Evaluation report: Shore Primary School – Quantum circuits workshop

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FLEET members:
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Objectives

Quantum circuits

- 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 Shore Primary school to present the quantum circuits workshop their year 5 and 6 students. Total student numbers: N=42.

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.
- Students learned that the flow of electrons is necessary to generate electrical energy.
- 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 energy consumption of our digital technology.

Method

Quantum circuits

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 graphite circuits/worksheet
- Understanding resistance
- Post-evaluation/reflection/ completion of 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 questions, What comes to mind when you think of electricity and what comes to mind when you think of quantum physics. 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 and quantum physics. These responses were compared to responses to the same question in the post-evaluation sessions. We did not repeat the question asking about quantum physics. This is deliberate to see whether students describe quantum-based concepts without prompting.

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 student learning.

Introduction to FLEET

Students were given an overview of FLEET's research. 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, while useful, has limitations. Students 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 electron's 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).

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 (it sometimes repels, sometimes attracts the cup). Based on their existing knowledge 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 energy that is used to do the work, in this case making a light work. We emphasized that it is not the flow of electrons that is electricity, or what turns on the light, but for the purpose of primary students, it is what is necessary to generate the electrical energy that we use to do work. 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?

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. It is based on Activity 7, from FLEET Schools resource, Electricity, conductors and insulators. 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. A FLEET member acted as the battery and applied a small amount of continual force to the student electron by gently pushing them in the back as they moved through the lattice. As the electron passed by a student 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. The FLEET member acting as the battery applied more force to the student electron's back making them move faster through the lattice. 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? We then discuss topological insulators and FLEET's research to try and develop them for use in digital technologies.

To simulate a topological insulator, 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. The FLEET member acting as the battery applied the gentlest of pressure on the student electron's back to simulate a tiny battery. 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 activity. Students also completed the last question in the worksheet about resistance.

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. In this instance, time constraints meant we only spent a small proportion of this activity on the question about FLEET research.

Draw an atom

Because of time constraints, the students completed the task some time after FLEET had left. They were scanned along with the worksheet (see below) and emailed to FLEET.

Worksheet

We developed a work sheet for students to complete in class. See Appendix ? The students were to complete question 3 (Why do you think the LED gets dimmer the further it moves away from the battery?) as part of the reflection activity. As noted above, time constraints meant student completed this question along with the post-draw an atom activity some time after FLEET had left the school.

Results

The results analyzed in this section of the report are the pre- and post-evaluation responses (brainstorm and draw-an-atom) and the worksheet.

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 students were grouped under specific themes. See Table 1.

The pre-workshop brainstorm responses for both year levels generated the following themes:

- What generates electricity
- Technology components used to generate/conduct electrical energy
- What is or has energy
- Sciency connections to how electricity works
- Electricity history
- Thinking quantum (Following question, what comes to mind when you think of quantum physics)
- Digital impact

The post-workshop brainstorm responses for both grades generated the following themes:

- Sciency connections to how electricity works
- Making sciency connections: What is involved in generation of electricity
- Digital impact
- Thinking quantum
- What is energy
- Random

While the pre- and post-workshop brainstorm themes were similar, the responses under each theme differed. The responses shift from mostly single word responses to more in-depth explanations or conceptualizations of electricity and energy. The post-workshop brainstorm responses for the theme, Thinking quantum shift from the big picture popular science topics (black holes, worm holes and string theory) to a more in-depth consideration of the quantum nature electricity and energy. Note, although Antman and Marvel were mentioned in the pre-workshop brainstorm about quantum physics, which is typical of primary students when asked about this topic, this group of year 5/6 associated a larger than typical range of quantum physics concepts than other schools that have completed this workshop.

The exception in their pre-workshop brainstorm activity to the single word responses is the student responses under the theme, Making sciency connections. Here they have two relatively detailed descriptions: one about electrons and the other the UV light spectrum. The latter is lacking some accuracy. See Table 1 below.

Table 1. Shore year 5/6 Quantum circuits. Pre- Post-workshop brainstorm. What comes to mind when you think of electricity?

Pre-workshop brainstorm	**Post-workshop brainstorm**
Theme: What generates electricity: Renewable energy; solar; hydro; wind	**Theme: Sciency connections to how electricity works**: Insulators and conductors; insulators stop electricity; graphite is a conductor; Currents positive and negative; if you put an insulator in a circuit, it stops the circuit; batteries create good circuits

