read if you put the main point at the start of each paragraph.
 - *Don't include a lot of detail.*
Data or graphs can go in an appendix.

Subject: Tactile sensor and QTC

Thanks for the info about QTC you sent me. It definitely looks worth exploring its use in our tactile sensor - could you have a look at this? We'll need to make sure that it produces reliable results and can tell the difference between a force of say 5 N and 10 N.

Could you let me have a report by the end of the week?

Thanks

MAKING A TACTILE SENSOR USING QTC: WHAT ELSE COULD QTC BE USED FOR?

Making a tactile sensor is just one use for QTC. Many other applications are being researched and developed. You may have ideas of your own too.

Task A Applications being developed

1. Read through Resource R2 'What can QTC be used for?' and make a list of each of the applications described. Write them in a table like this:

Application	Properties of QTC

2. For each application, write down the properties of QTC that make it suitable.

Task B Your own ideas

3. Think of your own ideas about what QTC could be used for. Don't worry about how sensible they are. One idea can lead to another. Many things have been invented or discovered like this – including QTC. Use your imagination!

USING QTC TO MAKE A TACTILE SENSOR: FURTHER INVESTIGATIONS



QTC is a very safe material, though it does contain the metal nickel. Some people have allergic reactions to nickel-containing items (e.g. jewellery, coins). Follow your teacher's instructions on using QTC.

Although researchers are investigating the properties of QTC, very little data has been published. So there are lots of possibilities for further investigation. Some suggestions are given here.

Task A How quickly does QTC respond?

The resistance of QTC does not immediately reach a steady value when you put a load on. It tends to creep. This is because it is a rubbery material. As the QTC gets squashed, the load continues to move down slightly until eventually it stops. How long does it take for QTC to give a reasonably steady reading?

1. Use the tactile sensor you have already made and the QTC testing kit.
2. Choose a load of a suitable size.
3. Put the load on the pan and take readings of the resistance at suitable time intervals. Do the readings go down smoothly, or do they jump around?
4. Repeat this several times. Are your sets of readings fairly similar, or is there a wide variation between them?

Task B How do the pill and sheet compare?

5. Make another tactile sensor, this time using a QTC pill. The cross section is shown below. (Make it the same size as before so that it will fit the testing kit.)

☐ Cardboard
 ☐ Aluminium
 ☐ QTC pill

Dimmer switch using a QTC pill



Further Investigations continued...

6. Test it out in a simple circuit.
7. The QTC pill is much thicker than the thin layer of QTC on the sheet form. How might this affect its responsiveness? Test your prediction by measuring the resistance over time as in Task A. How does this compare to the sheet?
8. Now test the variability in the resistance of the pill, by using two different loads as in Activity B3. How do the pill and sheet compare?

Task C What affects the extent of creep?

When QTC is loaded with a weight, it takes some time for the resistance to reach a steady value. The reason given earlier was that being rubbery, the QTC creeps. If this explanation is correct, then if QTC is put in a clamp, the resistance should quickly reach a steady value. It should not creep, as the jaws of the clamp do not move.

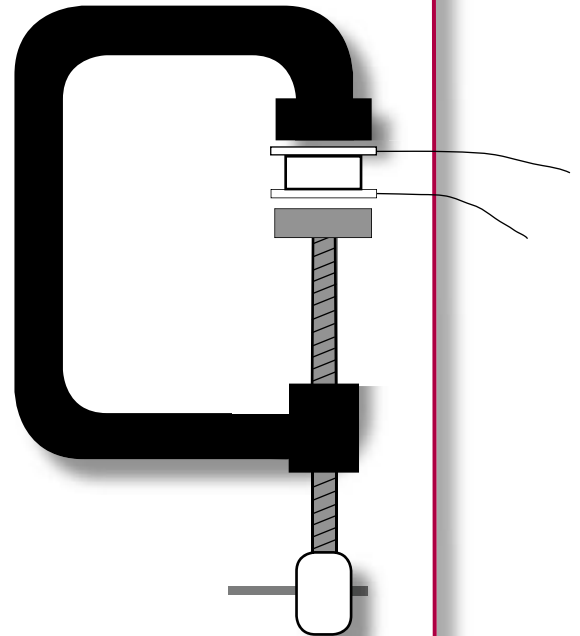
Test this idea. Is there less creep in a clamp than with a weight on it?

Task D Does QTC obey Ohm's Law?

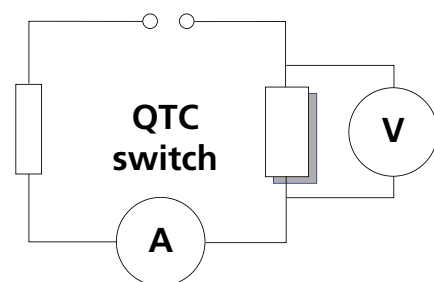
Resistance is defined by the formula $R = V/I$. For some components (e.g. a standard resistor), R stays the same as V is changed – these components obey Ohm's Law. Other components (e.g. a filament lamp) do not obey Ohm's Law, because their resistance depends on the voltage applied across it. For a lamp, as the voltage is increased, more current flows, and the filament gets hotter. This means that its resistance increases. Such a component is called *non-ohmic*.

Does the resistance of QTC depend on the voltage across it? Is it an ohmic or non-ohmic material?

You can investigate this question using this circuit. Connect up a power pack, a resistor and one of your QTC switches. Put a load on the QTC and wait till it stabilises. By varying the power supply (up to 12V), record a set of values of V and I , and calculate the values of R . Is R constant or does it vary?



connect to multimeter
to measure resistance



USING QTC TO MAKE A TACTILE SENSOR: WHAT MAKES A GOOD MATERIAL FOR A TACTILE SENSOR?

The resistance of QTC changes when you squeeze it – but does the way it changes make it a suitable material for a tactile sensor? This activity helps you to think about what properties are important for a material used to measure forces.

