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

Evaluation report: St Brigids College – Quantum electricity, Light workshops

Date: 1 September 2023
Venue: St Brigid's College, Horsham (Western Victoria)

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Objectives

Quantum circuits workshop

- 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
- An understanding of the features and functions of circuits and how resistance works at the quantum level and affects the efficiency of digital technologies

Light workshop

- For students to have a basic understanding of what light is, reflection and refraction

Both workshops

- For students to think critically about how we (society) use digital technologies and the implications for energy consumption

Overview

FLEET visited St Brigid's College in Horsham to deliver two different workshops to year 8 and 9 students (N=100). The year 8 students participated in a workshop on light that got students to play with hands-on activities that demonstrated reflection and refraction. The 9 students did the Quantum circuits workshop.

The Quantum circuits workshop was developed to get students to learn about and understand how electricity and resistance works at the quantum scale, starting with the atom. Students used role playing activities and built graphite circuits to build this understanding. Because this workshop was developed for years 5-8, we included the extra activity where students use multimeters to measure resistance and then use Ohm's law to determine the minimum current necessary to make an LED work.

The light workshop used activities from an optics kit from the Optical Society of Australia and the FLEET Schools resource, Light: reflection, refraction and diffraction. The activities and associated worksheets introduced students to reflection and refraction.
Pre-and post-workshop evaluation activities were developed to evaluate the objectives of each workshop.

Key findings

In both workshops, data indicates that students developed a more in-depth or scientific conceptualization of light, the atom and electricity.

Method

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

- Pre-evaluation
- Introduction to FLEET
- Hands-on activities
- Post-evaluation/reflection

We assessed the impact of the workshop relative to our objectives through pre- and post-workshop evaluation activities and to a lesser extent, student worksheets. Students typically only partially completed a worksheet and often not at all. The Method section also includes description of hands-on 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-workshop evaluation activities.

Pre-evaluation

For each workshop FLEET facilitated a student brainstorm on one of the following two questions, what comes to mind when you think of electricity or what comes to mind when you think of light?

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

For the Quantum circuits workshop, students were also asked to draw an atom. Butchers papers and pencils/pens were provided for students to do this. The brainstorm and draw-an-atom activities helped determine students' baseline understanding of what an atom looked like and their conceptualization of electricity.

Unfortunately, in the Quantum circuits workshop we ran out of time to conduct an effective post-workshop evaluation. This was exacerbated by a rushed and incomplete briefing and role play experience about resistance. This means the post-workshop evaluation data for this workshop are limited.

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. Because of a shorter workshop (50 minutes), the introduction in the Light workshop was a truncated version of the one used in the longer (100 minutes) Quantum circuits workshop.

The next sections examine first the method used for the hands-on activities in the Light workshop, followed by the method used in the Quantum circuits workshop.

Hands-on activities: Light workshop

The Light workshop was intended to be broken into two sections: Reflection and Refraction. Each section would have an introduction to the topic then hands-on activities accompanied by a worksheet. The different activities were set up at stations around the classroom and a teacher or FLEET volunteer was stationed at each one to help the students with the activity. Following the first workshop which went overtime, we brought the background discussion of reflection and refraction together, then the students went and selected different activities. The teachers called for students to rotate activities every 5-10 minutes.

Before students went free range on the activities, FLEET did demonstrate the Pepper's Ghost activity with the whole class because this required a mobile phone. As an example of reflection students were asked if they could explain how it worked and this was worked through as a group before sending them on to other activities. The Pepper's Ghost activity was based on the activity used in the FLEET Schools resource, Light, Reflection, refraction, Diffraction.

Hands-on activities: Quantum Circuits

The Quantum circuits workshop had the following three core components:

- Understanding the atom and its role in generating electricity
- Constructing circuits
- Understanding resistance

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 the limitations of the Bohr model and while still a useful model, how it can be misleading. We wanted students 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 year 9 students have a reasonable understanding of).

