FLEET ARC CENTRE OF EXCELLENCE IN FUTURE LOW-ENERGY ELECTRONICS TECHNOLOGIES

Evaluation report: Ashburton Primary School – Quantum electricity workshop

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Objectives

- To have participants understand the basics of electricity, conductors, insulators and the structure of the atom, specifically the quantum model of the atom
- For students to be aware of and have some basic understanding of the wave-particle duality concept and how this works with atoms and electricity
- To think critically about how we (society) use digital technologies and the implications for energy consumption
- An understanding of the features and functions of circuits and how resistance works at the quantum level and affects the efficiency of digital technologies

Overview

FLEET visited Ashburton Primary school to deliver a second pilot workshop on quantum physics for primary students. The workshop was conducted with the school's year 5 and 6 students (N=140).

The workshop was developed to get students to learn about and conceptualize how electricity and resistance works at the quantum scale, starting with the atom. Students used role playing activities and built graphite circuits to do this.

Pre-and post-evaluation activities were developed to evaluate the objectives of the workshop.

Key findings

- Students successfully conceptualized the quantum model of the atom and understood that electrons have a wave-like behaviour, and that their position is based on probability.
- Students learned that the flow of electrons is necessary to generate electrical current
- Student began to conceptualize the nature of resistance at the quantum level and link this to FLEET's research to develop low energy electronics

- Students became aware of and, to some extent, began to think critically about the unsustainable nature of our digital technology's energy consumption

Method

The workshop was divided into the following broad sections that are expanded on below:

- Pre-evaluation
- Introduction to FLEET
- Understanding the atom and its role in generating electricity
- Constructing circuits
- Understanding resistance
- Post-evaluation/reflection/worksheet

We assessed the impact through pre- and post-evaluation activities and a student worksheet. The Method section also includes description of role-playing activities and the outcomes of those activities. Such outcomes are not included in the Results section, which focuses mostly on the outcomes of the pre- and post-evaluation activities.

Pre-evaluation

The pre-evaluation involved two activities. The first was a student brainstorm on the question, What comes to mind when you think of electricity? The second was drawing an atom. These activities helped determine students' baseline understanding of what an atom looked like and their conceptualization of electricity.

The brainstorm session occurred with a FLEET member writing down on a whiteboard the student responses about electricity. These responses were compared to responses to the same question in the post-evaluation sessions.

For the atom drawing, students were provided with paper and pencils and asked to draw what they thought an atom looked like. This activity was repeated as part of the post-evaluation. The pre- and post-drawings were compared to understand the student learning.

Introduction to FLEET

Students were given and overview of FLEET's research and introduced to the FLEET volunteers. The narrative was framed around the FLEET research problem of the unsustainable rise in energy consumption of digital technologies. The workshop activities and student discussions were linked to this narrative wherever relevant.

Understanding the atom and its role in generating electricity

A FLEET member used a slide show and student role playing to help students understand the structure of the atom and its role in generating electricity. Crucially for this workshop, students examined the classical models of the atom such as the Bohr model and compared this to the quantum model. A key component of this activity was for students to learn that the Bohr model of the atom is essentially flawed and to begin to conceptualize the quantum nature of the atom, specifically the electron cloud model, and that electrons have a wave function (or have wave-like behaviour).

Certainty versus probability

Students were shown an image of a Bohr model with electrons depicted as particles in orbits around a nucleus. Based on their pre-atom drawings, it is this model that students were most familiar with. Students could confidently point out the position of an electron in this model.

To help students understand the quantum model of the atom, specifically the wave-like behavior of the electron and that its position (and momentum, energy) is based on probability, students were shown an image of the cloud model and then asked to do some role playing where they pretended to be protons, neutrons and electrons.

Students playing the protons and neutrons formed a tight nucleus. Between 6-8 students played the role of one electron. The student electrons joined hands surrounding the nucleus and then performed the Mexican wave to simulate the wave-like behaviour. It was emphasized that the student electrons represented just one electron. Other students were then asked to determine the position of the electron. Students struggled to definitively state where the electron is. This exercise is followed by an explanation of probability (which most year 5-6 students have a basic understanding of). See student responses in the results section that suggest by the end of the workshop students have begun to conceptualize the concept of probability and uncertainty relative to the quantum nature of the atom.

An analogy provided by one of the Ashburton Primary School teachers was to get students to think about where their principal was at this time based on what they know about his behaviour. What was the likelihood they would be in their office versus the staff room versus the roof? This appeared to resonate with and make sense to the students to help them further conceptualize the quantum nature of the electron's position, momentum and energy.

The aim of role-play and discussion is the get students to rethink or challenge how they conceptualize the structure of an atom.

To help reinforce the role of electrons and protons, we did a small demonstration. We used a balloon that we rubbed on a student volunteer's hair and then observed what happened when we put the charged balloon near tissue paper, a bit of aluminum foil and a styrofoam cup. The balloon attracted the paper and foil, but repelled the cup. Based on their understanding that like charges repel and opposite charges attract, we asked students what was happening. We then broke a piece of the styrofoam cup off and tested the charged balloon against that. The piece of foam is attracted to the balloon, but as noted it repels the foam cup. We got the students to come up with hypotheses to explain what was happening and a way they could test their hypothesis.

Constructing circuits

Students were introduced to a circuit and what is necessary to make one work. We also describe here the role of the electron in generating current (described simply as electricity for students). It is emphasized that it is the flow of electrons that enables the generation of electrical current, but we also emphasized that this is not the electrical energy used to do work such as make a light turn on. We did not go into the detail of how the kinetic energy in the electrons and potential difference established when a closed circuit is formed generates electrical energy. We simply said that the flow of electrons is necessary to generate the electrical energy.

We explained to students how to construct their graphite circuit and asked them to consider the following questions:

1. What happens to your LED as it moves further away from the battery?
2. Why do you think this is happening? (Discuss resistance and electrons losing energy as they move through the circuit)

The construction of the graphite circuit is based on the FLEET Schools Graphite Circuits activity.

To establish a competitive spirit, we also ask students to see who could make the longest circuit and still have their LED work.

Understanding resistance

During the construction of the graphite circuits we discussed with students their observation that their LED got dimmer the further it got from the battery. In this instance, the depth of discussion varied between students, but the key point we tried to get across was that the electrons lose energy as they move through the circuit.

Following the circuit construction activity FLEET volunteers showed images to help describe the nature of resistance and how electrons transferred some of their energy to phonons, which we describe as sound waves that the atoms in lattice produce as they jiggle. But when the phonons absorb the energy from the electrons they jiggle even more and give off heat.

