Activity 7. Conduct and resist: The Dance

Learning intentions

Students will have a deeper understanding about the nature of resistance at the quantum level and its implications for how we produce and use energy.

Materials

- Lots of students
- Three funky hats that you can stick pipe cleaners in
- Lots of long pipe cleaners
- Funky music, should you choose

Teacher notes

There are two main objectives with this exercise: to help students visualize how resistance works at the quantum level, and to challenge potential student understanding of resistance, which is typically based on the classic model of the atom and the intuitive concept of the electron as a particle.

Conductors V insulators

Conductors allow electrons to flow more easily than insulators. The more electrons per unit of time that move through a space, the greater the current and therefore the amount of electrical energy that can be generated*. For the electrons to move in the first instance, they need a force or form of energy such as the chemical energy from a battery.

But even the best conductors in today's circuits have some resistance. This resistance you can feel as heat. In this activity, student atoms that gain more energy and jiggle and dance more vigorously will hopefully notice they are giving off more heat. This is essentially what is happening in a circuit where kinetic energy is being transformed into heat.

In a good insulator the electrons are too tightly bound to their atoms and do not flow. Without electron flow there is no current and therefore no generation of electrical energy.

Phonons and resistance

Electron waves interact with the atomic lattice waves (phonons) and transfer some of their energy and momentum into the lattice waves. Phonons are similar to a sound wave given off when the atomic lattice jiggles, which all atomic lattices and

Teaching notes: running the activity

Method

This dance, come in three Acts. The first two Acts demonstrate resistance in materials. In Act 3, students simulate the flow of electrons in a material where there is zero resistance.

Students will play either the role of the atoms in the atomic lattice of the conductor or an electron.

The pipe cleaners will be inserted into the hats and represent the energy of the electron. The more pipe cleaners in the hat the more energy you have given the electron. The student electron will wear the relevant hat for each Act.

In the hat for Act 1. Insert about 5 pipe cleaners.
For Act 2, insert about 15-20 pipe cleaners in the hat.
For Act 3. Insert just one pipe cleaner in the hat, which will represent the minimum amount of energy required to do the work required, eg make an LED light up.

Get students to arrange themselves in 3 lines of 5-8 students per line (although the longer the line the better, if you have the students to spare). Each student in the grid represents an atom in the atomic lattice. Students playing the atoms should place themselves at least one arm's length from each of the other atoms. See Figure 1 below. IMPORTANT: student atoms are fixed in place. They cannot move their feet. First, this more correctly simulates the actual behaviour of an atom in such a lattice. Second, it prevents student atoms being tempted to chase the student electron and steal all the energy (pipe cleaners).

atoms do unless they are cooled to absolute zero, which is theoretically impossible. This extra energy gained by the atomic lattice makes the lattice jiggle a bit more and this greater kinetic energy = loss of energy as heat. The electrons have lost energy in the process.

In room temperature metals/conductors, nearly all the resistance is from phonons. See Figure 2 below.

*It is important to note to students that electrical energy is not the flow of electrons (current). The kinetic energy of electrons moving through a circuit is what enables the generation of the electrical energy used to do the work. To understand more about the concept of energy and work see the section, Energy and work in the FLEET Schools resource on Energy

Limitations
In our scenario, the electrons (students) stop moving when they run out of pipe cleaners (energy). In reality they would still be being pushed and pulled through the circuit but at such a slow rate (because of resistance) there is insufficient electrical energy to do the work.

The further along the circuit from the battery the more resistance there will be. This can be observed with the LEDs in Activity 10 Graphite circuits.

Answers to student questions to explore
In Act 1 and 2. Students should observe that the electron loses energy and the atoms gain that energy. The student atoms that gain electron energy should observe that they start giving off more heat (if they are dancing harder). Ask students what they feel when they use their mobile or laptop for a while? What are the devices giving off? Hopefully they eventually say, heat. This heat is lost energy. It is energy unavailable to do work.

In Act 2. To ensure we had sufficient current and therefore electrical energy to do the necessary work, we had to use a higher voltage battery.

Each atom will use one of their arms to represent a phonon. This phonon wave is waving (in time to the music, if you have a beat going).