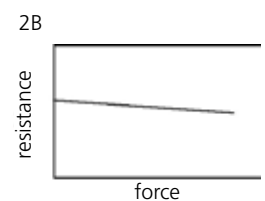
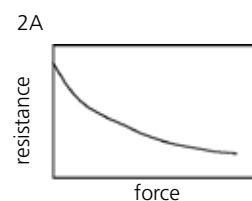
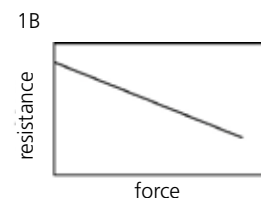
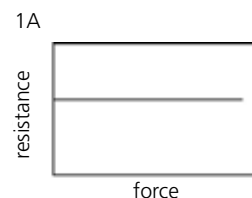
A good tactile sensor needs to:

- show a wide variation in resistance with applied force;
- have a reasonable response time, so that feedback can be given quickly;
- be reasonably reliable, so that the same force always give similar readings.

Task A Looking at data on different materials

The following graphs show 'invented' data about different materials (imaginary materials, not QTC). For each pair, choose which one makes a better material for measuring force. Explain your choices.

1. These graphs show how the resistances of two different materials vary with the applied force. Which one would be better as a force sensor? Why?
2. These also show how the resistance varies with the applied force for another two materials. Which one would be better? Why?



What makes a good material for a tactile sensor continued...

3. Graphs for another two materials. Which material would be better? Why?

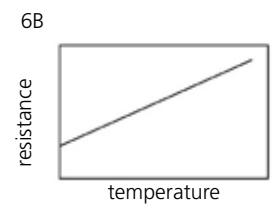
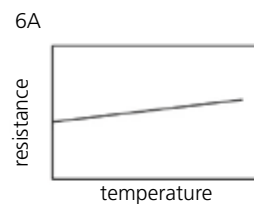
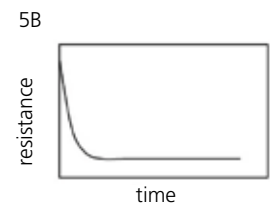
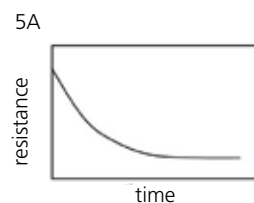
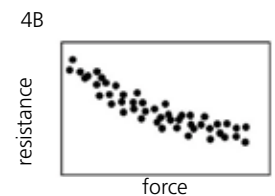
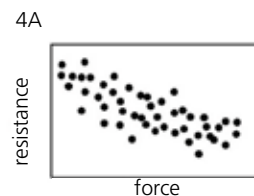
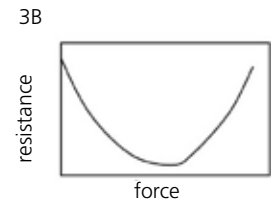
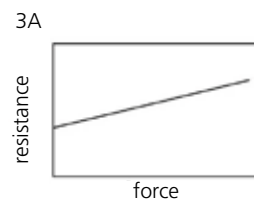
4. Here, instead of showing a line of best fit, the graphs show the results of many measurements. Which material would be better? Why?

5. In the experiments on these two materials, a constant force was used, and the resistance was measured over a period of time. Which material would be better? Why?

6. In these experiments, a constant force was used, and the resistance was measured at different temperatures. Which material would be better? Why?

Task B Identifying the properties of a good material

7. Using the ideas from the previous task, write down a list of important properties that a material should have to make it a good force sensor.



MAKING A TACTILE SENSOR USING QTC: WHAT IS QTC?

QTC (Quantum Tunnelling Composite) is a remarkable new material with an enormous number of applications. It has won many major awards for innovation.

Its name may sound complex, but what it does is easy to understand – when you squeeze it, its electrical resistance drops. Different forms can be made that are sensitive to a light finger-touch or to very large forces.

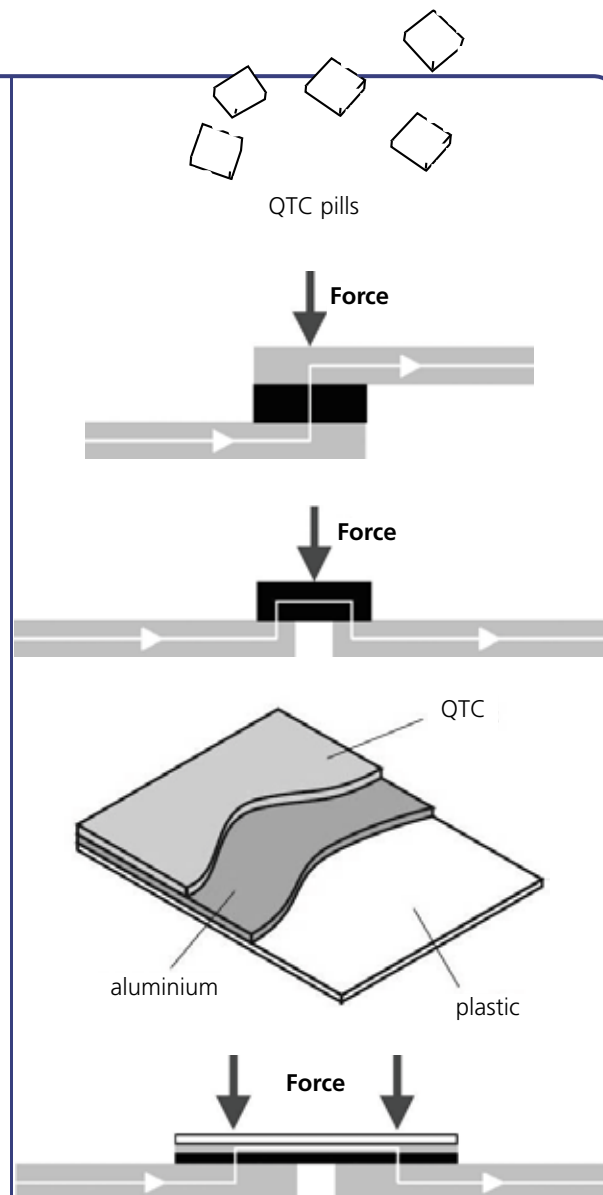
What does QTC do?

QTC pills are made of a rubbery material containing grains of nickel. In its 'rest state', its resistance is over 10 million ohms. But when squeezed between two metal contacts, there can be an electrical current from one side of the pill to the other.