This is simulated using students that play the role of atoms in the lattice and students that play the role of electrons. The student electrons were given a hat with a small number of pipe cleaners stuck in it. The pipe cleaners represent the energy of the electrons.

The student electrons were asked to pass through the lattice. As the electron passed by an atom the student atom (waving one arm to simulate a phonon) would take a pipe cleaner and start to jiggle more (having absorbed a bit of electron energy). The electron continues to pass through the lattice until it runs out of pipe cleaners (energy).

Student were asked what would we need to change about our circuit to ensure the electrons could continue to move. In this workshop there was some discussion and prompting before the students came up with using a bigger battery to give the electron more energy. Another hat was placed on the student electron's head with a lot more pipe cleaners than the first hat. This time the electron made it a lot further through the atomic matrix. There was also a lot more heat generated.

FLEET facilitated a discussion about the sustainability of this solution – ie using bigger batteries. We posed the question, what would be the implications if we could invent a conducting material that enabled electrons to move through the lattice without resistance?

To simulate this, a student is given a hat with just one pipe cleaner and then asked to walk around the outside of the lattice and not interact with the phonons. This is linked to FLEET's research on topological insulators. A short discussion with some prompting got students to understand that the energy required to move this one-pipe cleaner electron is tiny or would only need a very small battery to provide the necessary force to generate current (electricity). See the post-evaluation comments that suggest students understand that resistance is heat and wasted energy.

Post-evaluation/reflection

The post-evaluation and reflection involved a repeat of the brainstorm and draw an atom activities.

Brainstorm

In the post-brainstorm activity, we ask students again, what comes to mind when they think of electricity? This was followed up with the two prompts, what can you tell me about resistance and what can you tell me about the research of the FLEET volunteers? While this affects a direct comparison with the pre-evaluation activity, the two prompts are not leading questions and are considered sufficiently open to illicit responses to provide insight into student comprehension about electricity and whether students have begun to think critically about the societal implications of how we use digital technologies. These additional prompts are also part of students' reflection to help reinforce their learning.

Draw an atom

In this workshop, both classes completed the activity, although because of time constraints, the Grade 5 class completed the task the following day and posted them on a share drive that FLEET could access.

Worksheet

We developed a work sheet for students to complete in class. See Appendix 1. The worksheet posed questions to assess what students understood about what they observed in their functional (or non-functional) graphite circuits. There was insufficient time for students to complete the worksheet in the workshop. As noted, however, the grade 5 students completed it the following day (along with their post-atom drawing). The grade 6 students did not complete the worksheet. This is the first time the worksheet was to be tested in a workshop environment and we became belatedly aware that question three in the worksheet would require some elaboration to ensure students interpreted the question correctly. Because of time constraints we did not get an opportunity to explain specifically what we wanted students to consider with this question, and because we were unable to supervise the students completing the worksheet, it was unclear how well they would interpret or understand all the questions.

Results

The results analyzed in this report are the pre- and post-evaluation responses to the two activities, draw an atom and the brainstorm. The brainstorm activity sought responses to the question, what comes to mind when you think of electricity? We also considered responses to the worksheet questions from the Grade 5 students, but as noted above, the worksheet had not been tested nor could we supervise students while they completed it. Despite these limitations, there is some value to the worksheet data and it is used to support the results from the pre- and post-evaluation activities.

Brainstorm: What comes to mind when you think of electricity?

The pre-evaluation simply asked students what comes into their minds when they think of electricity. For some responses, students were asked to elaborate on what they meant. In the post-evaluation activity, the same question was repeated, but then followed up with the two prompts, what can you tell me about resistance and what can you tell me about the research of the FLEET volunteers?

The pre- and post-responses from the grade 5 and 6 students were grouped under specific themes. While there were differences between the grade 5 and 6 students in the specific pre- and post-responses, the same themes emerged from these responses. See Tables 1 and 2.

The pre-responses for both grades generated the following themes:

- What electricity is
- Technology that uses electricity
- Generation of electrical energy

In contrast, the post-responses for both grades generated the following themes:

- Digital impact
- Making sciency connections: What is involved in generation of electricity
- Thinking quantum
- Generation of electrical energy

The responses for both grades also shift from mostly single word responses to more in-depth explanations or conceptualizations of electricity and energy. See Tables 1 and 2.

Table 1. Grade 5 pre- and post-evaluation. What comes to mind when you think of electricity?

Pre-evaluation responses	Post-evaluation responses
Theme: What electricity is (students trying to conceptualize what electricity is) [3 responses] Lightning; lightning bolts; sun	**Theme: Digital impact [7 responses]** FLEET trying to stop heat; making technology to stop climate change; making technology that will use less energy; making materials with no resistance; don't waste energy; resistance is wasted energy; heat energy from phones makes heat
Theme: Technology that uses electricity [6 responses] Light; powerpoints; phones; street lights; chargers to charge your phone; technology – needs electricity to work	**Theme: Making sciency connections: What is involved in generation of electricity? [7 responses]** Electrons; protons; neutrons; electrons and protons attract; positive-positive repel, negative-negative repel, positive-negative attract; positive and negative are opposite ?energy? (trouble articulating ie opposite what?); atoms; neutrons and protons are in

	the middle – nucleus; Electrons still have energy (when there is no resistance)
Theme: Generation of electrical energy [5 responses] Sun – generates electricity through solar panels; power stations – connect to powerlines, generate electricity from metal; solar panels; wind turbines	**Theme: Thinking quantum [3 responses]** Electrons move in waves; electron wave is like movement (of electrons); electron waves
Theme: Making sciency connections: What is involved in generation of electricity [2 responses] Atoms; electrons	**Theme: Generation of electrical energy [1 response]** batteries

Table 2. Grade 6 pre- and post-evaluation. What comes to mind when you think of electricity?