The aim of role-play and discussion is the get students to rethink or challenge their conceptualization of the atom.

To help reinforce the role of electrons and protons (charged particles) in electricity, 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 represents 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 (current) 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 in a worksheet:

1. What happens to your LED as it moves further away from the battery?
2. Why do you think this is happening?
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)? 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?

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

Because these were year 9 students, we introduced some basic math for them to do to help understand the relationship between current, voltage and resistance (OHM's Law). Using a multimeter, students were asked to measure the resistance in their circuit at the point their LED stopped working. They then had to work out the minimal current required make their LED work. While there were large variations in student calculations of I (current), the number was always really tiny. This was used to emphasize the remarkable technology that underpins the LED. That is, an LED can generate light with almost no current.

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.

In previous Quantum Circuit workshops, we have followed the circuit construction activity with images and discussion to help describe the nature of resistance and how electrons transfer 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 has been simulated using students that play the role of atoms in the lattice and students that play the role of electrons to simulate how electrons transfer their energy to the atomic lattice via the phonons. Time constraints meant this was quickly demonstrated by FLEET rather than role-played by the students. The discussion that gets students to think about what they could change in this circuit to ensure the electrons could begin to generate sufficient current (flow faster) to make their LED work again was also truncated as a result.

Post-evaluation/reflection

The post-evaluation and reflection involved a repeat of the brainstorm based on the questions, what comes to mind when you think of light / electricity.

In the Quantum circuits workshop, alongside drawing their perception of an atom, we planned to get students to include their perception of resistance by drawing or describing it. As noted, a shortage of time meant students did not have a time for an effective reflection and discussion to support their hands-on activity, which resulted in their post-workshop drawing activity also being cut short. What was done by students in this session therefore lacked the appropriate context that comes from the discussion and role play about resistance.

Results

The results analyzed in this report are the pre- and post-workshop evaluation responses to the questions, what comes to mind when you think of electricity / light?

The year 9 students' draw an atom data is used, but because of the time constraints of that workshop, the data from this activity are limited.

Both year levels had worksheets associated with the hands-on activities, but only the year 9 students doing the graphite circuit activity attempted to complete the worksheet. In the light workshop, teachers and FLEET volunteers typically just used the worksheets associated with each activity as a reference for what questions to get students to think about and try to answer.

We first present the results from the Light workshop, then the Quantum circuits.

Light

Brainstorm

The pre-workshop brainstorm simply asked students what comes into their minds when they think of light. For some responses, students were asked to elaborate on what they meant. In the post-workshop evaluation activity, the same question was repeated.

The pre- and post-workshop responses from the students were grouped under specific themes. See Table 1.

The responses typically shift from single word responses in the pre-workshop brainstorm to more in-depth explanations or conceptualizations of light in the post-workshop evaluation. See Table 1.

Table 1. St Brigid's College, Year 8 pre- and post-workshop evaluation. What comes to mind when you think of Light?

Pre-workshop responses (number of times comment made)	Post-workshop responses (number of times comment made)
Theme: What we see because of…: Bright(3) – how bright; light globe(3); fire (it's got light); candle; projector; flash (on your mobile phone); flashlight(3); headlight; phone, Sun (3), the Moon	**Theme: Higher scientific conceptualization**: Light travels in straight lines(2); light reflects off a window; mirror – they reflect; refraction; reflection; light does not bend; water changes direction (of light); it changes direction – refraction; reflection – it bounces off objects at same angles; colours – we can only see so many colours; light waves; frequency of light waves determines colour; it has magnetic waves alongside it; refraction – it changes direction of the light as it passes through different mediums
Theme: Enabling: Eyes; see stuff; reflections	**Theme: Simpler scientific conceptualization:** Speed; It's fast; On a big scale and we can only see a little bit (referring to electromagnetic spectrum)
Theme: Philosophical: God (let there be light); life	**Theme: Observations**: Rainbow, Mixing of colour
Theme: Sciency – what light is, can do: Light wave; it is really fast; it goes around the Earth 7 times/minute; waves of light; speed of light; heat (light bulbs get hot)	
Theme: Outlier: light switch	

Quantum circuits

The results examined for the Quantum circuit workshop are the pre- and post-workshop evaluation (brainstorm and draw/ describe an atom/resistance), and the worksheet data.

