FLEET

ARC CENTRE OF EXCELLENCE IN FUTURE LOW-ENERGY ELECTRONICS TECHNOLOGIES

FLEET outreach impact report

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Introduction

FLEET outreach mission

FLEET's mission in outreach was to do more than just tell people about the science. Public engagement is an opportunity to have a critical dialogue with the public.

The Australian Research Council mandates that Centres of Excellence outline their research impacts relevant to their production of new knowledge and /or their innovative economic, commercial, environmental, social and/or cultural benefit to the Australian and international community. In line with the ARC mandates, FLEET has aimed, as part of its outreach impact, to deliver the following benefits:

- Social-informed decision making
- Social-enhanced skill base

FLEET engaged the public in a critical dialogue about the unsustainable energy consumption of digital technologies. This involved examining the research (especially FLEET's) being conducted and what constitutes acceptable solutions. In other words, what does the public consider to be the public good outcomes of quantum-based research relevant to this problem?

Public good

Despite attempts to define public good, its description through varied lenses provides equally varied definitions (McKinnon et al 2022; Roberson et al 2021). For instance, descriptions of public good that benefit the whole of society (McKinnon et al. 2022) leave open the interpretation of benefit. Economic prosperity may benefit some but not others. That same prosperity may come at a cost to the environment that may be acceptable to some but not all.

Australia's National Quantum Strategy reflects in many ways those of other nations such as Canada and the UK, where public good is framed around economic prosperity, driving commercialisation and protecting national interests (Australian Government Department of Industry, Science and Resources, 2023; UK Government Department for Science, Innovation & Technology 2023).

It mirrors arguments by Roberson et al. (2021) that the rhetoric in national strategies is typically described through an economic lens and a need to win the 'quantum race'. This is evident in Australia's quantum strategy, which describes a need to connect and grow Australia's quantum research and industry to compete with the world's best and drive commercialisation through new programs to incentivise the continued growth of quantum use cases (Australian Government Department of Industry, Science and Resources, 2023).

Roberson et al. consider this a too narrow view of what are public good outcomes for quantum technologies. To emphasise this and the varied lenses the public can consider public good outcomes, Roberson et al, found that physicists interviewed in their research contested the economic framing used by key nations such as Australia. The physicists put greater emphasis on community and social considerations, and gaining skilled people to support the quantum technology industries. Others, such as deWolf (2017) and McKinnon et al. (2022), argue that social considerations, such as the potential for inequitable distribution of the wealth and power that underpins the economic framing of the nationalistic quantum strategies, also need to be considered.

FLEET's research is still largely at the fundamental stage, and the potential technological outcomes are uncertain, which means it is early enough in the research journey for any research direction and agenda-setting to be influenced and result in publicly accepted public good outcomes. Once the research translation process gets into full swing, there is considerable investment locked in, and it can be difficult to reverse.

Given the early phase of the research, one role of FLEET's public engagement was to facilitate the narratives and dialogue on what constitutes public good outcomes for quantum technologies, at least those relevant to FLEET's research. Indeed, once the public became aware that there was a problem with the energy consumption of digital technologies, they initiated alternative discourses and critically considered what constitutes public good when it comes to quantum research. This was most evident among the participants at public events. The same high level of critical thinking was not expected in school students, especially at the primary and lower secondary levels.

Outreach objectives

FLEET outreach had two key audiences: school students and the general public. The strategic goals were different for each. For students, the goals were improved science literacy, a broader and deeper understanding of physics as a career and discipline and the ability to think critically about FLEET's research, its value and our problem of the unsustainable energy consumption of digital technologies. For the public, it was improved awareness of FLEET research and research problems and the same critical thinking outcomes as students. Part of the dialogue with these audiences included what outcomes of FLEET's research they consider a public good.

Each outreach event was designed to enable the measurement of our objectives. This involved recognised social science research methods based on varied pre- and post-evaluation activities, and observation. The methods are detailed in the relevant sections of this report.