Pre-evaluation responses	Post-evaluation responses
Theme: What electricity is (students trying to conceptualize what electricity is) [9 responses] Static electricity; lightning; electrical current travelling along wires; electricity in our brains; different metals that conduct electricity; cabling; circuits; energy; power; magnets North and South	**Theme: Making sciency connections: What is involved in generation of electricity? [4 responses]** Conductors and insulators; energy; circuits – how big can they get; positive/negative charges; Heat = resistance; resistance takes energy and volts away; resistance creates heat
Theme: Generation of electrical energy [1 response] Solar panels	**Theme: Thinking quantum [6 responses]** Electron waves; protons, neutrons, electrons; phonons; sound waves; quantum – at the size of an atom; quantum – doesn't apply to the real world (that they see)
Theme: Technology that uses electricity [1 response] Light	**Theme: Digital impact [3 responses]** FLEET making materials that save energy; FLEET making material with less friction/heat; Better conductors = less wasted energy

Draw and atom. Pre and post drawing

For grades 5 and 6 there is a distinct shift in their interpretation of the atom. In the pre-atom drawing, students' conceptualization is largely of the classic Bohr model where electrons are distinct particles in an orbit around the nucleus. In the post-atom drawing this conceptualization shifts to the quantum model where the position of the electrons around the nucleus resembles a cloud and their precise position is uncertain – or is based on a probability. Note, that there is likely a proportion of students that were drawing electron cloud models based on their memory of images they were shown in the workshop. That is, there is the potential for an element of rote learning rather than a level of understanding of the electron cloud model or electrons as waves. Note also that students worked in groups of two or three and in some groups everyone in a group drew an image, sometimes not. This is the reason for the pre- and post- numbers being different.

Tables 3-6 outline the types of atom models each grade drew in their pre- and post-evaluation draw-an-atom activity. See Figure 1-6 and Figures 1-12 that show the student drawings in the pre- and post-atom drawing activity.

Grade 5 Pre-atom drawing

In the Grade 5 pre-evaluation activity, most students (N=37) drew a representation of the Bohr atom model that was unlabeled and often with abstract components that we had to make an assumption about regarding their identity or purpose. A small number of students (N=6) drew more accurate and labelled models of the Bohr atom. Student also drew atoms as tiny dots on the paper to represent the small size of the atom. Other representations included a virus and a non-descript blob or bunch of scribble. See Table 3 and Figures 1-6.

The post-evaluation activity saw students shift their mental image/conceptualization from what was largely the Bohr model to the quantum model with many including descriptions of the electrons as waves (N=53). See Table 4 and Figures 7-8.

Table 3. Grade 5 Pre-atom drawing. Themes that describe the type of models students drew in the pre-evaluation activity

Theme: Bohr model. Abstract, unlabelled (N= 37) Resembles the classic image of the Bohr model but has abstract components that are left to the imagination. No labelling of protons, neutrons or electrons.
Theme: Bohr model. Definitive and labelled correctly (N= 6) Has a distinct nucleus and electrons in orbit around the nucleus. There is correct labelling of one or more of the protons, neutrons and electrons.
Theme: Bohr model. Mixed Bohr (N= 3) Students drew a model that showed students were trying to replicate the Bohr model, but labelled the protons, neutrons and electrons incorrectly
Theme: The tiny dot (N=13) Students knew atoms were tiny and depicted them as such – as a tiny dot made with the tip of the pencil. Some students drew lots of these and noted that there are lots of them in everything
Theme: The virus (N=4) Students drew the atom with a central core and spikes coming out from the central core in a way that resembled images of a virus
Theme: The blob (N= 3) Such images were a non-descript blob or scribble

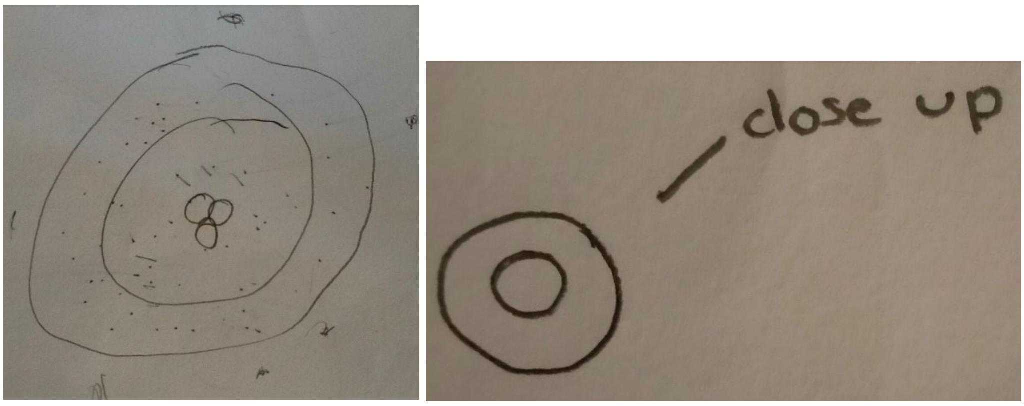


Figure 1. Grade 5 pre-atom drawings – Bohr model: abstract, unlabeled

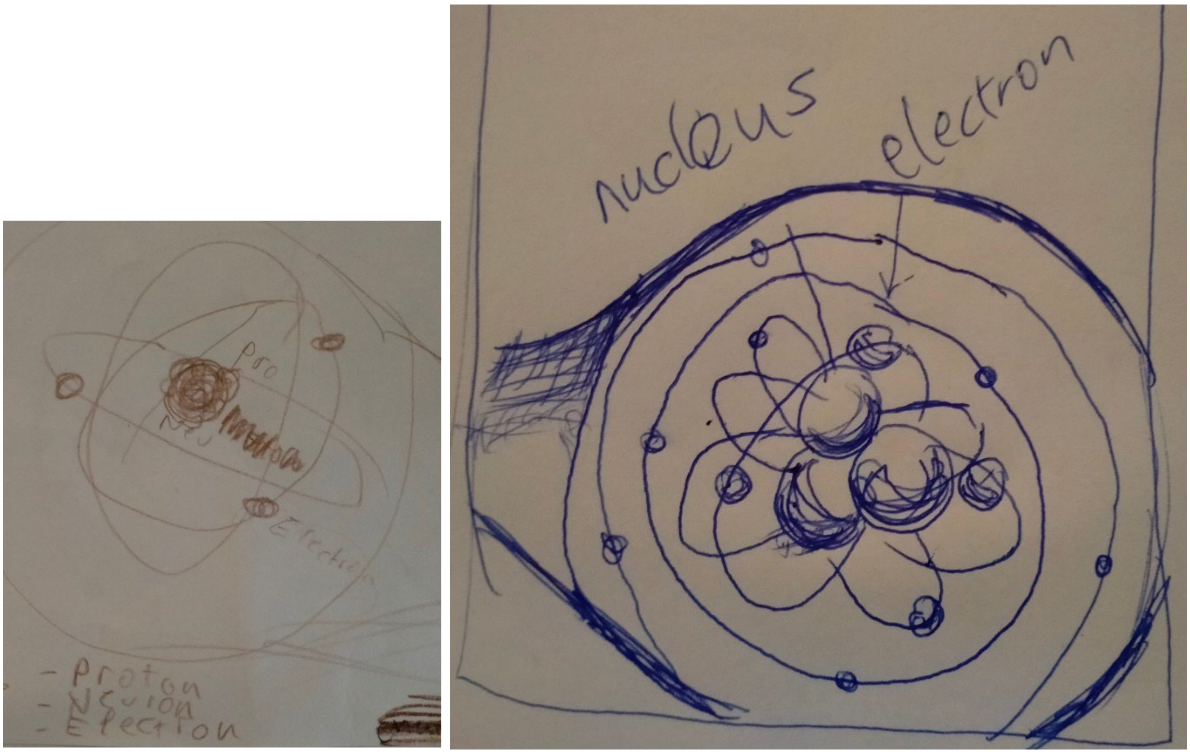


Figure 2. Grade 5 student pre-atom drawings from the category Bohr model definitive, labelled correctly.