Select one or two students to be electrons. Remember electrons are waves (or have a wave function).

Student electrons will be performing a one-person Mexican wave and move randomly through the atomic matrix, but through the length of the circuit. That is, we have connected a battery to the circuit with certain force and this applies the necessary force that enables the electron to flow through the circuit.

Student electrons (doing the Mexican wave) will interact with atoms (doing the one-arm phonon wave).

Student atoms use their wavy phonon arms to steal one (just one) pipe cleaner, if the electron passes within reach

In Act 1. Place a funky hat with the approx. 5 pipe cleaners on the student electron.

Pretend to connect the battery which is the signal for the electron to “flow” through the circuit.

As the student electron loses pipe cleaners (energy) they slow down and get less wavy. The student atoms that steal a pipe cleaner gain energy and should start wriggling and getting extra wavy (in the funkiest way they know how).

Observe how far the student electron got through the lattice.

Questions for students
Ask students what happened. What was happening to the electrons? What are the implications for the amount of current and the amount of work that can be done?

What was happening to the atoms that gained energy from the electrons. (Ask them what they were feeling as they started dancing with more vigour?)

Discuss this scenario with students. How sustainable is it to use a larger battery? The same scenario applies to our centralized energy sources that supply the grid. If a device requires 10 joules of energy to do the required work, we will need to burn an amount of coal that contains a lot more energy (say 15 joules) to ensure there is enough energy for the device to work. That is because 5 joules is lost as heat (resistance) as the current flows through the grid and circuits to our device. In Act 3, where our conductor is a topological insulator there is no resistance and therefore no heat and no energy loss. The battery in this scenario would be a tiny fraction of the voltage used in Act 1 and 2 because without resistance, it only takes a small amount of force to generate the required current. Or, we would only need to burn the amount of coal containing 10 joules. Note: topological insulators are still part of on-going research and development. They are not ready for commercial application – yet. You can read more about the problem of the unsustainable energy consumption of digital technologies here and FLEET's research on topological insulators here.	Assuming the electrons lacked enough energy to flow through the circuit at a rate necessary to do the work, what do we need to change to ensure there is enough energy to do the work required, eg make the light work. In Act 2. Place on the student electron's head the hat with up to 20 pipe cleaners. Repeat what you did for Act 1. In Act 2. The extra energy in the electrons comes from a bigger battery (one with more volts). Select a student to act as the extra force supplied by the bigger battery. That student will gently push the student electron through the atomic lattice. The student battery should push the student electron hard enough so the electron is propelled faster than they went in Act 1. How far did the electron travel through the circuit this time compared to Act 1? How much extra energy did the atomic lattice gain? (A lot more) What are the implications of this? (More heat generated – possibly the conductor catches fire.) Questions for students Ask students whether the outcomes of Act 2 are desirable. What might be a better way to ensure there is sufficient current (energy) to do the necessary work. Act 3. Place the on the head of the student electron, the hat with just one pipe cleaner. In Act three we change our conductor to a novel 2D material called a topological insulator. In such materials, electrons will flow around the edge of the material without resistance – no energy loss. See links below for more information about topological insulators. Simulate the closing of the circuit (ie connect the battery). This time the electron should pass down the outside of the atomic

	lattice and there is no interaction between the atoms and electron. The electron continues to move through the length of the circuit without losing its energy. That is, there is no resistance. Questions for discussion What are the implications of this for the function of circuits and energy consumption? In our scenario, where the force used to enable electrons to flow comes from a battery, what would it means for the type of battery we now need – assuming we require the same amount of energy as in Act 1 and 2.?