Brainstorm

Similar to the brainstorm activity in the Light workshop, responses shifted from single words in the pre-workshop brainstorm that came under the themes, Source of electricity, What uses electricity and the Science of electricity, to deeper conceptualizations of light that reflected what they learned or observed in their activities (Graphite is conductive; LED gets dimmer – less current – the further it gets from the battery). Some of these responses (N=2) reflected some recollection or learning about the quantum nature of the atom (Electrons are waves). See Table 2.

In the pre-workshop brainstorm, students were asked what comes to mind when they think of quantum physics and their responses suggest they knew nothing about it, nor could they think of any connection to it. See Table 2.

Table 2. St Brigid's college, Year 9. Pre- and post-workshop responses to the question, What comes to mind when you think of electricity and what comes to mind when you think of quantum physics?

Pre-workshop responses	Post-workshop responses
Theme: Source of electricity: Batteries	**Sciency observations:** Graphite is conductive; LED gets dimmer – less current – the further it gets from the battery; electrons move from negative to positive; resistance = particles and dots
Theme: What uses electricity: Technology; devices; phones; TV; electric key; light	**Theme: Thinking quantum:** electrons are waves; electrons are a cloud
Theme: Science of electricity: power; amps; current; voltage; resistance; circuits; parallel circuits	**Theme: Basic recall:** Static electricity; batteries get hot when joined; what quantum physics is
What comes to mind when you think about quantum physics	How to make LED work in graphite
What is quantum physics? Nah! Not sure	

St Brigid's College Year 9 Draw an atom, describe resistance.

In the pre-atom drawings, student drew three distinct models. The Bohr model was the most common and split into a labelled and unlabelled version. Two other versions, I called the tiny dot and early embryo. See below for descriptions and number (N) of each version drawn.

Bohr model. Two versions of the Bohr model were drawn, one labelled, the other unlabelled.

Unlabelled (N=10)
These drawings resemble the classic Bohr model but without a distinct nucleus or labelling of protons, neutrons or electrons. See Figure 1.

Definitive and labelled correctly (N= 5)

These drawings had a distinct nucleus and electrons in orbit around the nucleus. There is accurate labelling of protons, neutrons and electrons. See Figure 2.

The tiny dot (N=1)
The students knew atoms were tiny and depicted them as such – as a tiny dot made with the tip of the pencil.

Early embryo (N=2)
Students drew an atom that resembled a clump of cells resembling the early embryo stage of animals. See Figure 3.