It can also be used so that the current is along the length of the pill.

QTC sheet consists of three layers. The first is made of white plastic to give the sheet strength. Next is a thin layer of aluminium that acts as a conductor. Finally there is a thin layer of QTC. This is the grey side of the sheet.

When QTC sheet is pressed, current can pass through the QTC to the aluminium. The current can then pass along the aluminium layer.



MAKING A TACTILE SENSOR USING QTC: WHAT CAN QTC BE USED FOR?

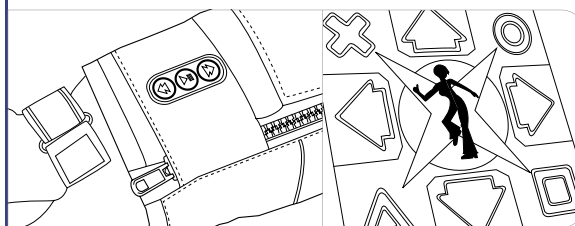
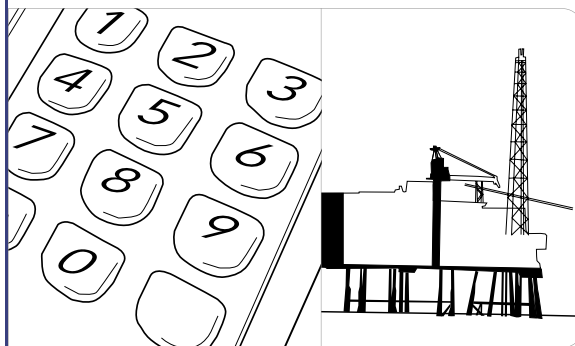
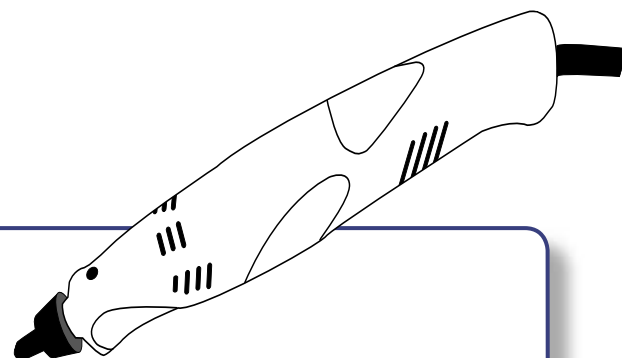
The first thing made using QTC was this power drill. The manufacturers of QTC used it to demonstrate to their customers what QTC could do. The handle contains QTC. Squeezing it controls the speed of the drill. Since then, many ways of using QTC have been found.

Telephones and remote controls contain membrane switches. These contain two metal surfaces that are pressed together. This movement makes them eventually wear out. QTC switches have an advantage because they have no moving parts.

Another advantage of QTC is that it can be used in high voltage switches. This avoids the 'sparking' that happens in traditional switches as the two metal contacts come together. These 'spark -free' switches would be very useful in places with flammable vapours, such as an oil rig.

QTC is a flexible material, and QTC-coated fibres can be used to make 'fabric switches'. There are many potential applications for this. For example, jackets can be made with a 'soft keypad' that can be used to control a built-in audio player. Dance mats could be made with flexible QTC switches that could be simply folded when not in use.

As well as these 'novelty examples' there are also more serious applications. Much research is now being done into making these kinds of 'smart' fabrics.



What can QTC be used for? continued...

QTC is finding medical uses. For a bandage, it is very important to get the pressure right – too little and it may slip, and too much may prevent blood flow. QTC sheet, being thin and flexible, can be placed inside the bandage. If it is too tight, the QTC detector can give a warning signal.

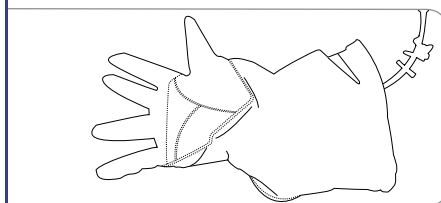
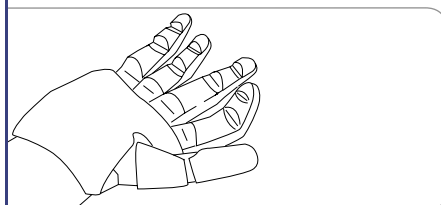
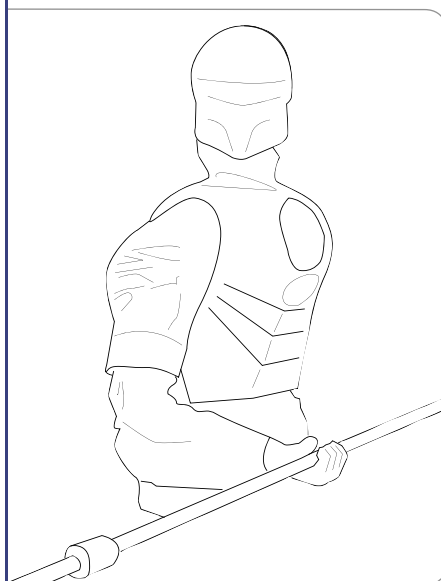
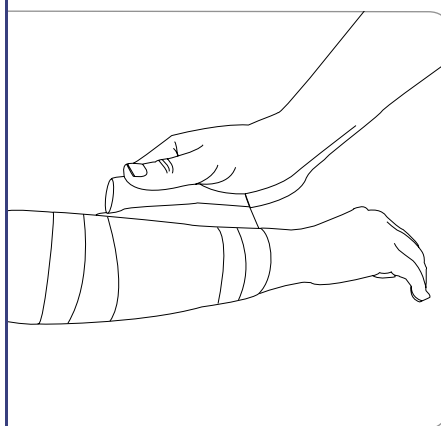
Robots can be given touch-sensitivity by building QTC into sensors on the robot's body. NASA are using QTC in the development of their 'Robonaut' – a robot that can carry out human-like functions. They have built a mechanical hand that can grasp and manipulate objects. A 'tactile glove' containing QTC sensors fits over the hand. These sensors can give feedback about the forces on the glove.