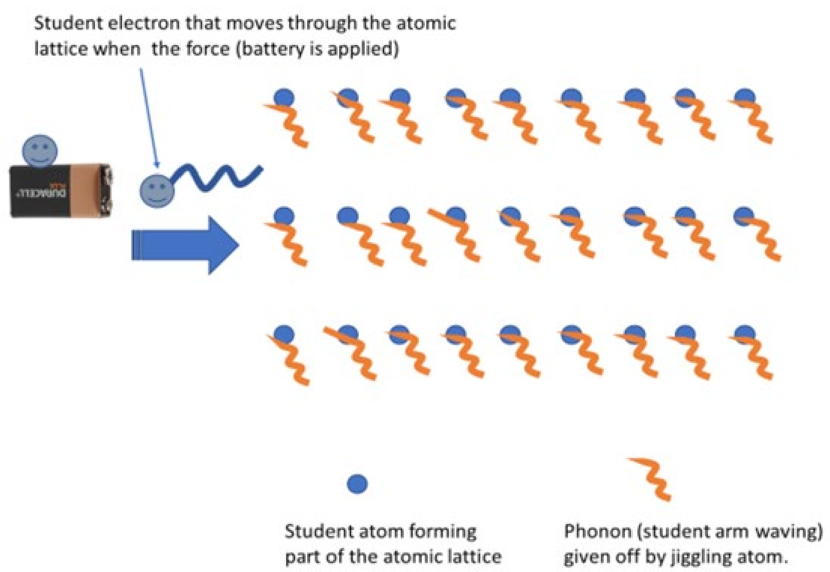

Figure 1 Role playing scenario to represent how resistance works at the quantum level. Students played the role of electrons (with specific amounts of energy) and atoms/phonons.

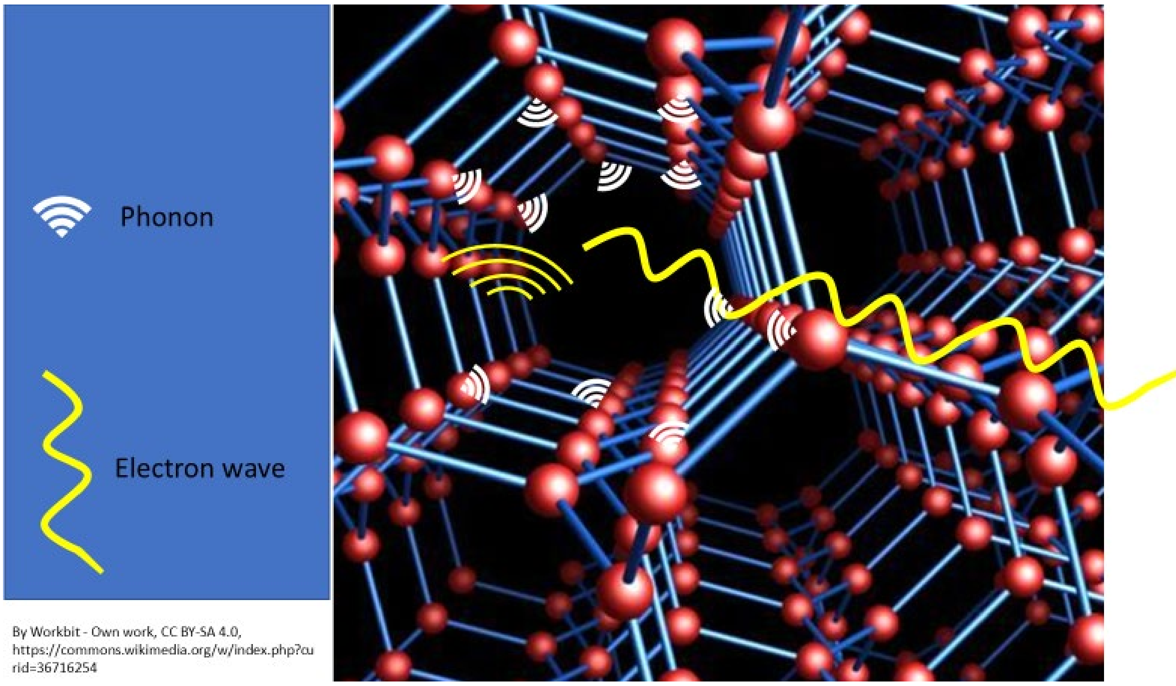

Figure 2. Electrons have a wave-like behaviour. They don’t actually physically hit the atoms as they flow through a circuit. The electron wave interacts with the phonon (which is a form of sound wave) that is given off by a vibrating atom. Energy is passed from the electron to the atom via these waves