Theme: Technology components used to generate/conduct electrical energy: Conductor; dynamo; transformer; AC/DC; generators – generate electricity; transmitter – transmits sound or energy; electronics; batteries; conductors; circuits; wires and stuff	**Theme: Thinking quantum**: Positive proton attraction – electrons are drawn toward protons; neutrons(2); protons(2); electrons(2); moving electrons=electricity; circuits have wasted energy from them; wasted energy is heat; electrons are waves; phonons; too many electrons flowing through a circuit=fire; resistance is left behind; resistance is wasted energy; wasted energy=heat; conductors encourage electrons to spread; resistance generates heat; resistance = wasted energy; graphene is a near-perfect conductor; resistance is when atoms attract the energy from the electrons; batteries generate heat when energy flows through the circuit; nucleus has positive energy; transfer of energy from electrons to protons
Theme: What is or has energy: Energy; power	**Theme: Digital impact:** FLEET – ways/solutions for the future eg stopping climate change; how materials can conduct electricity; wasted energy is unnecessary as we have ways to use less energy – we can do better; Trying to create devices that use less energy
Theme: Sciency connections to how electricity works: Electrons – they circle around the nucleus; electromagnetism; UV light spectrum is what travels through the electrical current; positive and negative	**Theme: What is energy**: Energy
Theme: What use electricity: Satellites – connect places, connect the world, wireless connections	**Theme: Random**: We did an experiment to see how far electrons can travel
Electricity history: Thomas Edison (2) invented the lightbulb; kites-Benjamin Franklin; Nicola Tesla – tesla coil (2)	
Theme: Thinking Quantum: Einstein; particles; periodic table; organisms and micro-organisms; quantum entanglement; atoms; Antman; really tiny; dark matter; black holes; string theory; quantum realm – Marvel; worm holes; quasars	

Theme: Digital impact: Emissions; energy uses fossil fuels=bad for environment	

Draw an atom. Pre- and post-drawing

There is a distinct shift in the students' interpretation of the atom. In the pre-workshop 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. 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 new understanding of the electron model. Students descriptions of the atoms and their answers to the worksheet questions suggest, however that most of the students had a genuine shift in understanding and conceptualization of the atom and electricity. 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 2 and 3 outline the types of atom models the students drew in their pre- and post-workshop draw-an-atom activity. See Figure 1-4 for the pre-workshop atom drawings and Figures 5-7 for post-workshop atom drawings.

In the pre-workshop draw-an-atom activity, most students (N=46) drew a representation of the Bohr atom model that was one of two types: a Bohr model with (usually) accurate labels, or the Bohr model without labelling of the protons, neutrons or electrons. A smaller proportion of students (N=10) drew an atom that closely resembled old models of the solar system with the electrons in different orbits around the nucleus. Five students drew atoms that resembled an early embryo. See Table 3 and Figure 1-4.

The post-evaluation activity saw students (N=37) shift their mental image/conceptualization of the atom to something close to quantum (electron cloud) model with many including descriptions of the electrons as waves. See Table 4 and Figures 5-7.

Pre-workshop drawing of an atom

Table 3. outlines the themes that represent students' different atomic conceptualizations at the beginning of the workshop. Examples of each conceptualizations can be seen in Figures 1-4.

Table 3. Shore years 5/6 Atom drawing themes that describe the type of atomic models students drew in the pre-workshop atom drawing activity

Theme: Bohr model. Abstract, unlabelled (N= 26) Resembles the classic image of the Bohr model but it may have abstract components that are left to the imagination. No labelling of protons, neutrons or electrons. See Figure 1.
Theme: Bohr model. Definitive and labelled (N= 20)

Has a distinct nucleus and electrons in orbit around the nucleus. There is correct or mostly correct labelling of one or more of either the protons, neutrons and electrons. See Figure 2.
Theme: Early embryo (N=5) Atom is depicted as circular forms clumped into a random arrangement that resembles an early embryo. There is no distinct nucleus or electrons. See Figure 3.
Theme: Solar system (N=10) Atoms resemble drawings of our solar system with the sun (nucleus) in the middle with the planets (electrons) in different orbits around it. Some are labelled, others are not. See Figure 4