"The next generation tactile glove was assembled, installed and tested on the right hand of Robonaut. This 33-sensor glove represents a significant advance over its predecessor with almost twice as many sensors in a more form fitting, considerably less bulky design. This glove is the first version to incorporate a Quantum Tunneling Composite (QTC) sensor material that permits much greater coverage on the primary fingers and palm."

NASA monthly status report

QTC can also be used in other kinds of sensors. When QTC is heated, it expands and its resistance increases. It can therefore be used as a temperature sensor.

One exciting development is the 'electronic nose'. The resistance of QTC is affected by contact with vapours. As vapour is absorbed, the QTC expands and its resistance increases. Different forms of QTC are affected in different ways. By using an array of sensors, specific vapours can be identified. An experimental version of an 'electronic nose' has been made. It is even sensitive enough to detect the difference between the front and the back of someone's hand.



MAKING A TACTILE SENSOR USING QTC: THE DEVELOPMENT OF AN IDEA

How was QTC discovered?

QTC was an 'accidental' discovery. David Lussey, a research engineer in Darlington, was developing an adhesive that would conduct electricity. Electrical connections could be made simply by sticking metal contacts together.

He tried mixing fine grains of metal powder in a rubber polymer. He didn't make a conducting adhesive, but produced something with very strange properties. It seemed unlike anything made before. He asked scientists at the University of Durham to look at the material. They confirmed that it was a completely new material, and QTC was patented.

At first it wasn't clear whether this material had many uses. They had some preliminary ideas, but it was only later that the huge number of applications become apparent.

"It happened at my home lab. The substance showed unusual electrical activities but I didn't realise what I had was special straightaway. It wasn't so much a eureka moment as a eureka fortnight."

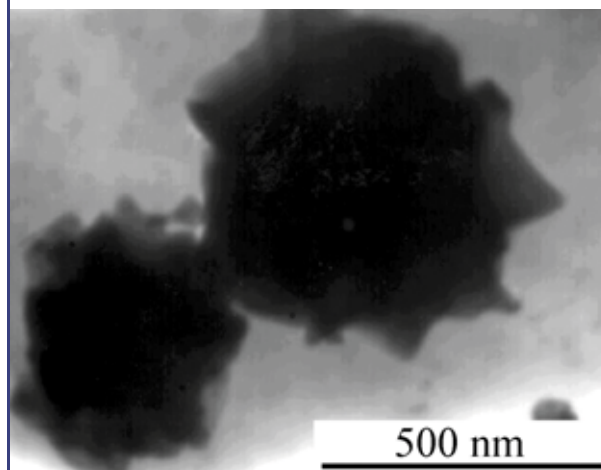
David Lussey

How does it work?

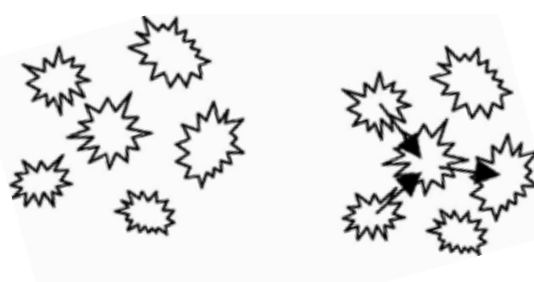
The photograph was taken using an electron microscope. It shows the very tiny grains of nickel in QTC. When the material is squeezed, these grains get closer to each other and the material can conduct electricity.

Although the grains of metal get closer, they do not actually touch each other. So, if they don't touch, how do electrons flow through the material?

What happens is that when the metal grains get very close, electrons can 'jump' from one grain to another. This process is called 'quantum tunnelling', and hence the material is called Quantum Tunnelling Composite.



Reproduced with permission, Professor D Bloor,
Department of Physics, Durham University



BACKGROUND SCIENCE

This section gives further information about how QTC was discovered, how it behaves and the science of quantum tunnelling.

THE STORY OF QTC

QTC began its life in 1997 when David Lussey was working in his home laboratory trying to make a conducting adhesive. What he made was in fact was something rather different - a material that changes from being an electrical insulator to a conductor when pressure is applied. This unusual property opens up its use for an enormous range of commercial applications.

On the SEP website, you can download video clips of David Lussey talking about how he discovered the remarkable properties of QTC, and how he began to develop it into a commercial product. The transcripts of these clips are given in the boxes below.

The origins of an idea

David Lussey was approached by a local college in 1997 to develop a security system to prevent thefts of their computer equipment. The idea he came up with was to make a security tag that was connected by a wire to an alarm system. He wanted to attach the tag using an electrically conducting adhesive, so that if someone pulled the tag off, the alarm would be triggered.

At the time, there were very few such systems around, and he did not have access to an adhesive that conducted electricity. So, working in his home laboratory, he tried to make one by mixing various combinations of metal powder with adhesive. As he made each of these materials, he used a test meter to measure their conductivity.

"The reason why I was developing a conductive adhesive was because I had a problem - I wanted to make a security tag. I'm not a scientist, but I am a practical person with a technical background from the military. When I needed a conductive adhesive, and found there wasn't one available, I decided to make one. I'd been working on the problem for a few weeks, by mixing different conductive powders with different adhesives, and I wasn't getting very far. I wasn't obtaining the results I really wanted."

He spent some time experimenting with different combinations, but could not get what he wanted. One of the materials that he made was clearly of no use for his security system, since it did not conduct electricity - but it turned out to have some very remarkable properties.

Exploring a new material

At first, he did not realise that this new material he had made was particularly special. When he stuck two plates together with it and tested it, he found that it did not conduct electricity. However, he began to realise that the material had some very unusual properties - it changed from being an electrical insulator in its rest state to an electrical conductor when he tried to pull the plates apart.

Although this was an 'accidental' discovery, what was not accidental was David's insight that this was a material that was worth exploring further. It was not immediately apparent to him that the material had commercial potential. As David put it himself 'it was not so much a eureka moment as a eureka fortnight'.

At that time, the material did not yet have a name. He believed that he had an unusual material, but he did not yet know why it exhibited this strange behaviour.