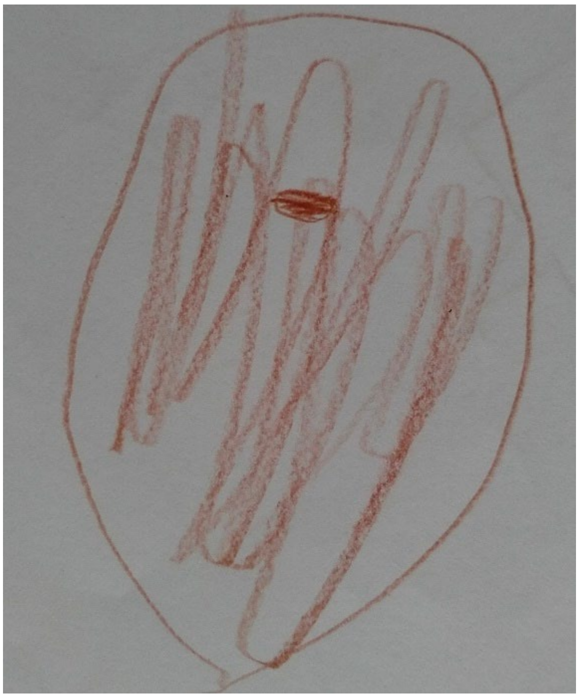


Figure 3. Grade 5 students pre-atom drawing – the blob

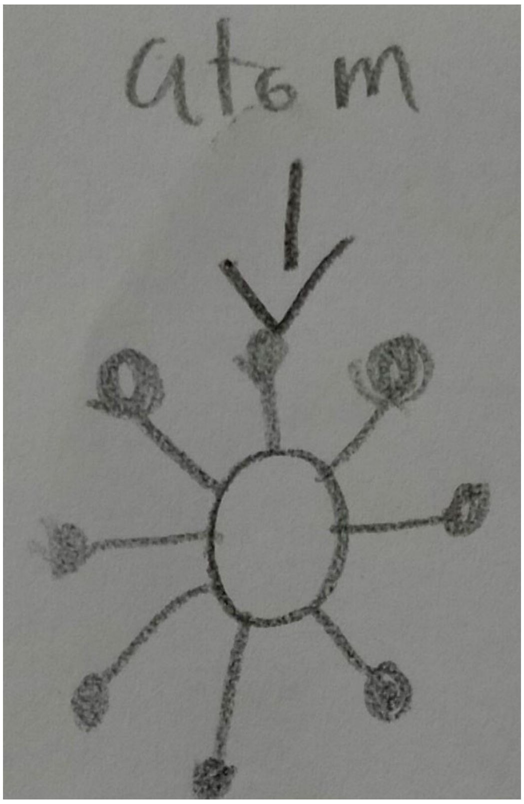


Figure 4. Grade 5 student pre-atom drawing: The virus

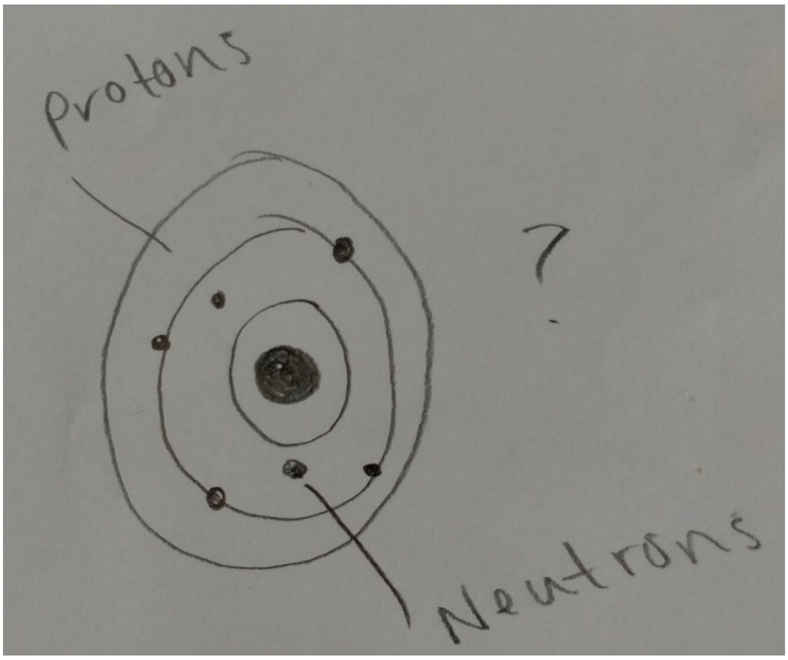


Figure 5. Grade 5 Pre-atom drawing. Bohr model: mixed

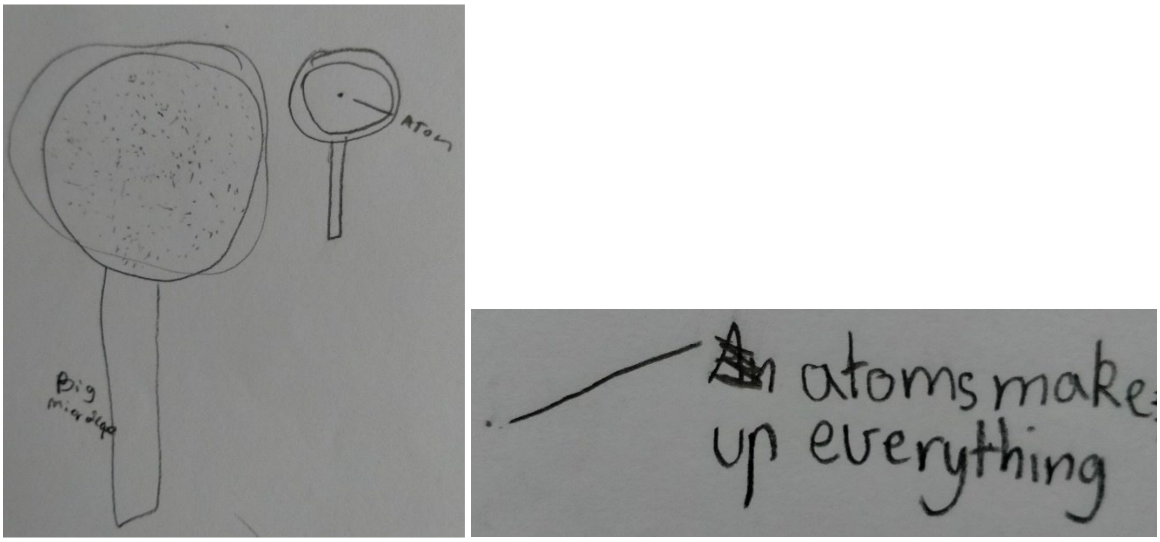


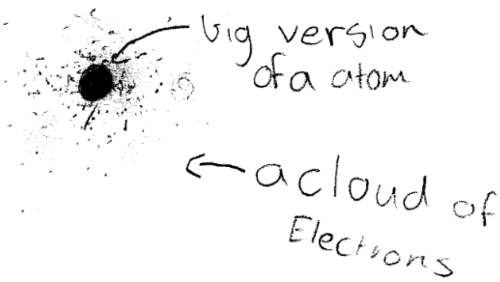
Figure 6. Grade 5 pre-atom drawing The tiny dot

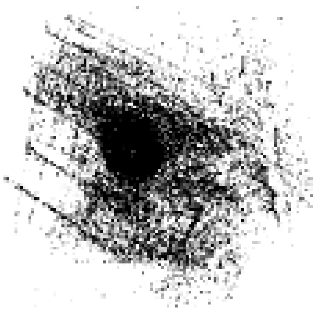
Grade 5 Post-atom drawing

Most students drew some form of an electron cloud model. See Table 4.

Table 4. Grade 5 Post-atom drawing. Themes that describe the type of models students drew in the post-evaluation activity

Theme: The Electron cloud (N= 53) Drawings were a definitive image of an atom with a distinct nucleus (often labelling protons and neutrons) and an electron cloud, also often labelled as such. Some students' labels even made a reference to the electrons' positions being a probability. There was some interpretation required for unlabeled drawings, but given they were starkly different to what had been drawn in the pre-evaluation drawing, it was considered the students were drawing electron clouds. See Figure ? At least 19 of these electron cloud images also contained or had descriptions of the electrons as waves. See Figure ?