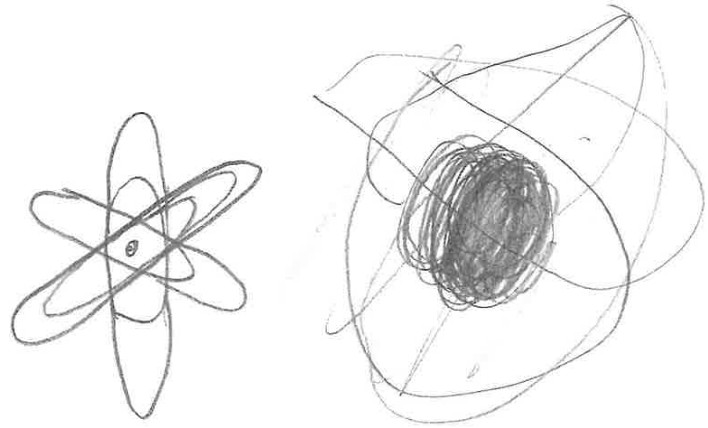


Figure 1. Shore years 5/6 pre-atom drawings – Bohr model: abstract, unlabeled

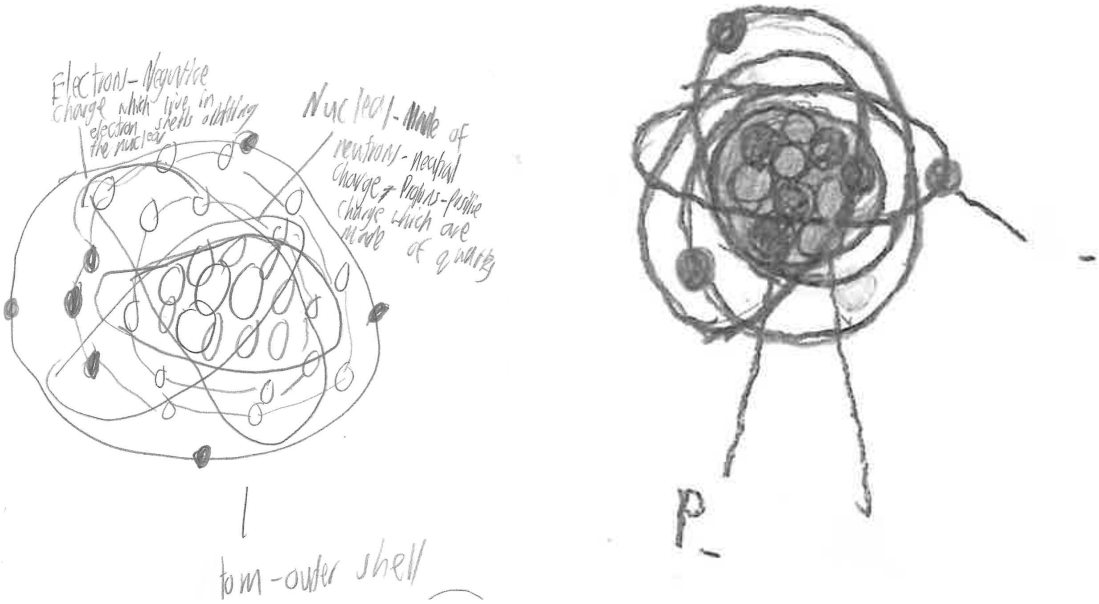


Figure 2. Shore year 5/6 student pre-atom drawings from the category Bohr model definitive, labelled (mostly) correctly. (Note labelling in right hand drawing is present and accurate in original drawing, but missing in scanned version)

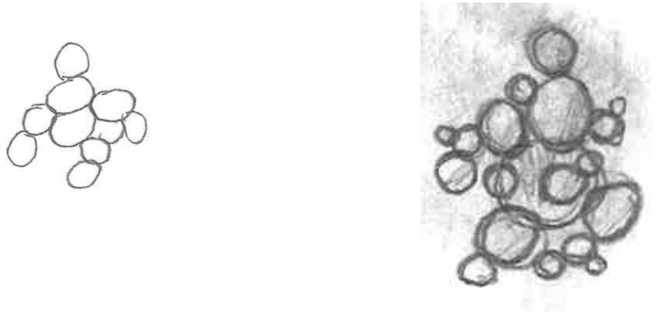


Figure 3. Shore year 5/6 pre-atom drawing. Molecular model

Figure 4. Shore year 5/6 student pre-atom drawing: The solar system

Post-workshop drawing of an atom

Table 4. outlines the different student conceptualizations of the atom at the end of the workshop. Examples of each conceptualizations can be seen in Figures 5-7.

Table 4. Shore years 5/6 Atom drawing themes that describe the type of atomic models students drew in the post-workshop atom drawing activity

Theme: The Electron cloud (N= 15) Drawings were a definitive image of an atom with a distinct nucleus (often labelling protons and neutrons) and an electron cloud with no distinct electron orbits. 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 5.
Theme: Electron cloud with electrons as waves (N= 22) As above, but students drew and/or described the electron as waves. In one instance the electrons were just drawn as a wave around the nucleus. See Figure 6.
Theme: Electron cloud – no nucleus (N=1) In this model the lone student drew a dense electron cloud, but it lacked a distinct nucleus. See Figure 7.

Theme: Bohr model – labelled (N=3)
Students drew the classic Bohr model and labelled the protons, neutrons and electrons.