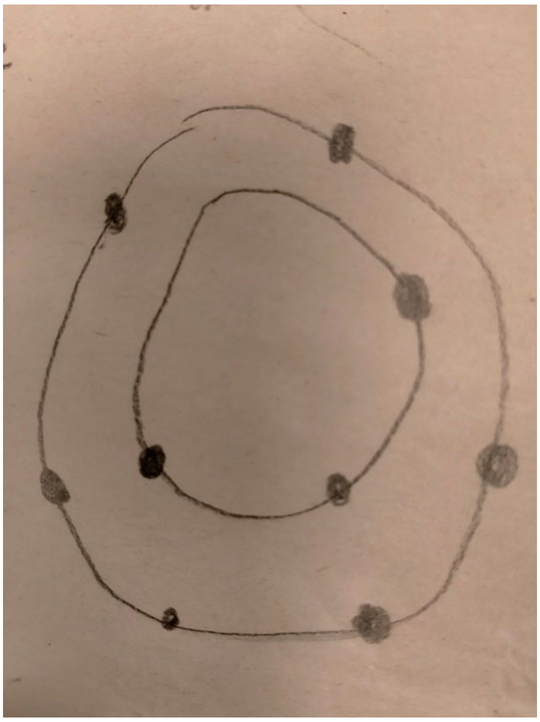

Figure 1. Year 9 St Brigid’s College. Pre-atom drawing: Bohr model, unlabelled

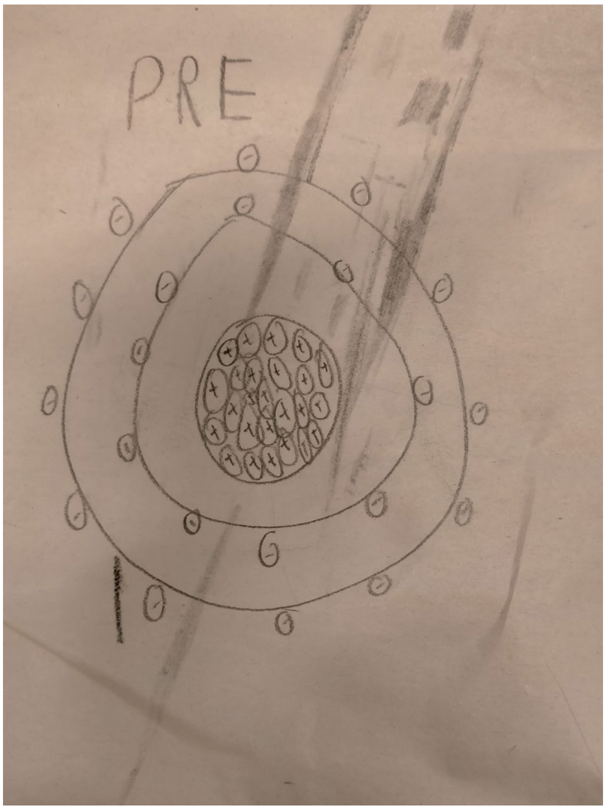

Figure 2. Year 9 St Brigid’s College. Pre-atom drawing: Bohr model, definitive and labelled

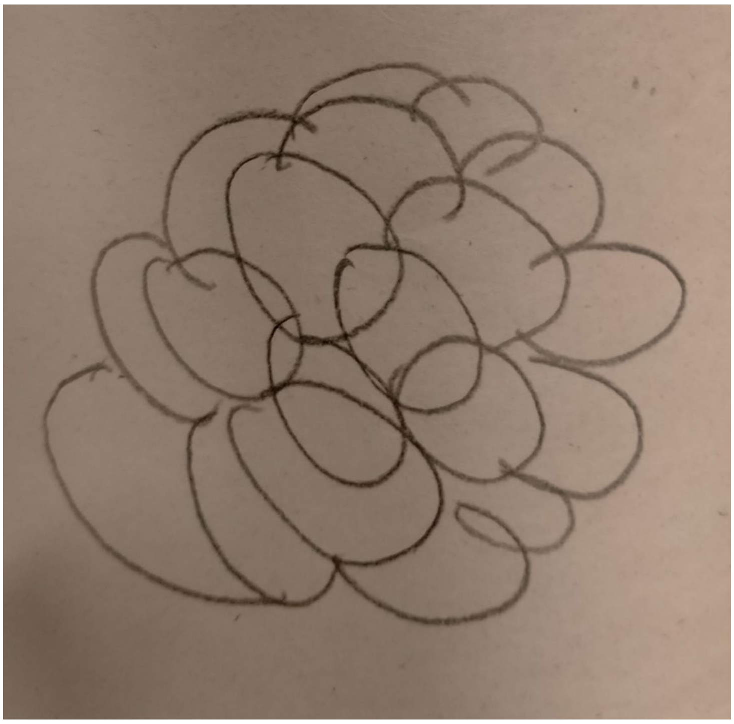

Figure 3. Year 9 St Brigid’s College. Pre-atom drawing: Early embryo

Post-workshop drawings/description of atoms and resistance

As noted, we ran out of time to conduct an effective reflection and to draw a post-conceptualization/description of the atom and resistance.