Theme: Hybrid – Bohr with electron clouds/waves (N= 7) A handful of students drew a distinct Bohr model of the atom, but either labelled the electrons in the orbitals as an electron cloud or as waves, or drew what appears to be a hybrid of the electrons as a cloud and as distinct particles in orbit around the nucleus. That is, students appeared to understand that the electrons' position around the nucleus resembled a cloud or fog rather than a distinct particle in a designated orbit around the nucleus but struggled to articulate that visually. See Figure ?
Theme: Bohr model definitive and labelled (N= 2) A definitive Bohr model with clear and correct labelling of the protons, neutrons and electrons.
Theme: Bohr Definitive – no labels (N= 3) An image that is distinctly a Bohr model, but without labels
Theme: Unclassified (N= 6) It was unclear whether these drawing were supposed to represent an atom or were random and abstract drawing of something else.





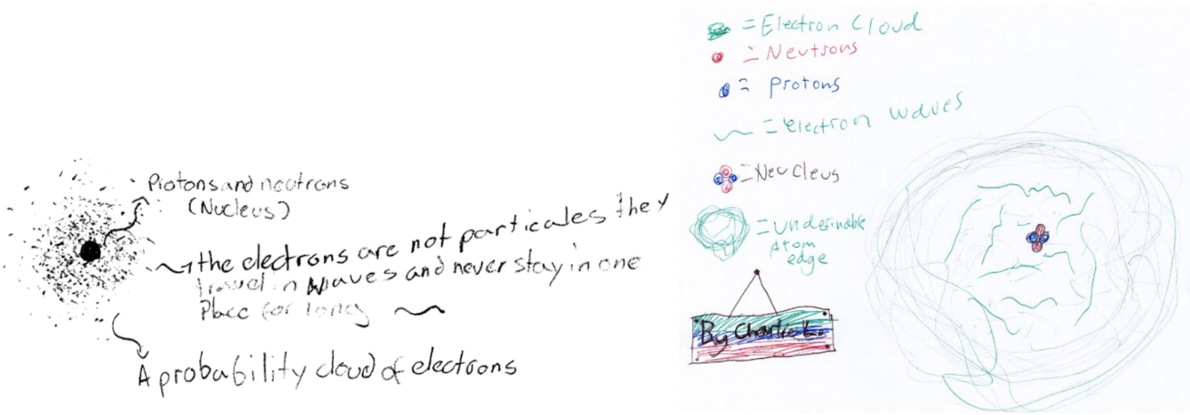


Figure7. Grade 5 post-atom drawings. Electron cloud model with descriptions of electrons as waves