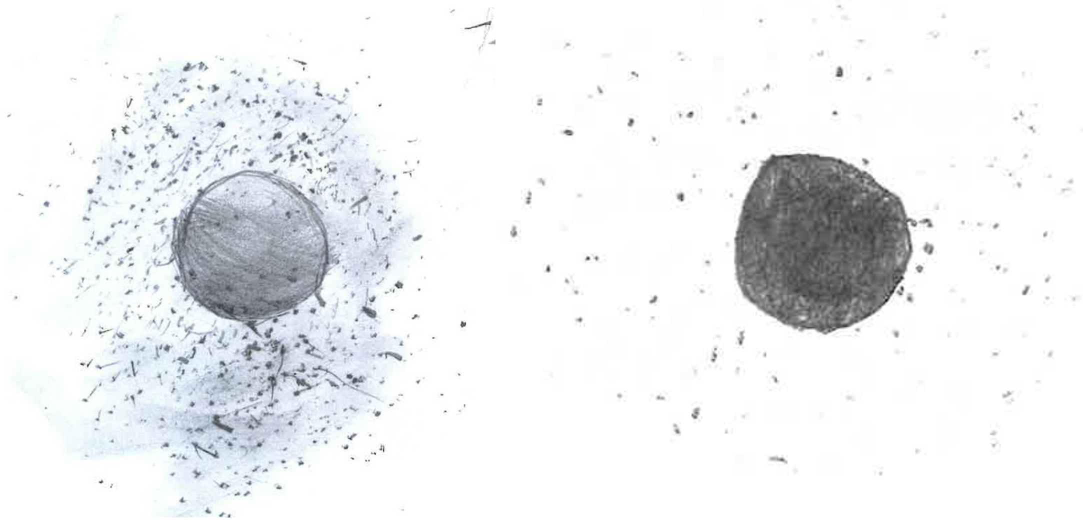


Figure5. Shore years 5/6 post-atom drawings. Electron cloud model

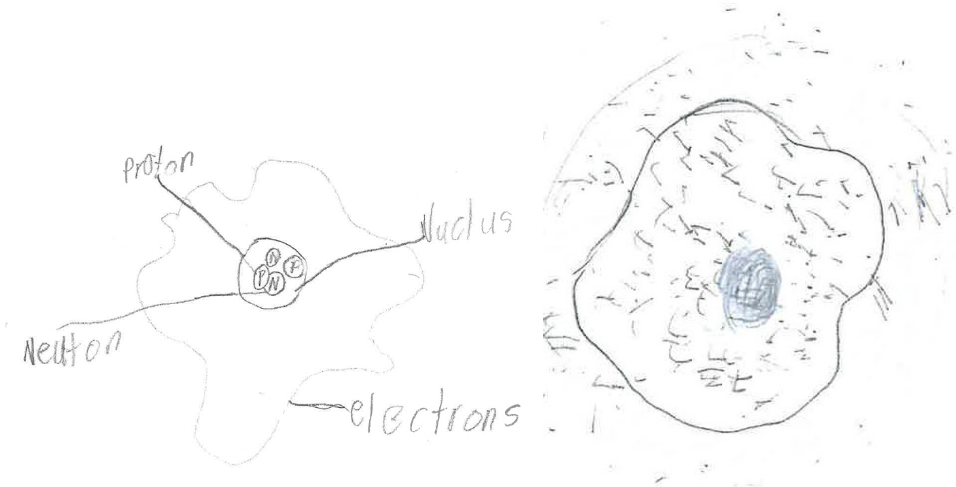


Figure 6. Shore years 5/6. Post-atom drawings of atoms as electron clouds including electrons as waves.

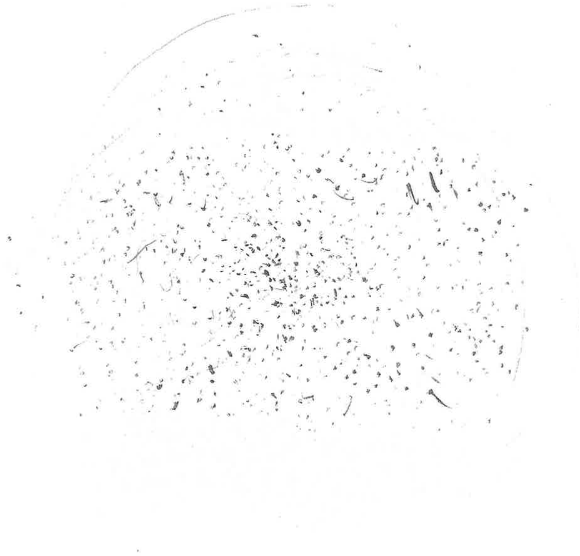


Figure 7. Shore years 5/6. Post-atom drawings of atoms as electron cloud – no nucleus

Worksheet analysis

The worksheet was intended to be completed by students during at the end of the workshop, and with assistance from teachers and FLEET volunteers. See Appendix 1 for worksheet used. The worksheet contained questions to help assess student understanding of the graphite circuit activity. Time constraints meant that not all students completed the worksheet including the post-workshop reflection activity. The Shore teacher had students complete the worksheet in the days following FLEET's visit and them emailed scanned copies of the student worksheets to FLEET. Complete student responses to the worksheet and associated images are in Appendix 2.

Student responses to the graphite worksheet are in Table 5. Not all students answered every question, hence the different response numbers for each question. Responses to Questions 2 and 3 were thematically analyzed and the number of responses to each theme is presented in Table 5. Responses to question 3 includes some relevant images that students drew to help explain their written response.

Table 5. Shore years 5/6 responses to graphite circuit worksheet

Worksheet questions	Student responses
1. What happens to your LED as it moves further away from the battery?	Total responses = 22 Most students (N=20) recorded that the LED got dimmer the further it was from the battery. The other two responses are below ➢ The light goes dim because the atoms lose energy ➢ After the LED repels from the negative it continues to attract to the positive due to the electrons and the negative not attracting
2. At the point your LED stops working, what could you do or	The total number of student responses are not recorded here because some responses contained more than one theme. **Theme (N= number of responses)** ➢ Making graphite thicker or adding more graphite (N=12)

change in your circuit to make it start working again (other than move it closer to the battery)? Note: the components of your circuit are the battery, the conductor (graphite) and the LED. What changes to these components could you make to get you LED working again?	➢ Using a larger battery or increasing the voltage (N=3) ➢ Replacing graphite with a better conductor (N=4) ➢ Use a better or more energy efficient light (N= 1) ➢ Other (N=3)
3. Now think about question 1 again. Why do you think the LED gets dimmer the further it moves away from the battery?	Total responses = 31 Most students (71%) could correctly describe that the reason the LED got dimmer was because there was energy lost in the system. Most of these students understood that the energy was lost from the electrons. There was a mix of misconceptions (N=9). One or two examples for each theme/sub-theme is provided here. The complete list of student responses and images can be found in Appendix 2. **Theme: Electrons lose energy as they flow through the circuit. [N=22]** Most students could describe the reasons for their LED getting dimmer was because the electrons were losing energy as they moved through the circuit. As noted below in the sub-themes and associated images, some students also noted that the energy was lost as heat, transferred through to the atomic lattice, or with 1 student noting that this energy transfer occurred via phonons. See Appendix 2. for complete student responses. **Sub-theme: Electrons lose their energy. [N=6]** *The LED dims because the negatively charged particles (electrons) lose electricity to the atoms of the conductor* [image below showing electrons as a wave] 