"I found it to be non-conductive until I tried to pull the plates apart, and then I found that conduction occurred - which was very strange and wasn't what I was looking for. So, I put that on one side (in fact I threw it on one side!) and it wasn't until some little while later that I thought 'Well, that was a strange reaction'. I went back and I measured it with a meter, and found I got something very unusual - something that became conductive when I pulled it, but wasn't conductive in its natural quiescent state."

Involving others

Exploring the properties of the material, he realised that it seemed quite unique. Its conductivity changed from being an almost perfect insulator to conducting as well as a metal. This was quite unlike anything ever discovered before.

Getting QTC from a laboratory curiosity to a commercial product involved drawing on a range of expertise. His first approach was to Professor David Bloor, who worked in the Physics Department at the University of Durham. As he performed tests on the material, an understanding of its behaviour emerged.

When the material is deformed, the particles of metal become closer together. However, the reason the material becomes a conductor is not that the metal particles touch each other. Instead, as the particles become closer, electrons can 'jump' from one particle to another across the gap - a process called 'quantum tunnelling'. At this point the new material acquired a name - 'Quantum Tunnelling Composite', or 'QTC'.

"I was a bit miffed at first because I hadn't got my conductive adhesive - which by the way I did eventually make! But in thinking about it, this curious property I'd seen in the thing that I had made, I checked out. I found it was a very unusual property. Everything seemed to work in reverse logic!"

"First of all I needed a scientist to verify what I'd found, and I found one in the shape of Professor David Bloor at Durham University. I took the first lump of this material that I'd made to him and he did the specific tests that he needed to do and drew me some graphs. Those graphs actually formed part of the first patent that we put in on this. All this happened about eight years ago now."

Bringing it to the market

In 1997, David set up a company 'Peratech' to produce QTC commercially - this was the same year that he had discovered the material. It was when he started to work with designers that the enormous range of applications of QTC began to become apparent - from switches in household appliances to smart fabrics, tactile sensors and electronic noses.

There are so many devices that we use in our everyday lives that need components to control the flow of electricity, that we could all find ourselves users of QTC in the near future. All of this is a long way from the initial experiments in the laboratory - though it has happened in the space of just a few years.

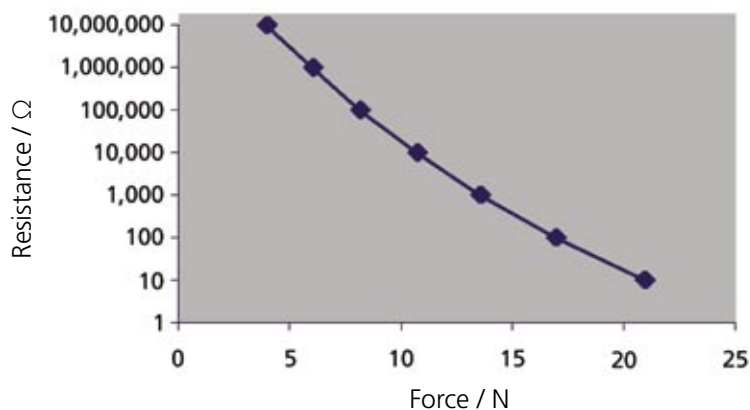
It seems surprising that although people have been making metal composites for many years, no one had come across a material with this strange behaviour before. It turns out that the key to David's discovery was that he was not using a mechanical mixer, which alters the structure of the metal particles - but simply mixing by hand in his home laboratory

"Once I decided to patent this, it was obvious that I needed to form a company as well, and that was when Peratech was formed, about eight years ago now. Within a few years I think that you will see QTC in different forms perhaps but in many different uses. We can do so many things with it, that some of these things are going to very quickly become very commonplace. That's a great drive in itself, that keeps me going, because what I want to see is everybody using it everywhere we can. It's just the thrill of getting it to market, and making sure it does what it's supposed to do, that keeps me going. That's what drives me!"

QTC AND ITS PROPERTIES

The following data have been supplied by Peratech, the manufacturers of QTC. The graph shows the relationship between the resistance of a QTC pill (plotted on a logarithmic scale) against the force applied to it. Theory predicts that the resistance should fall exponentially with linear compression (see the next section on quantum tunnelling). However, it is difficult to achieve linear compression - the material may not be uniformly compressed, and also the compression is not proportional to the applied force. This is why the line is slightly curved.

Dimension	
Width	3.6 mm
Length	3.6 mm
Thickness	1.0 mm
Mechanical	
Weight	0.04 g
Density	4.0 g cm ⁻³
Force Range	0 - 100 N
Lifetime	> 1 000 000 compressions
Op Temp Range	-20 °C to 120 °C
Electrical	
Unrestrained Resistivity	> 7 x10 ¹² Ωcm
Typical Resistance Range	>10 ¹² Ω to < 1 Ω
Operating Voltage	0 to 40 V
Max Current	10 A

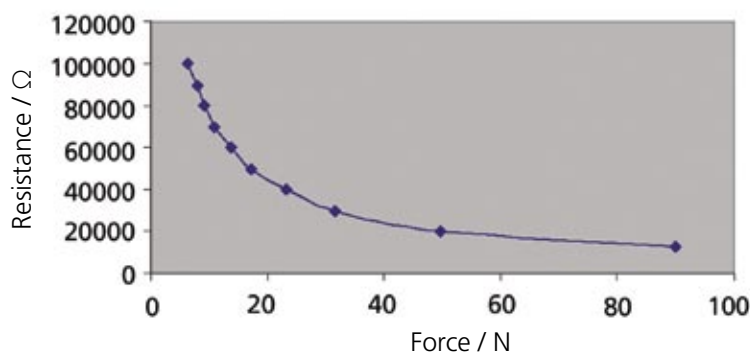


QTC Pill

In its rest state, the resistance of a QTC pill is very high (over 10 000 000 Ω). When squeezed with a moderate force, the resistance can fall to just a few ohms or less. The pills can carry quite large currents - up to 10 A.