Only one student attempted to draw an atom post-workshop, which appears to represent the quantum model in that the electrons' position around the nucleus is based on probability. They did however, incorrectly draw negatively charged particles in the nucleus. See Figure 4.

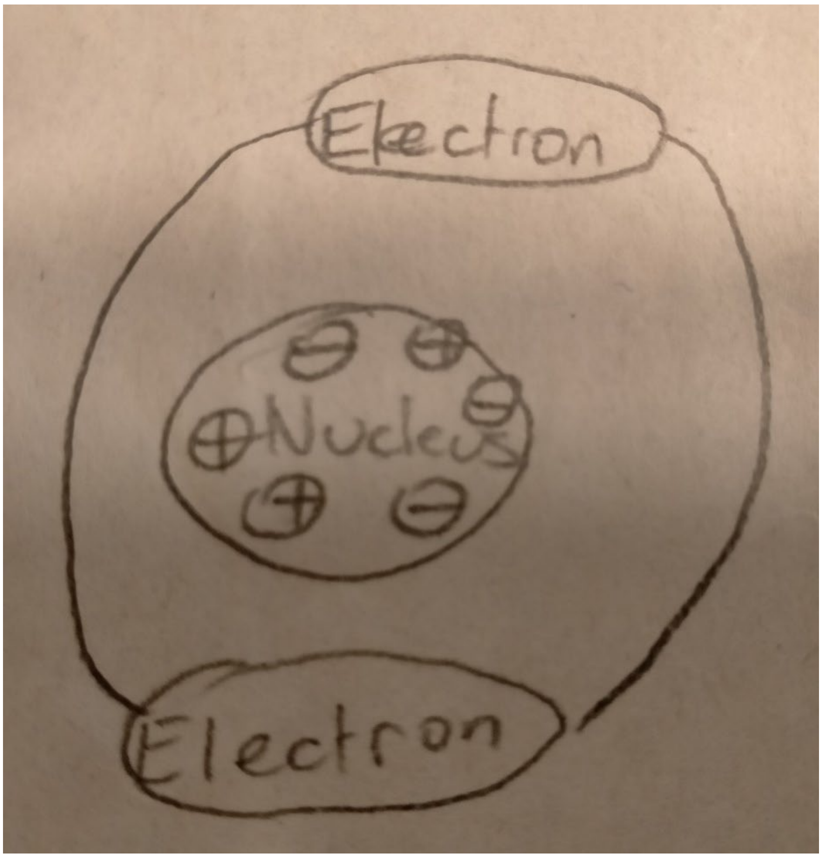

Figure 4. Year 9 St Brigid's College student post-workshop drawing of an atom that potentially represents the electrons in superposition

As noted, a lack of time meant we rushed through the explanation of and role play about resistance. This is reflected in the few attempts to draw and describe resistance.

Four students attempted to draw their conceptualization of resistance, with one including a description, and one student simply described it.

The lone description is essentially correct, but lacks a depth of understanding.

> Resistance is something that slows down electrons

The drawings (and associated description) suggest a mixed understanding of resistance with nothing that definitively indicates they understand resistance at the quantum level.

The drawing with associated description ("Resistance: something that doesn't but repels") in Figure 5, I think is confusing the description of quantum tunneling with resistance. That is, at one point I described how the sun works via the phenomena of quantum tunneling.

Two drawings appear to resemble a slide shown in the presentation that shows the classic model of resistance where particles (electrons) collide with the atoms in the matrix as they flow through a circuit. See Figure 6. The third image depicts a circuit, but with positively charged particles. See Figure 7.