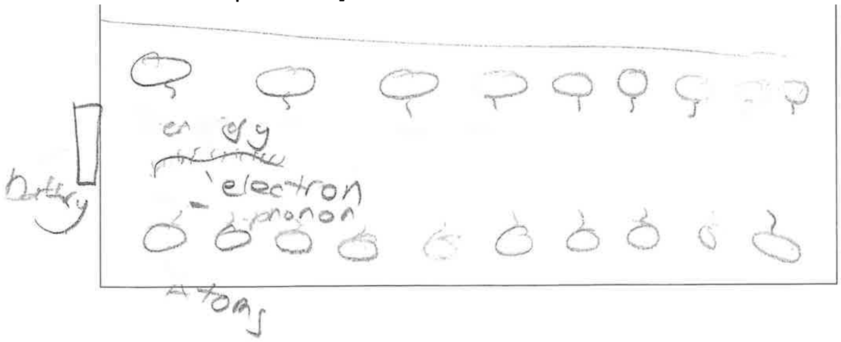
Sub-theme: Electron lose their energy as heat [N=2]

The LED gets dimmer because the electrons lose energy through heat and eventually come to a stop

Electrons transfer their energy to atomic lattice. Describes the role of phonons N=10]

Some of the energy of the electrons is being passed onto the phonons in atoms as it goes along. So when it gets to the end it won't have as much energy for the LED therefore making it dimmer

[image below showing the electron as a wave transferring its energy to the atoms via their phonons]

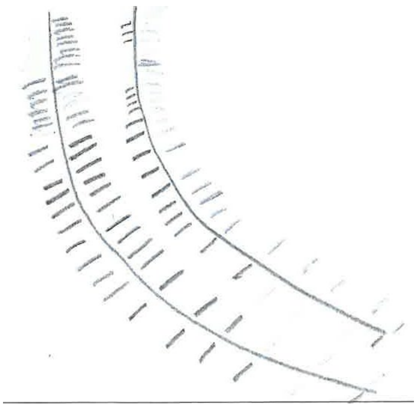


Sub-theme: Energy is lost – unclear what energy [N=4]

The responses are conceptually correct and some students note that the energy is lost through resistance, but the source of the energy lost is unclear, although an image associated with one of the responses suggests that this student understands it is the electron's energy that is lost See response and image below.

There is more resistance (energy being lost) which means less power to the LED – and the LED dims

The energy is slowly being lost the further it travels [see image below]



	Misconceptions **Theme**: **Circuit gets weaker [N=2]** *Because when the light starts to dim, it means that the circuit is becoming weaker* **Theme: Travelling currents [N=1]** *The LED gets dimmer because the battery's current is trying to travel further* **Theme: Losing voltage [N=3]** Students perceived that voltage is reduced the further you get from the battery *The light dims because the voltage isn't strong enough to reach the end of the circuit* **Theme: Losing electrons [N=3]** Students seemed to think that electrons somehow get lost as they travel through a circuit, though it is unclear if this is literally how they interpret what is happening. *Because the electrons got lost on the journey*

Other images and commentary from worksheets

The following are notes that students made in the blank pages of their worksheets that are relevant and contribute to our understanding of the impact of the workshop. The written comments and images describe and depict how circuits and transistors works, that electrons are waves and that they lose energy as they flow through a circuit. They describe how lightning works and the components of atoms.

Written comments

Electron is a wave not a particle

Copper, metals, etc are good conductors

Recalling how a transistor works

1=on / 0=off

One layer of graphite is graphene and it is a perfect conductor

One layer of graphite (graphene = no resistance. Graphene (perfect conductor)

Protons (positive) Electrons (negative). You can generate electricity by moving electrons with a force.

Atom = number of protons inside, eg 26 protons: Fe or sodium

Lightning: build up of electrons in the cloud. Electrons head towards earth (positive Lightning = flow of charge

2 protons and 2 neutrons=neutral atom

Next 10 years we will not be able to meet people's electronic demands

Images

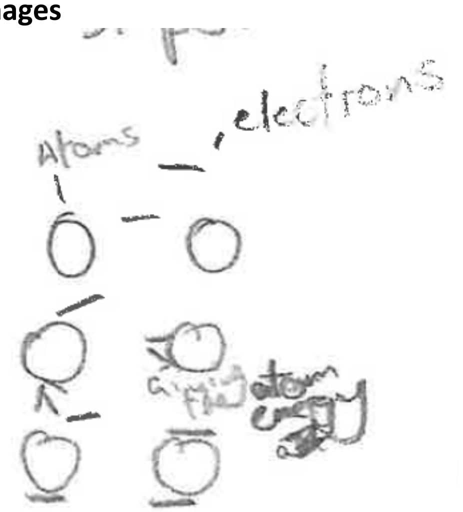


Figure 8 Shore year 5/6 extra worksheet image that describes resistance as the electrons giving atoms energy

Figure 9. Shore year 5/6 extra worksheet images. The student is describing how electrons existing near the nucleus are strongly attracted to it. Electrons that exist further away from the nucleus have only a weak attraction. Part of the discussion and role playing with students emphasized that it was these electrons at the furthest distance from the nucleus that were mobile and able to flow through a circuit when a force (battery) was applied.