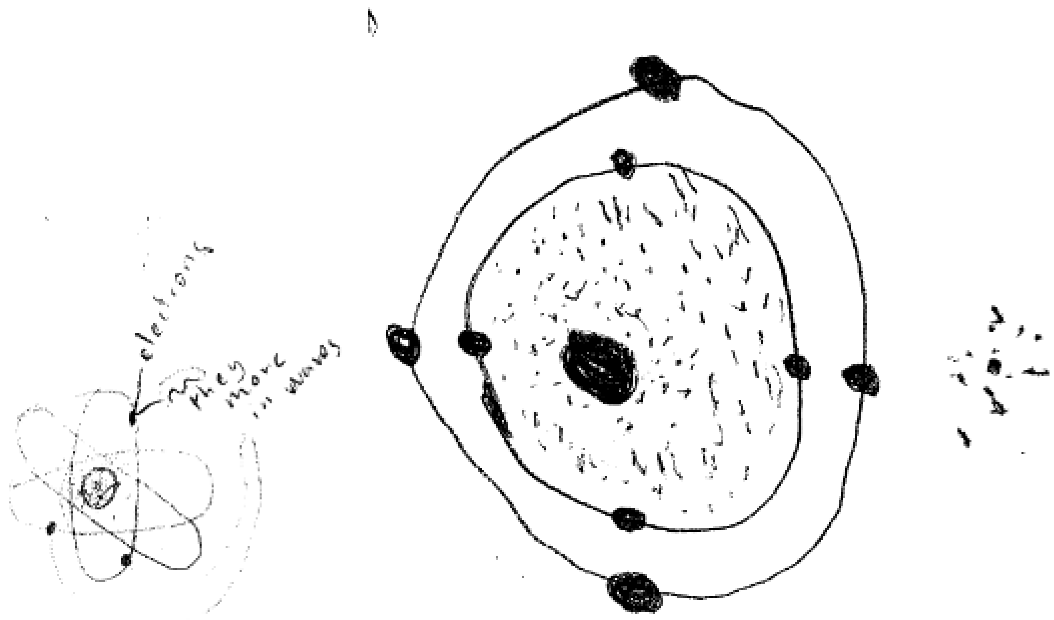


Figure 8. Grade 5 post-atom drawings. Hybrid – Bohr with electron clouds/waves.

Grade 6 pre-atom drawings

The pre-atom drawings of grade 6 students was similar to the grade 5 students in that the majority represented the Bohr atomic model (Mixed Bohr, N=18 and Bohr model definitive and labelled, N=9). Grade 6 students also drew the virus model atoms. A small number of grade 6 students (N=5), however, included drawings of atoms that more closely resembled a molecular model. See Table 5 and Figures 9-10.

The grade 6 post-atom drawings fall under the same themes as the grade 5 student drawings and show a similar shift toward the electron cloud and waves model. The proportion of drawing in this category is also similar. See Table 6 and Figures 11-12.

Table 5. Grade 6 Pre-atom drawing. Themes that describe the type of models students drew in the pre-evaluation activity

Theme: Mixed Bohr (N= 18) Students drew a model that showed students were trying to replicate the Bohr model – though with varying degrees of success - but either left the image unlabeled or labelled the protons, neutrons and electrons incorrectly
Theme: Bohr model. Definitive and labelled correctly (N= 9) Has a distinct nucleus and electrons in orbit around the nucleus. One had protons, Neutrons and electrons are correctly labelled. Four had labelled the nucleus and electrons correctly.
Theme: The virus (N= 7) Students drew the atom with a central core and spikes coming out from the central core in a way that resembled images of a virus
Theme: Ball and stick model (N= 5) Similar to the above in the sense that there is some semblance of a molecule, but in this instance the images clearly depict the ball and stick molecular models. Where labelling occurs, the ball components are labelled as either protons, neutrons or electrons.
Theme: Molecular Atom (N= 3) Students draw what appears to be a hybridized atom and molecule. Some have what looks like molecular bonds joining protons, neutrons and electrons. Others integrate different atoms (eg H and O) together with protons and neutrons, etc.
Theme: Just abstract (N= 2) There is some resemblance to an atom, but without the context of this exercise as a reference point, the drawing could just be interpreted as a pretty pattern.

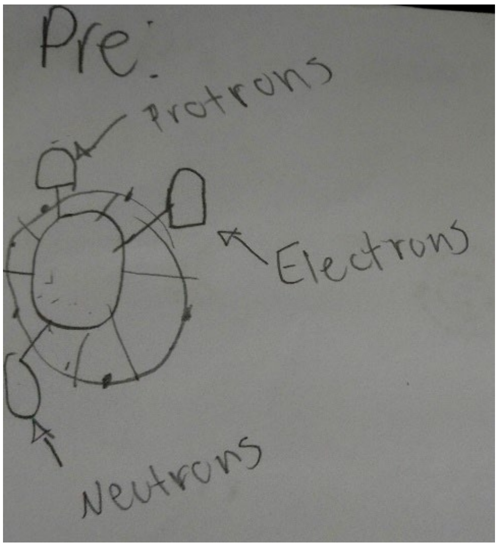


Figure 9. Grade 6 pre-atom drawing. Bohr mixed

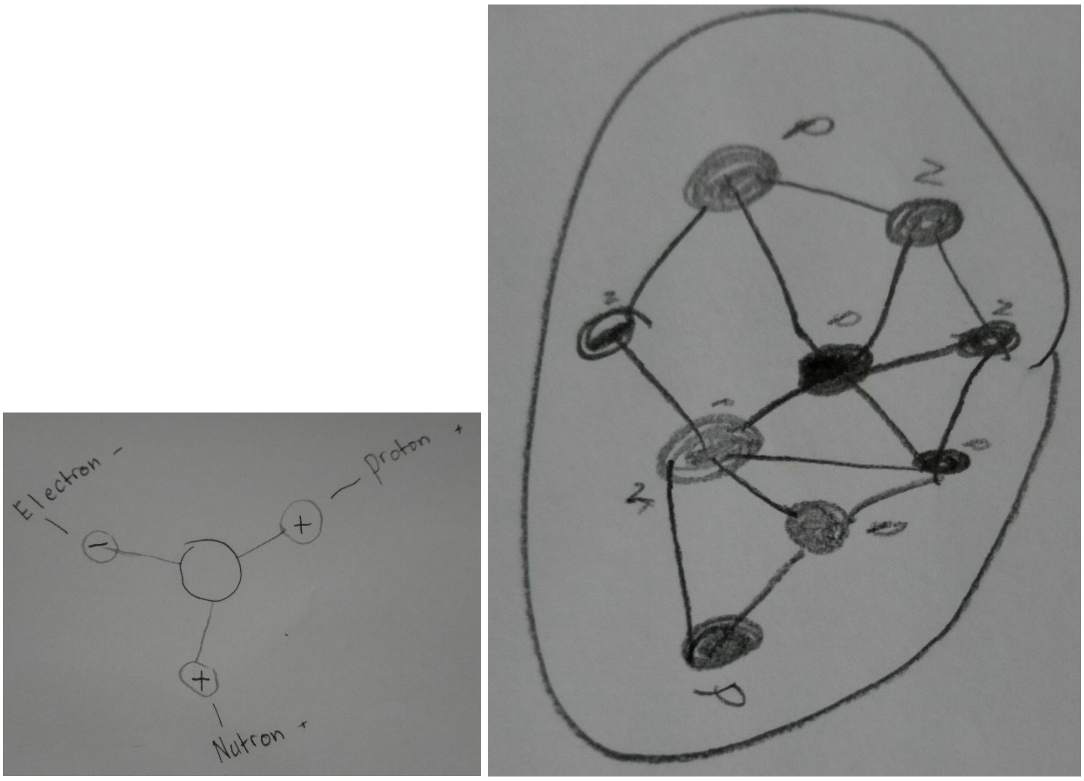


Figure 10. Grade 6 pre-atom drawing. Ball and stick

Table 6. Grade 6 Post-atom drawing. Themes that describe the type of models students drew in the post-evaluation activity