Evaluating impact

To understand FLEET's outreach impact, we developed novel methods to measure it. Our evaluation shows that we have had a positive impact relative to our strategic goals.

Measuring the impact of FLEET's outreach events is one component of understanding its impact beyond the academic research itself. The report analyses the impact of the two audiences (public and school students) separately, and then an overall discussion examines the impact of FLEET's outreach relative to the ARC goals for Centres of Excellence.

Public events: This report evaluates the impact of two public events: Melbourne Knowledge Week (2021 and 2022) and the Sydney Science Trail (2023). Both involved similar FLEET interactive exhibits that were part of a larger event open to the public. With some exceptions explained below, the evaluation method for each event was similar, and the data from all three events is therefore combined and analysed for this report.

Student workshops: This report assesses two student activities: interactive quantum circuit workshops for years 5-9 and a John Monash Science School (JMSS) elective for year 10 students.

FLEET conducted various hands-on workshops for primary and secondary students, including holiday programs. Most outreach with primary and secondary students was conducted in more curriculum-aligned formal workshops, which are the workshops analysed for this report. The quantum circuits workshops were selected for analysis because of their greater frequency. Separate evaluation reports for most outreach events are available on the FLEET Legacy website.

In collaboration with JMSS, FLEET ran a Future electronics elective for year 10 students. This has happened each year from 2018 to 2024. It will continue to run after FLEET has ended. The elective, run over a full semester, introduces students to quantum physics intuitively and expands on this fundamental understanding to explain complex, useful quantum states such as superfluids and topological materials. This elective is evaluated in a separate report that combines the data from the 2020-2023 evaluation reports.

Overall key findings

Students

- Students improved their scientific literacy, including literacy of quantum physics
- Students thought critically about the problem of unsustainable energy consumption of digital technologies
- JMSS Future electronics elective: students developed new perspectives on physics and increased their breadth and depth of understanding of the topics taught.

Public

The public that engaged with FLEET began with a low awareness of the unsustainable energy consumption of digital technologies.

Following their experience with FLEET, the following outcomes emerged from the analysis of the data:

- The public gained an awareness and appreciation for the purpose and value of FLEET's research.
- The public thought critically about FLEET's research and the problem of unsustainable energy use of digital technologies.
- People put emphasis on two approaches to solving FLEET's research problem: a perception that technology will be the key driver in solving the problem and cultural or socially focused solutions. There were two value-based lenses in which the public determined what constitutes public good.
- All visitors desired a sustainable and socially responsible digital future with some emphasis on any research in this area needing a social licence to operate.
- FLEET outreach volunteers gained a new perspective and understanding of the public as an audience. They saw the value in communicating with the public and the skills they gained from the experience.

Method

Finding novel evaluation methods

We developed evaluation methods for two broad event types: student workshops and interactive exhibits at public events. We used recognised, largely qualitative social science methods integrated into each event's experience to avoid detracting from that experience. A thematic analysis was done on the qualitative data, and basic statistics was performed on the quantitative data.

The following two examples, a student workshop and a public interactive exhibit, briefly overview the methods used to understand FLEET's outreach impact. The analysis of the event gives a more detailed description of the methods. Individual event evaluations can be found on the FLEET website here.

Student workshop

FLEET ran three main hands-on school workshops for students in years 4-9: Quantum circuits, Catapults, and Balloon rockets. Quantum circuits began as a simple workshop on circuits and electricity but evolved to integrate quantum concepts to introduce students to quantum physics.

In this report, we describe the method used for the Quantum circuits workshop, which was novel and it was the most conducted workshop between 2022 and 2024. All workshops, however, integrated similar forms of pre- and post-evaluation activities to help understand the impact. See the link above to view the individual outreach reports.

Quantum circuits method (Year 5-9)

The results for the quantum circuits workshops are the combined data from nine workshops conducted at five different schools, in year levels ranging from years 5 to 9. The pre-evaluation, conducted at the beginning of the workshop, involved two student 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 how they conceptualised electricity and the structure of an atom. This was followed by a short introduction to FLEET's research problem and the unsustainable energy consumption of digital technologies, including a critical thinking exercise about potential ways to solve this problem.