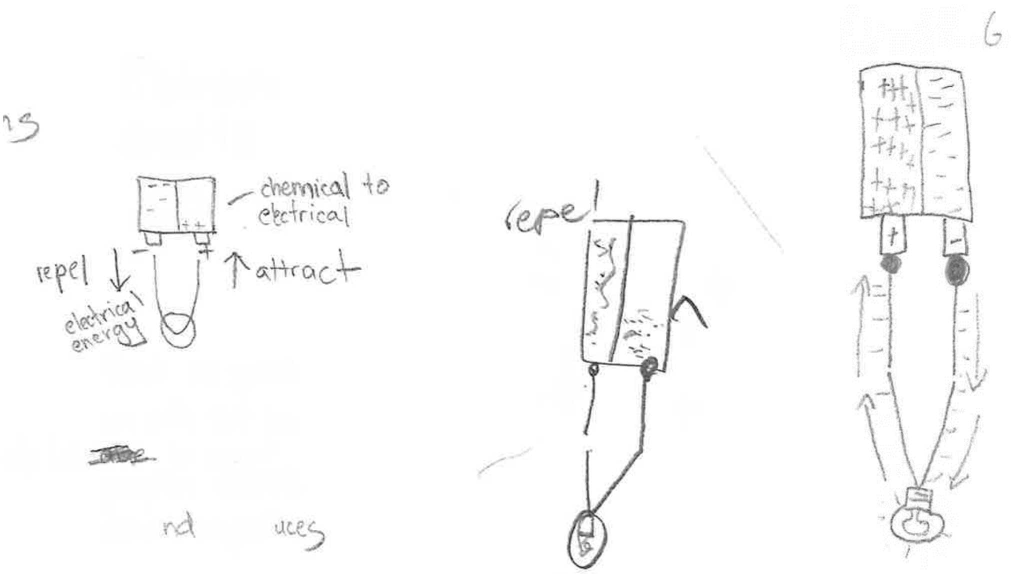


Figure 10. Shore year 5/6 extra worksheet images. Three images each depicting how batteries work to apply the necessary force to achieve flow of charge

Figure 11. Shore years 5/6 extra worksheet images. Similar to Figure 10 above, except there is greater detail on the type of energy in the battery versus the circuit and that the flow of electrons as waves help generate electrical energy

Discussion/outcomes

The workshop had two core outcomes: First, students shifted their understanding of the atom from the classic to the quantum model and developed a basic conceptualization of how electricity and resistance works at the quantum level. Second, students started to think critically about the increasing energy consumption of digital technologies and the implications this has for society.

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, although there was minimal evidence to indicate that students understood that the electron's position is based on probability rather than existing as a particle in a precise and measurable point in space. Based on answers to just the question 3. worksheet responses, at least of students (71%) understood that resistance involved electrons losing their energy as the flowed through a circuit. A good proportion of the students (39%) could articulate this in greater depth, stating that the electrons transferred their energy to the atoms in the conductor and/or 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

> *"*Some of the energy of the electrons is being passed onto the phonons in atoms as it goes along. So when it gets to the end it won't have as much energy for the LED therefore making it dimmer*.".*
>
> *"Circuits have wasted energy from them; wasted energy is heat; electrons are waves; phonons; too many electrons flowing through a circuit=fire; resistance is wasted energy; wasted energy=heat."*

There was, however, some misconception that the electrons had to reach and pass the LED to transfer their energy to the LED and make it work. How to correct this misconception is something to consider for future workshops.

Further, the additional student comments and images suggest that they understood how a circuit works at a quite detailed level. That is, the students who drew the images and made the relevant comments understood that the battery is the force the enables the electrons to flow through a circuit and they the flow is enabled by the electrons being repelled from the negative end of the battery and attracted to the positive end.

Comparison of the pre- and postworkshop drawing of the atom strongly suggests that students have a new conceptualization of the atom and when combined with the worksheet and brainstorm data, such as quotes above, it indicates that primary students are capable of conceptualizing the quantum model of the atom, its role in generating electrical energy and how resistance works at the quantum level and affects the efficiency of digital devices.

This workshop reinforces the findings from previous Quantum circuit workshops that 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. Part of the reason might be attributed to the lack of time in the reflection activity exploring this. Further, 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. In this workshop also, we had no FLEET scientists to assist who would normally be able to chat to students about their research during the activities.

Only five responses in the post-workshop brainstorm related to the theme of digital.

> *Impact: how materials can conduct electricity*
>
> *Wasted energy is unnecessary as we have ways to use less energy – we can do better*
>
> *Trying to create devices that use less energy*
>
> *Resistance is wasted energy*
>
> *Next 10 years we will not be able to meet people's electronic demands*

These responses, however, provide some indication that at least some students are now aware that there is a problem with how much energy digital technology uses and the implications of this.