Theme: The Electron cloud and waves (N= 24) Students drew a definitive image of an atom with a distinct nucleus (often labelling protons and neutrons) and a description and/or visual representation of the electrons as waves. Some students' labels even made a reference to the position of electrons as being a probability. As with the Grade 5 post-atom images, there was a degree of interpretation required for unlabeled drawings, but given they were starkly different to what had been drawn in the pre-evaluation drawing, it was considered the students were drawing electron as waves and/or clouds. For the grade 6 cohort however, only 3 drawings depicted the electrons as a cloud only. The majority drew or described the electrons as waves or both waves and clouds. See Figure
Theme: Hybrid – Bohr with electron clouds (N= 2) A handful of students drew a distinct Bohr model of the atom, but either labelled the electrons in the orbitals as an electron cloud or drew what appears to be a hybrid of the electrons as a cloud and as distinct particles in orbit around the nucleus
Theme: Bohr model definitive and labelled (N= 3) A definitive Bohr model with clear and correct labelling of the protons, neutrons and electrons.
Theme: Bohr Definitive – no labels (N= 9) An image that is distinctly a Bohr model, but without labels

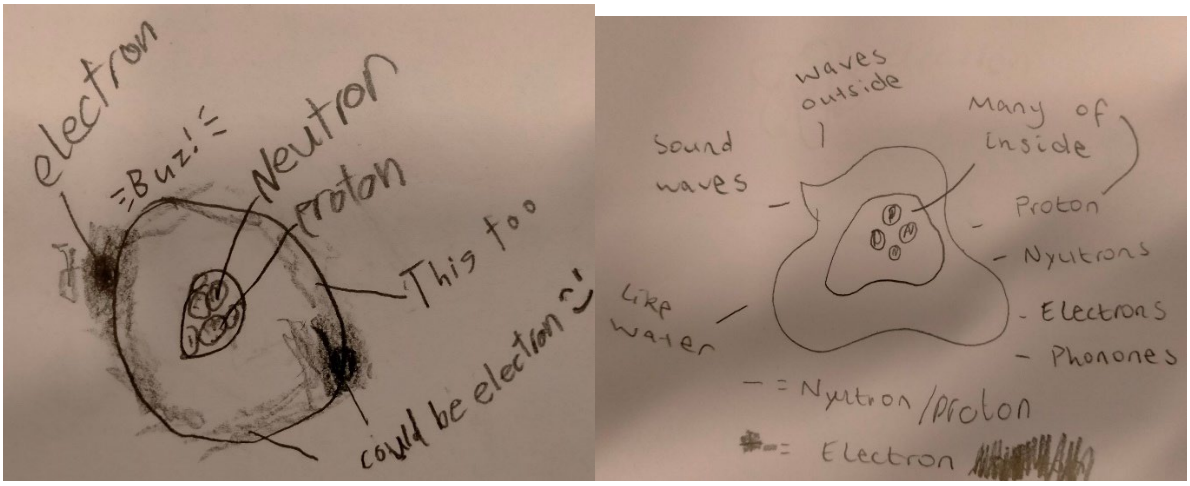


Figure11. Grade 5 and 6 post-atom drawing. Electron cloud

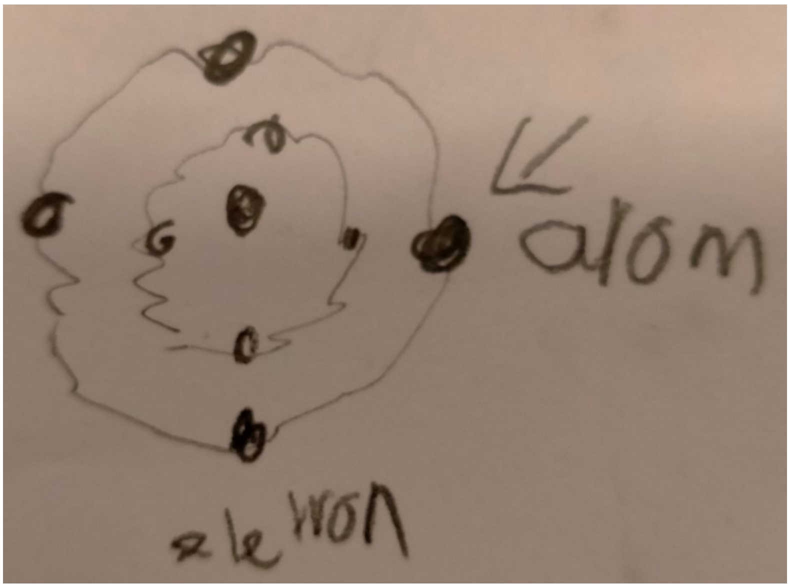


Figure 12. Grade 5 and 6 post-atom drawing. Hybrid Bohr with electron clouds

Worksheet answers

We developed a worksheet that was intended to be completed by students at the end of the workshop and with assistance from teachers and FLEET volunteers. The worksheet contained questions to help assess student understanding of the graphite circuit activity. Time constraints meant that this did not occur.

The grade 5 students did, however, complete the worksheet the following day by themselves and uploaded it to a share drive for us to access. As suspected, some of the responses suggest there was some confusion. The worksheet contained three questions. For questions 2 and 3, a handful of themes emerged and these are outlined below in Table 7. See Appendix 2 for all the student responses.