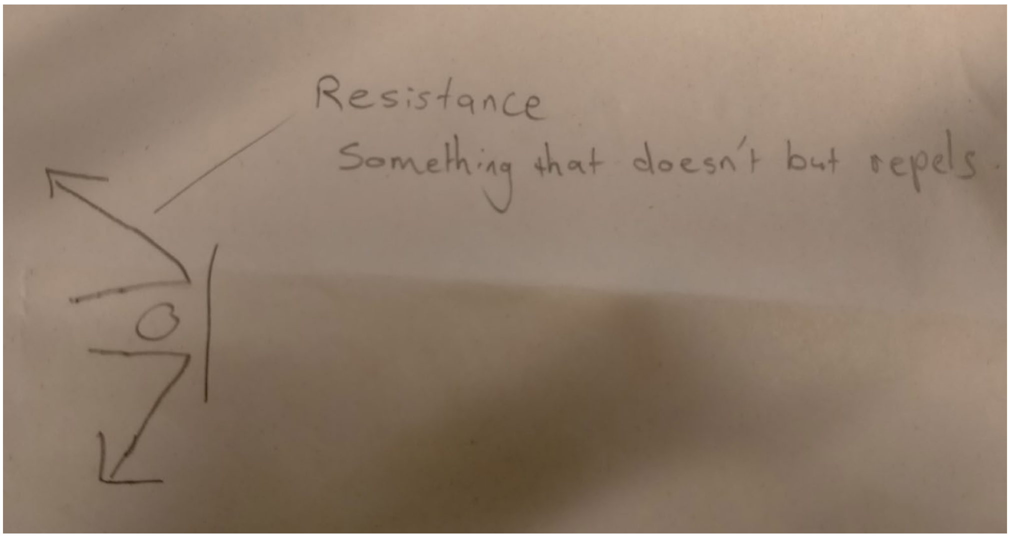

Figure 5. Year 9 St Brigid's College students' drawing and description of resistance, possibly confusing resistance with quantum tunnelling

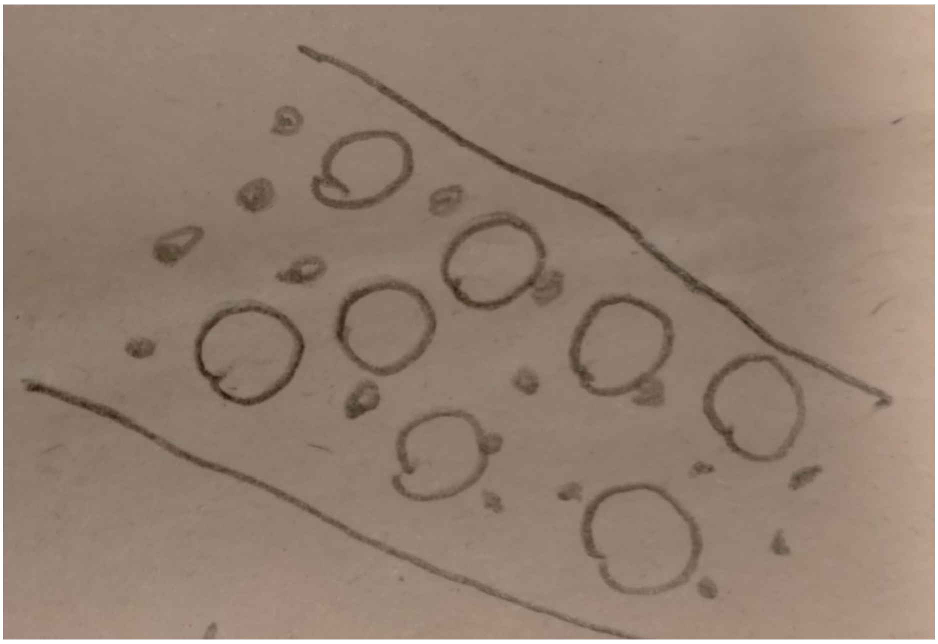

Figure 6. Year 9 St Brigid's College students' drawing of resistance that resembles that classic depiction of electrons colliding with atoms in the matrix.