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.

FLEET reflection

The workshop worked well in its third 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 more effectively. As noted in previous quantum circuit workshops, some 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.

Further, we should put some thought into the student misconception that the electrons have to reach and pass the LED to transfer their energy to the LED and make it work. I am already considering a short role play activity that might help with this problem.

Appendix 1.

Worksheet for quantum circuits workshop

This is the worksheet provided to the Shore years 5/6 to complete as part of the quantum circuits workshop.

Quantum circuits worksheet

1. What happens to your LED as it moves further away from the battery? 2. 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: the components of your circuit are the battery, the conductor (graphite) and the LED. What changes to these components could you make to get you LED working again?
Now think about question 1 again. 3. Why do you think the LED gets dimmer the further it moves away from the battery? Explain with words and diagrams what you think is happening (Use the back of page if needed.)

Appendix 2.

Complete student responses to the question 3 in the quantum circuits worksheet. Some students drew images to help explain their written response. These are included underneath the relevant response.

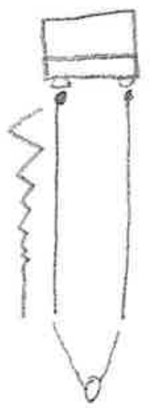
Shore years 5/6 responses (written and images) to the Quantum worksheet question 3.

[Electron lose energy as flow through circuit N=22]

Most students could describe the reasons for their LED getting dimmer was because the electrons were losing energy as they moved through the circuit. As noted below, some students also noted that the energy was lost as heat, transferred through to the atomic lattice, or with 1 student noting that this energy transfer occurred via phonons. See appendix ? for

[Electron lose their energy N=6]

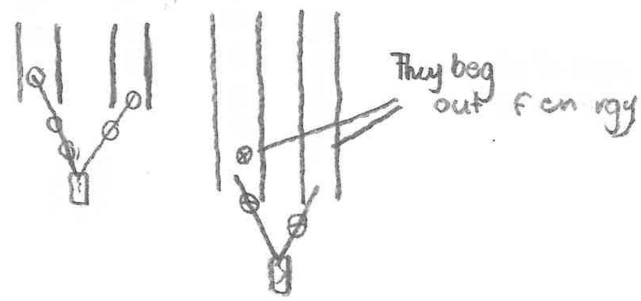
The electrons will get tired and the electrons will run out of energy or 'die'
Electrons are lost by getting used by atoms and the electrons lose their energy
The LED grew dimmer because the electrons lose energy the further it travels down the graphite [image below showing electron's wave – energy – decreasing with distance from the battery]



The LED dims because the negatively charged particles (electrons) lose electricity to the atoms of the conductor [image below showing electrons as a wave]

The LED light gets dimmer because the electrons run out of energy the further they have to go
LED gets dimer because there is more resistance which means less flow of the electrons and protons through the graphite. The flow is slowed and the neutrons slow and stop flowing giving less power toward the light [Note, some confusion about which atomic particle flows, but they recognize that the slowing of these particles means more resistance and less power]

Other images



[Electron lose their energy as heat N=2]

The LED gets dimmer because the electrons lose energy through heat and eventually come to a stop

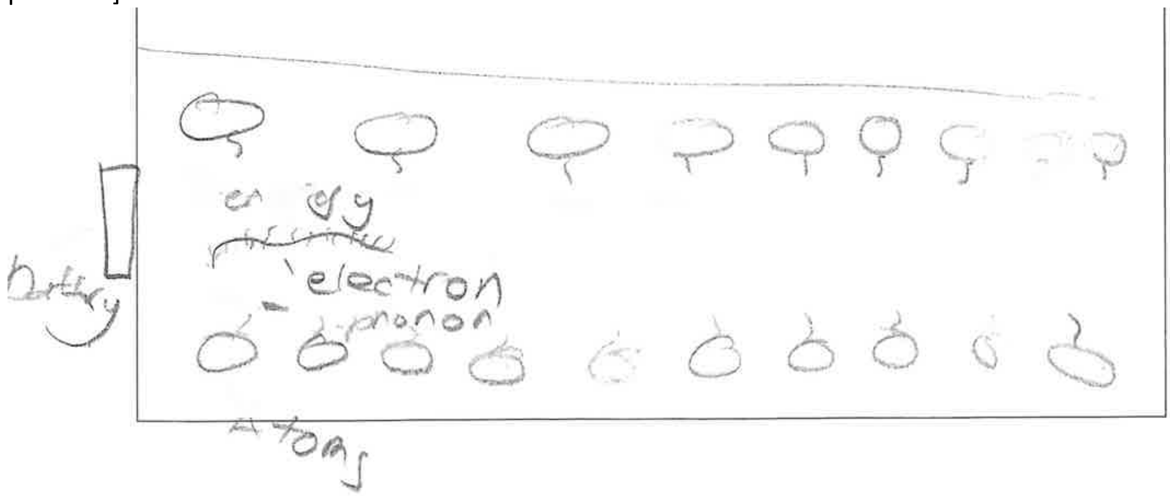
The electricity is lost through the journey as a form of heat

[Electrons transfer their energy to atomic lattice. Describes the role of phonons N=10]

The longer the circuit the more power drained from the electrons meaning less power for the LED [see image below showing electrons as waves transferring energy to atom waves (phonons)]