Table 7. Worksheet questions and answers completed by grade 5 students to help assess understanding of graphite circuits

Q1. What happens to your LED as it moves further away from the battery? (N=21)	All students noted that the LED got dimmer the further it was from the battery
Q2. Why do you think this is happening?	**Theme: The problem is energy loss (N=10):** The majority of students understood that the dimming LED had something to do with energy being lost or dispersed as the LED got further from the battery. They realized that the more energy that was lost, the dimmer the LED. One student even correctly articulated that the energy from the electron is being lost to the atoms in the atomic lattice and this energy is then lost as heat as the atoms "bounce around" more. Another student recalled that FLEET is developing ways to avoid the "things that steal the energy", referring to the development of topological insulators that enable electrons to flow without resistance. **Theme: All about the battery (N=3)** Of the three students that considered that the battery was fundamental to the LED getting dimmer the further it got from the battery, only one correctly surmised that the battery lacked sufficient force to enable sufficient current to make the LED work when it got further away from the battery. The other two students appeared to suggest that the dimming LED was caused by the battery getting weaker or losing power the further the LED was away it **Theme: It is something about the conductor (N=2)** Students understood that their conductor affected the brightness of their LED, specifically that if there was a break in the conductor the LED

	would not work, or that if they made the graphite thicker the LED would work better. **Theme: The electron effect (N=1)** The single response under this theme was, “The further away, the less electrons”. Despite being a misconception, the student at least surmised that electrons were playing a role.
Q3. At the point your LED stops working, what could you do or change in your circuit to make it start working again (other than move it closer to the battery)? Note: N=15 but each response may have contained more than one sentence/idea with each sentence/idea falling under a different theme.	**Theme: Change/improve the conductor (N=14)** The majority of students worked out that making the graphite thicker or without gaps would improve the conductivity and make their LED work. **Theme: Bigger battery – increase the force (N=7)** Seven of the 15 students thought that a stronger or more powerful battery would make their LED work again. **Change the LED (N=1)** The one student response was, “Better LED”. It is unclear what this one student meant by “better”? For instance, better suited to this circuit, or more efficient, etc.

Discussion/outcomes

The workshop had two core outcomes: students will shift their understanding of the atom from the classic to the quantum model and develop basic conceptualization of how electricity and resistance works at the quantum level; that students will start to think critically about the increasing energy consumption of digital technologies and the implications of this.

Understanding quantum

The results strongly suggest that students can conceptualize the quantum nature of the atom. Students started to think about and attempt to articulate how electrons act like waves and that their position is based on probability rather than existing as a particle in a precise and measurable point in space. Students understood that resistance involved a transfer of energy from the electrons. Some students could articulate this in greater depth, stating that the electrons transferred their energy to the atoms in the conductor and that this energy was lost as heat. This loss of energy affected the amount of electrical energy available to do the work required, such as making their LED work ("Heat = resistance; resistance takes energy and volts away").

In other words, primary students are capable of learning quantum physics, albeit at a qualitative level.

Critical thinking about digital technology

There was a lack of in-depth responses to get a good understanding about the depth and breadth of student critical thinking about our use of digital technology and the energy it consumes. Only 7 of the 18 grade 5 responses and 3 of the 13 grade 6 responses related to this workshop objective. These responses, however, provide some indication that students are at least now aware that there is a problem with how much energy digital technology uses (don't waste energy; resistance is wasted energy), the implications of this (making technology to stop climate change) and they are considering the research to help solve the problem (making technology that will use less energy; FLEET trying to stop heat; making materials with no resistance; FLEET is developing ways to avoid the "things that steal the energy"). The focus of the workshop activities was on the understanding the quantum physics rather than critical thinking, which may have limited the amount and depth of responses on this issue.

Limitations

There are always limitations to data, and in this instance the data relevant to student critical thinking lacks depth. Ideally a follow-up study would focus on this.

As noted already, in the atom drawing exercise there is likely a proportion of students that drew their electron cloud models based on their memory of images they were shown in the workshop. But given the post-brainstorm discussions and worksheet responses there was also a high proportion of students that had successfully begun to conceptualize, at the quantum level, the nature of the atom and its role in generating electricity.

Noted also is the questions used in the worksheet had not been tested beforehand and we had hoped to monitor the students doing the worksheet and engage with them about how they interpreted the questions and if they had trouble understanding any of them. This monitoring could not occur, which could affect the value of the data from the grade 5 responses.

FLEET reflection

The workshop worked well in its second iteration, but there is still room to refine some aspects of this workshop, specifically the need to find ways to condense it into the required time frame. Somme of this time could be made up with more effective monitoring of student activities and to end them in a shorter time frame. We often got distracted with in-depth conversations with one or two students during an activity when the majority of students had finished the activity and were playing. There is also the potential to improve the links between the atom, electricity – resistance and sustainable energy consumption. This may be something to consider for the reflection phase of the workshop.

Appendix 1

Student worksheet to be completed at the end of the workshop as part of the reflection activity.

Worksheet 1. Quantum electricity

1. What happens to your LED as it moves further away from the battery?

All students noted that the LED got dimmer the further it was from the battery

2. Why do you think this is happening?

Theme: All about the battery (N=3)
Student responses
Battery gets weaker
Lost power from battery
Battery not strong enough

Theme: The problem is energy loss (N=10)
Student responses
Energy is wasted the further it gets
Battery uses more energy to get to the LED, so by the time the energy gets to the LED there isn't as much energy left
When the electron moves through conductor the atoms take some of the power and when it gets to the LED there is less power. The energy the atoms collect make the atoms bounce around creating heat and losing power
When the electrons travel further they lose energy and can't travel as far
The energy takes more time to reach the point and it tires – the LED receives less energy
The further away it is, the more energy it needs to spread out
Because the electron has to travel further, which means it loses energy which means it has less energy to power the LED
The electron doesn't travel that far and it loses energy so the less it lights up the LED
The power is being stolen from the electrons – FLEET is figuring out a way for the electrons to move around the things that steal the energy, which will help us more by getting more power flowing through our devices
Further the battery it is the less energy it has to use

Theme: It is something about the conductor (N=2)
Student responses
The stronger and darker the lines the brighter the LED
The graphite from the pencil helps activate the battery in a way connecting to the LED to the battery – the graphite somehow makes it flow to the battery and that why if there were any parts on the line that weren't joined, it wouldn't work because it can't flow.

Theme: The electron effect (N=1)
Student response
The further away, the less electrons

3. At the point your LED stops working, what could you do or change in your circuit to make it start working again (other than move it closer to the battery)?

Theme: Change/improve the conductor (N=14)

Student responses

Making thicker lines
Making lines longer and stronger
Make track [circuit] thicker
Put more graphite on
Make the lines thicker
Better conductor
Colour in the line darker so the conductor has more energy to transport the energy
Make the 2B lines thicker
Make your lines wider – make sure there are no cuts in the line stopping it from being able to flow
Draw the lines thicker and harder
Make the lines thicker – then the electron has more energy
Make the lines thicker
Better graphite
Make sure there are no holes in the graphite line

Theme: Bigger battery – increase the force N=7

Student responses

Add a stronger battery
Bigger battery
Get a battery with more than 9V
Use a more powerful battery – powered by solar energy
Put more batteries on
Change the battery
Put another battery closer to the LED

Theme: Change the LED (N=1)

Student response

Better LED