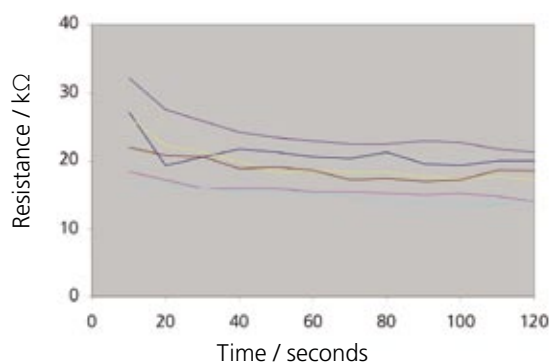
QTC sheet behaves similarly, with an exponential fall in resistance with force (this graph is plotted on a linear scale). It can be seen from this that the minimum resistance of the sheet is much larger than that for the pill, which is why it is not suitable for applications using large currents. The maximum current is about 100 μA cm⁻².

Op Temp Range	0°C to 60°C
Switch Capacity	100 μA cm ⁻²
Thickness	150 microns
Endurance	> 1 000 000 cycles

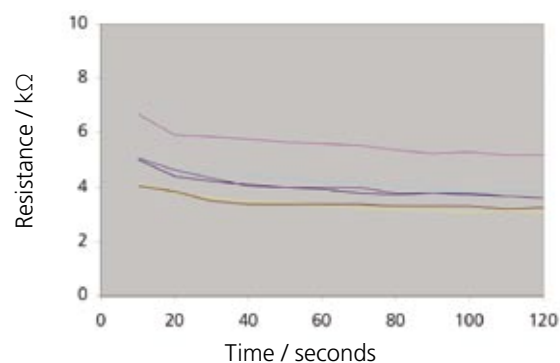


QTC Sheet

The following graphs show data collected using the QTC testing kit and a digital multimeter, using the techniques described in Activity B3. The first two graphs show the change in resistance over time for QTC sheet when loaded, for six different runs. The first shows the effect of a 500 g load (measurements made on the 200 k Ω scale); the second shows the effect of a 1000 g load (measurements made on the 20 k Ω scale).



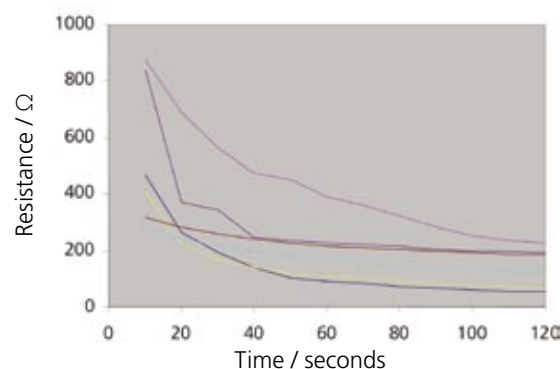
QTC sheet with 500 g load



QTC sheet with 1000 g load

Both graphs show some variability, but it is clear that in general the resistance of the sheet decreases over time due to creep. After 2 minutes, the resistance with a 500 g load is around 14 - 22 k Ω ; for a 1000 g load, the resistance is less, around 3 - 5 k Ω .

This graph shows the change in resistance over time for a QTC pill when loaded with 1000 g. Note that being thicker and subject to more creep, the resistance of the pill changes more over time than for the sheet. Also its final resistance (approximately 150 Ω) is much lower than for the corresponding test on the sheet (approximately 4000 Ω).



QTC pill with 1000 g load

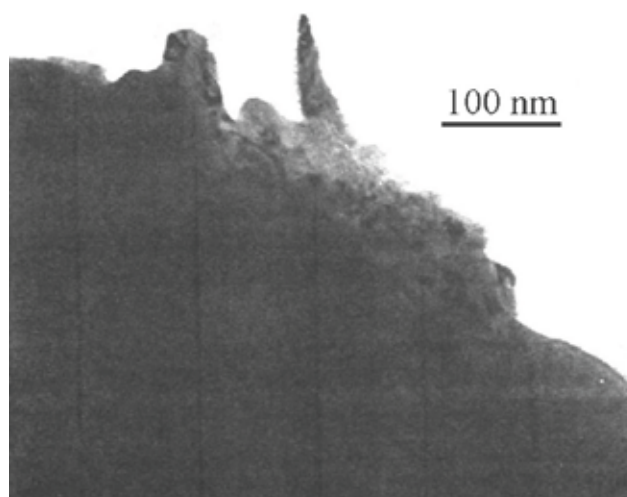
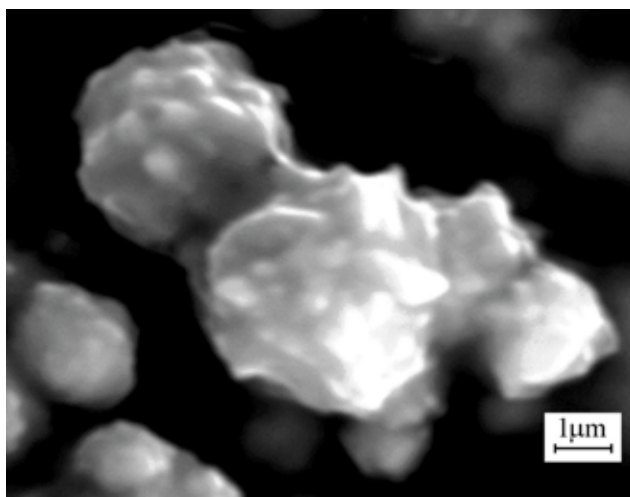
Looking at the relationship between voltage and current with a constant load produces surprising results. The table here shows the behaviour of a QTC pill with a load of 1200 g in series with a 100 Ω resistor as the voltage is increased then decreased at 15 second intervals. As the voltage across a pill is increased, the current increases, as might be expected. The resistance also increases - a QTC pill is non-ohmic. What is very surprising is that when the voltage is decreased, the resistance continues to increase.