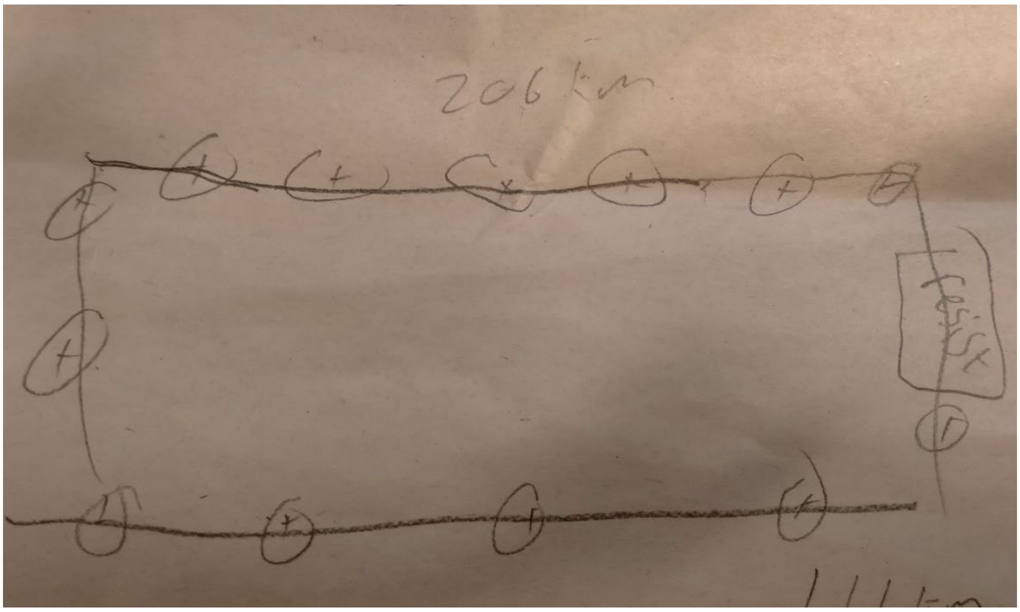

Figure 7. Year 9 St Brigid’s College students’ drawing of resistance that depicts a circuit, but with positively charged particles.

Worksheet

Students completed a worksheet while they were constructing and testing the graphite circuits. Responses to each question are in in Table 3 below.

All students observed that their LED got dimmer the further they moved it from the battery. See Table 3.

In Question 2, the 11 responses were split into the following four core themes:

- Current (N=3): Students perceived that the current was losing strength the further it got from the battery. This is effectively correct.
- Battery (N=2): Students thought the force of the battery diminished as the graphite circuit got longer
- Electrons (N=3): Students knew the flow of charge (electrons) was required to generate electrical energy and associated the distance the electrons travelled with the amount of electrical energy available to power the LED
- Lost energy (N=1): If we assume the single student in this instance was conflating power and energy, there was a correct assumption that the LED was getting dimmer because energy was getting wasted somehow.

Actual student responses to Question2 are listed in Table 3.

There was one response, ‘I don’t know’ and another that considered the reason for the LED getting dimmer was because the light had to travel further. These was not considered as part of the themes, the latter because it is difficult to know if the student is misinterpreting, mis-communicating or just struggling to articulate their thoughts.

Nearly every student (N=6) that responded to question 3, correctly said they could get their LED working again if they made the graphite circuit thicker (ie more layers of graphite). The other response was to make them thinner, though we lack an explanation for why the student thought this. See Table 3.