This is because we lose energy when the electron interacts with the protons and neutrons

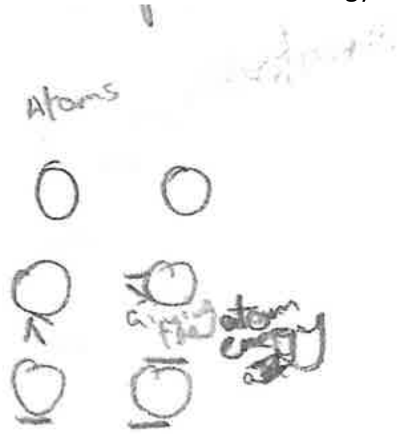
Some of the energy of the electrons is being passed onto the phonons in atoms as it goes along. So when it gets to the end it won't have as much energy for the LED therefore making it dimmer [image below showing the electron as a wave transferring its energy to the atoms via their phonons]



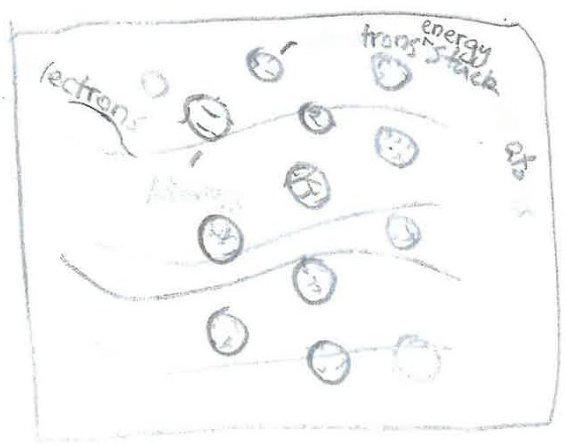
LED gets dimmer because the atoms suck electricity out of the neutron [typo I think given the next sentence]. So the further the electron goes, the more energy it loses so when the electron reaches the LED it has lost energy.

Our experiment showed the atom would take more energy so the electrons would slowly lose energy.

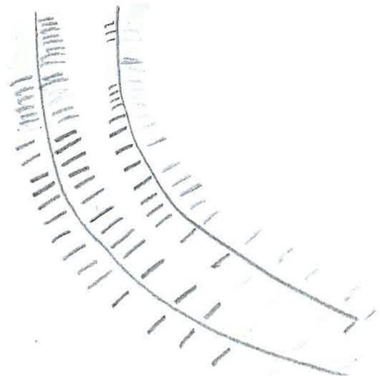
THE LED dims the further it moves away because it is losing more energy the further it goes down.
The more atoms the electrons pass, the more energy they lose so at a certain point there won't be enough energy for the light.
Because the electrons are bumping into the atoms causing some the atoms to receive the energy and the electrons to lose energy and the electrical current eventually stops



Because the electrons lose their energy the further they go. The electrons transfer their energy to the atoms making them [electrons] have no energy and can't carry it the whole way to the LED.
The electrons energy transfers more energy to the atoms as it passes and more resistance builds up
I think the LED gets dimmer because of the resistance in the conductor [Image below: Although the student doesn't describe how resistance works, their drawing suggest they understand that the electrons transfer energy to the atoms



[Energy is lost – unclear what energy N=4]
The responses are conceptually correct and some students note that the energy is lost through resistance, but the source of the energy lost is unclear, although an image associated with one of the responses suggests they understand it is the electron's energy that is lost See response and image below.
Running a marathon – loses energy over time
Energy resistance: loses energy as it goes on
There is more resistance (energy being lost) which means less power to the LED – and the LED dims.
The energy is slowly being lost the further it travels [see image below]

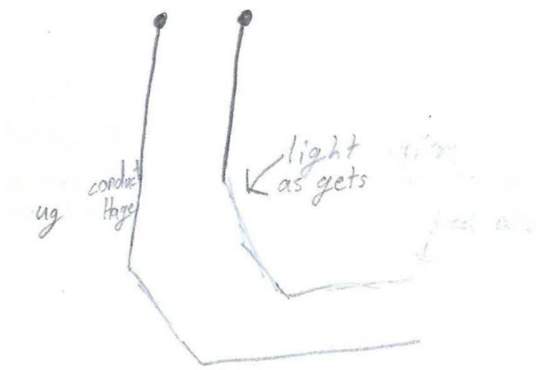


The further the LED moves from the battery, the more energy is lost through resistance and there is less energy to power the LED.

Misconceptions
[Circuit gets weaker N=3]
Because when the light starts to dim, it means that the circuit is becoming weaker
The LED gets dimmer as the graphite weakens due to it needing more [graphite], thus dimming the light
The graphite is becoming weaker and weaker because electrons are getting weaker – less of them.

Travelling currents [N=1]
The LED gets dimmer because the battery's current is trying to travel further

[Losing voltage N=3]
Because it doesn't conduct enough voltage



The light dims because the voltage isn't strong enough to reach the end of the circuit
The atoms cannot travel as long a distance / not enough volts

[Losing electrons N=3]
Electrons get attracted and lose along the way as the journey gets longer
It gets dimmer because a lot of electrons are lost along the way meaning there is less power
Because the electrons got lost on the journey