Voltage across pill / V	Current / mA	Resistance / k Ω
0.80	19.1	41.9
2.75	47.8	57.5
4.62	64.4	71.7
7.25	78.9	91.9
10.90	70.1	155.5
6.23	53.0	117.5
4.22	22.2	190.1
2.15	6.1	352.5
0.85	2.4	354.2

A simple way of accounting for this is that as the voltage is decreased, electrons become 'trapped' on the nickel particles, as they do not have enough energy to 'jump' to other nickel particles. Over time, the electrons eventually 'leak away', and the resistance drops back to its original value. More about this and other effects can be found in Peratech's technical literature on their website.

HOW QTC WORKS: THE SCIENCE OF QUANTUM TUNNELLING

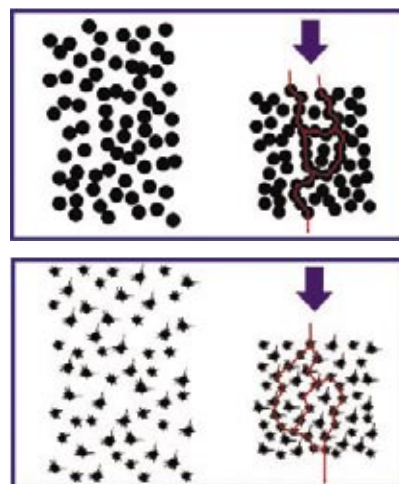
To understand the complex physics of QTC, Peratech formed a collaborative partnership with the University of Durham. These images, captured using scanning electron microscopy and tunnelling electron microscopy, show the metal particles embedded in the elastic material.



The particles themselves have dimensions of the order of microns and upwards (i.e. 10^{-6} m). However what gives QTC its unusual properties is the uniquely spiky surface of the particles. The image on the right shows that these spikes are of the order of nanometres in scale (i.e. 10^{-9} m).

Conventional composites, consisting of polymers containing carbon or metal particles, have been researched for over 40 years. In these, the particles are smooth and round; when the composite is squeezed, conduction occurs because the particles get closer together and touch each other. This process is called 'percolation'.

What gives QTC different properties from conventional composites is that the metal particles have an irregular structure with a spiky surface. Although the metal particles are close together, they do not touch each other even when the material is fully compressed. In simple terms, when the metal particles become closer to each other, electrons are able to 'jump' from one metal particle to another. This process is called 'quantum tunnelling'.

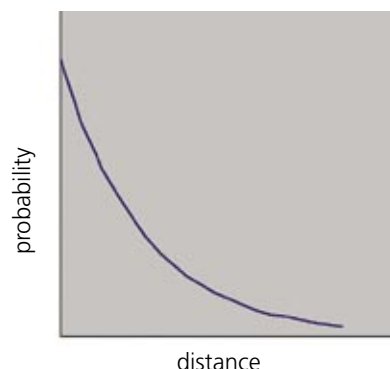


The key difference between carbon composites and QTC is their range of resistance. In the unstressed state, a carbon composite shows some conduction while QTC is an almost perfect insulator. And when a force is applied, the resistance of QTC drops to a much lower value than a carbon composite. Thus QTC has a very much wider range of resistance, with effectively an 'off' and an 'on' state (i.e. approximating to a zero resistance and an infinite resistance) at the extremes. This is what makes it useful as a switch.

The phenomenon of quantum tunnelling is well-known by scientists and is what underpins the operation of the transistor and the scanning tunnelling microscope. A key idea in quantum theory is that particles do not have definite positions in space. Instead, their behaviour needs to be understood probabilistically. Quantum tunnelling occurs because of the probabilistic nature of the electron.

If an electron is seen as a conventional particle, then getting from one nickel particle to another in QTC is like a rolling ball going up a hill and down the other side. It can do this if it is given enough energy to get over the top of the hill. Moving the nickel particles closer together would 'lower the height of the hill' - i.e. decrease the energy needed by the electrons to cross the non-conducting barrier.

From the quantum point of view, however, the electron does not need enough energy to reach the top of the hill. Its probabilistic behaviour means that there is a finite probability that the electron can be found on the other side of the hill. Thus the electron can 'tunnel' through the non-conducting barrier. As QTC is compressed, and the metal atoms become closer together, this should lead to an exponential increase in the probability of tunnelling and an exponential decrease in the resistance. It is this exponential change in the resistance that gives QTC its remarkable and useful behaviour.



Electron probability falls exponentially with distance from the atom.

In conventional metal composites, tunnelling does not occur because the potential is too high to be tunnelled through. In QTC, the 'spikiness' of the metal particles means that high concentrations of charge can build up at the tips of the spikes. The effect of the spikes is to lower the potential and to allow quantum tunnelling to take place. When David Lussey first discovered QTC in his home laboratory, what he did not know at the time was that by hand-mixing, and not using a mechanical mixer, he avoided damaging these spikes and was able to produce a material with these unique properties.

REFERENCES AND FURTHER READING

SEP website

For additional resources, visit the 'Innovations in practical work' section on the SEP website (www.sep.org.uk/practical). You can download the following:

- PDF file of this booklet
- PDF files of classroom activities (monochrome and colour)
- Word documents of classroom activities (can be edited)
- PowerPoint slides with photographs and graphics
- Video clips.

Other websites

Some particularly relevant websites are listed below. More links can be found on the SEP website.

[Peratech](http://www.peratech.co.uk) (www.peratech.co.uk)

QTC is manufactured by Peratech, a company based in Darlington, and their website gives a lot of very useful information. This includes a section on the science of QTC. There are pages giving details of QTC Pills and QTC Sheet (also known as QTC Switch Substrate), and examples of QTC applications. There is a download page with a number of pdf files, including an *Integration guide* that contains more detailed technical information.

[Photonics, Materials and Sensors Group, University of Durham](http://www.dur.ac.uk/psm.group/) (www.dur.ac.uk/psm.group/)

This research group is collaborating with Peratech on investigating the complex physics of quantum tunnelling metal-polymer composites and on supporting the development of commercial applications.

[NASA Robonaut](http://robonaut.jsc.nasa.gov/) (<http://robonaut.jsc.nasa.gov/>)

A humanoid robot called Robonaut developed by NASA. The aim is that it will be able to carry out tasks in space, either working side-by-side with humans or going where the risks are too great for people. QTC is being used in the construction of a tactile glove that will give the robot touch sensitivity when grasping and manipulating objects.