Table 3 St Brigid's Year 9 student responses to questions about their observations in the graphite circuit

Worksheet questions	Student responses
What happens to your LED as it moves further away from the battery?	All students noted that their LED got dimmer the further it got from the battery.
Why do you think the LED got dimmer the further it got from the battery?	**Current:** Because the current isn't as strong and it is further from the battery The current drops the longer it is The current drops the further it goes on **Battery:** Because the force of the battery weakens the further it goes I think the voltage of the battery started to wear out as it got further away **Electrons:** Because the electrons have further to travel; Because the electrons have further to travel; The electrons have further to travel
Q3. What would you change in your circuit	Six of the seven students responded that to make their LED work again they would make their graphite lines thicker. One student also added that they could use a stronger battery. One student said, 'make the lines thinner.

Discussion/outcomes

In both workshops, data indicates that students developed a more in-depth or scientific conceptualization of light and electricity. There was, however, no data to enable us to assess critical thinking about FLEET's research problem. Therefore, while there is evidence of some learning about light and the quantum mechanics of the atom and circuits, we lack the evidence to know if we have met all the objectives of this workshop.

Light

The year 8 students doing the light workshop went from thinking about light from the perception of what produces light (fire, flashlight) or what we can do with light (ie see stuff) to considering what light is (it is a wave, and it has magnetic waves coming off it) and how light behaves to enable us to "see stuff" (light reflects, light changes direction as it passes through different mediums).

This suggest students did increase their understanding of light.

Quantum circuits

The year 9 students had to rush through a post-workshop brainstorm, which makes it difficult to contrast the pre- and post-workshop brainstorm evaluations. But the post-workshop responses do suggest that some students at least recalled some of the quantum aspects of the atom and how circuits function (electrons are waves, electrons move from negative to positive). But it is harder to determine how much of this is simple recall and how much is understanding. A lot of the understanding of and reinforcement about resistance comes from the role playing and subsequent discussions that were skipped through quickly. It is therefore likely that the apparent limited student understanding of resistance reflected in the worksheets and post-workshop evaluations is accurate.

Understanding the quantum atom

The year 9 students doing the Quantum circuits had a similar conceptualization of the atom as years 5-6 students that have previously done this workshop. That conceptualization is largely based on the Bohr model of the atom. Again, because of the lack of effective time for the role play and discussion about resistance, and post-workshop reflection, there is insufficient data to draw strong conclusions about any impact on student literacy in quantum physics. The limited post-workshop evaluation data does indicate that students have shifted their perception of atoms and circuits to how it works at the quantum level, but it is more anecdote than data.

Critical thinking about digital technology

There was a lack of responses relevant to student critical thinking about the energy consumption of digital technology and FLEET research. This is largely due to time constraints that meant we were unable to initiate discussion about this during the reflection component of the workshops.

Limitations

As noted, the timing of each workshop was mismanaged by myself that meant the post-workshop evaluation data was too limited to draw robust conclusions about student learning and critical thinking.

There is also the potential problem of being able to distinguish between what is simply student recall, reflective of recency bias, and real understanding and critical thinking of the science. The effect of this limitation can be reduced with more time for reflection and discussion at the end of the workshop.

FLEET reflection

The Light workshop was being conducted for the first time and there are some refinements required to ensure greater room for reflection at the end. The lessons were also only 40-45 minutes long because of the school timetable. Future workshop should aim to have at least 50 minutes (preferably 60 minutes) of actual workshop time.

In the quantum workshop, mismanagement of the time on my part left insufficient time to effectively cover the topic on resistance and for reflection / post-workshop evaluation. This is a lesson learned. One reason for the timing was an assumption that year 9 students would have a certain level of understanding about the atom and circuits. This proved not to be the case and it meant covering material I had not planned to cover. I was surprised to find that year 9 students had a similar level of understanding of atoms and circuits as years 6-7, at least compared to the small number of schools where this workshop has been conducted.

Further, it appeared that many Year 9 students, at least, were, to varying extents, disengaged with the topic – except for the hands-on circuit making. I have talked to a handful of teachers about this and apparently this behaviour is typical for this year level. There is scope to consider tweaks to this workshop for this age group to try to increase engagement.