Books

[Making sense of secondary science: research into children's ideas](#)

Driver R, Squires A, Rushworth P and Wood-Robinson V (1994) Publisher: Routledge (ISBN 0 415 09765 7)

A very useful overview on the research into students' understanding, with a chapter on difficulties with key concepts in electricity.

[Teaching secondary scientific enquiry](#)

Sang D and Wood-Robinson V (eds) (1994) Publisher: John Murray (ISBN 0 7195 8618 6)

A variety of approaches to teaching different aspects of scientific enquiry, including concepts of accuracy and reliability.

SOURCES

The electron microscope images on pages 15, 53 and 58 are reproduced with permission from Professor D Bloor, Department of Physics, Durham University. The photograph of the electric drill on page 4 was supplied by Peratech Ltd. The robot images (front cover and page 11) were obtained from NASA, and the photograph of the oil rig on page 7 was taken by Bruno Girin (DHD Multimedia Gallery).

HEALTH AND SAFETY

QTC contains a high proportion of nickel embedded in a polymer material. Since the polymer coats the particles of nickel, the risk of allergic reactions is very much less than the risk from pure nickel. Many widely-used items, such as coins and jewellery contain nickel. The vast majority of users experience no problems at all. QTC has passed BS EN 1811:1999, the reference test method for release of nickel from products intended to come into direct and prolonged contact with the skin. The limit of nickel release for such products is $0.5 \mu\text{g}/\text{cm}^2/\text{week}$, and the value for QTC is less than $0.1 \mu\text{g}/\text{cm}^2/\text{week}$. By contrast, cupro-nickel coins (e.g. 5p and 10p), which like QTC are not intended for prolonged contact with the skin, have larger values - typically over $20 \mu\text{g}/\text{cm}^2/\text{week}$. It is very unlikely that students will experience any allergic reactions on handling QTC for the short periods of time in these activities, but they should be warned of the possibility and be asked to report to the teacher any irritation to the skin. The small squares of QTC are manufactured under the name 'QTC Pills'; teachers should ensure that this term does not cause any misunderstandings. QTC must not be swallowed.

By law, MSDSs (Materials Safety Data Sheets) now accompany most chemicals supplied to your school. QTC is available from Middlesex University Teaching Resources who provide an MSDS for the QTC. You can also obtain an electronic copy from the SEP website. MSDSs should be kept on file, for reference if required. Generally, the information given about QTC in the SEP materials will be entirely sufficient to ensure that it is used safely.

QTC is designed to be used in low-voltage, low-current circuits. For practical work in schools, voltages must not exceed 28 V ac or 40 V dc. The SEP activities with QTC use much lower voltages, which are quite adequate to demonstrate its properties. Current through the QTC material should be kept below 10 amps (pill) and $100 \mu\text{A cm}^{-2}$. Under no circumstances whatsoever should QTC be used in mains voltage electrical circuits.

The plastic bags, in which QTC is supplied to students, should be labelled appropriately to help initial and subsequent identification:

QTC (Quantum Tunnelling Composite) pills/sheet
Science Enhancement Programme / Middlesex University Teaching Resources
Full details available at www.sep.org.uk and www.mutr.co.uk

Since QTC contains a high proportion of nickel, it is probably classed as hazardous waste and should be disposed of appropriately. Wherever possible, after use, QTC should be recycled and reused. Should the occasional piece of QTC be accidentally lost or accidentally disposed of in the ordinary waste, this should not cause concern.

OBTAINING THE PRACTICAL RESOURCES

All of the QTC materials and equipment described in this booklet can be obtained from Middlesex University Teaching Resources, which supplies a wide range of low-cost resources for school science and technology. Check their website (www.mutr.co.uk) for the latest prices of the products shown below.



QTC 001 QTC pills

Small squares of QTC (3.5 mm x 3.5 mm) that can be torn off from a strip - intended for switching of moderately large currents.



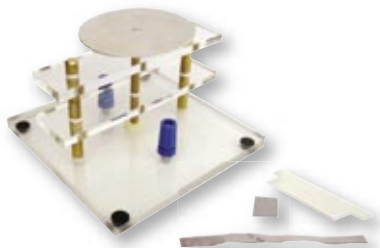
QTC 002 QTC sheet

Thin layer of QTC on an aluminium coated plastic film (50 mm x 305 mm) - can be used as a switch with low currents.



QTC 003 QTC cable

Co-axial cable (15 mm) with a layer of QTC between the inner core and the outer braid - acts as a continuous switch along its length.



QTC 011 QTC testing kit

This kit has been designed to test the behaviour of QTC under load. It allows the QTC to be held firmly with secure electrical connections; force is applied by adding weights to a loading pan. It includes a QTC sheet holder.



QTC 012 QTC sheet holders

The QTC sheet holder acts as a switching device, with the sheet across two aluminium contacts. It has been designed to fit the QTC testing kit. The pack contains sufficient materials to make 10 sheet holders.

Orders can be made by post, telephone, fax or email by providing an official school order number. Alternatively, payment can be made by credit card. See the back cover of this booklet for contact details. Further information can be obtained from www.mutr.co.uk, or by requesting their latest catalogue.

Notes

Notes

You can download the written materials in this booklet, and find further information from: Science Enhancement Programme (SEP) www.sep.org.uk

The Science Enhancement Programme (SEP) is part of Gatsby Technical Education Projects. It undertakes a range of activities concerned with the development of curriculum resources and with teacher education.



Gatsby Science Enhancement Programme
Institute of Education, University of London
Room 202, 11 Woburn Square
LONDON WC1H 0AL
Email: sep@ioe.ac.uk
Web: www.sep.org.uk



You can order QTC in a variety of forms, QTC testing kits and other resources from Middlesex University Teaching Resources

**Middlesex
University**



**teaching
resources**

Teaching Resources
Middlesex University
Unit 10, The IO Centre
Lea Road, Waltham Cross
Hertfordshire EN9 1AS
Tel: 01992 716052
Fax: 01992 719474
Email: sales@muventures.co.uk
Web: www.mutr.co.uk

www.sep.org.uk