The post-evaluation repeated the brainstorm and draw-an-atom activity and included some deeper reflection about how they conceptualise and connect quantum concepts such as resistance, FLEET research and the problem of unsustainable energy consumption of digital technologies.

A thematic analysis was conducted on the pre- and post-brainstorm and atom drawing activities, and on students' reflections and observations during the workshop. The thematic analysis compared the pre- and post-evaluation data to determine if there was a shift in student literacy and to determine whether students had thought critically about FLEET's research and its implications.

Public events (Sydney Science Trail Expo, Melbourne Knowledge Week)

The data from the public outreach is combined from two Melbourne Knowledge Week events (2021 and 2022) and one Sydney Science Trail (2023).

FLEET developed an interactive exhibit for these events that used its levitating superconductor as the core attraction to engage and initiate conversation. See Figure 1. At Melbourne Knowledge Week, because the space was larger, we also used build-a-circuit kits and a jumping rings demonstration. The jumping rings, especially (see Figure 2) was an excellent way to demonstrate resistance. All interactive demonstrations were effective in helping engage audiences in conversations about FLEET research, but none were individually evaluated.

FLEET's aim at these events was to actively engage the public with FLEET's research problem: the increasing and potentially unsustainable energy consumption of digital technologies. FLEET's focus was on our measurable objectives: awareness and critical thought.

To evaluate the event, the following pre- and post-evaluation tools were developed:

- A short pre-evaluation survey (one question)
- Mind map
- Online exit survey
- Observation (comments, and conversations with the public were noted in a record book)

Figure 1. Levitating superconducting at Sydney Science Trail

Figure 2. Using the jumping rings at Melbourne Knowledge Week, 2022. An excellent way to demonstrate resistance

The next two sections provide a detailed examination of the method, results and discussion for the quantum circuits student workshops and public events.

Student workshops: quantum circuits for primary students

Introduction

FLEET developed a variety of student workshops for year 4-9. In this report, we analyse the impact of the quantum circuits workshop for years 5-9.

FLEET has shown that primary students *can* learn quantum physics, so why not teach it?

FLEET developed a novel workshop based on the physics of electricity and circuits at the quantum level to teach primary and lower secondary students quantum physics. We conducted eight Quantum circuit workshops at five schools for years 5-7. A further workshop was conducted with one year 9 class. The workshop for years 5-7 was a qualitative exploration of quantum concepts. The year 9 class used basic maths to calculate current, resistance and voltage (Ohms' Law) when doing the hands-on graphite circuits part of the workshop.

Workshop 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

Key findings

- Primary school students can successfully conceptualise the quantum model of an atom and understand that electrons have a wave-like behaviour
- Students learned that the flow of electrons is necessary to generate electrical energy
- Students began to conceptualise the nature of electrical resistance at the quantum level and could link this to FLEET's mission to develop low-energy electronics
- Students, to different extents, could think critically about the unsustainable energy consumption of digital technologies.

Why teach primary students quantum physics?

The world we inhabit and interact with exists because of quantum physics. Everything from mobile phones to solar panels exists because of our understanding of quantum physics. Even the Sun exists because of quantum physics.

Despite this, there is a disconnect between the science taught in schools and the science of the modern world. The school curricula lack any topics on quantum concepts. The quantum circuits workshop, which has also been integrated into the FLEET Schools resource on Electricity, conductors and insulators, can help students become familiar with quantum concepts and the physical reality of how the world works. While quantum itself is not part of the Australian curriculum, understanding electricity and circuits is where FLEET links this workshop to the curriculum.

Method/Results

The quantum circuits 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 the worksheet

We assessed the impact by analysing pre- and post-evaluation activities and a student worksheet. This section also includes a description of role-playing activities and the outcomes of those 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 conceptualisation of electricity and quantum physics.

The brainstorm session occurred with a FLEET member writing the student responses about electricity and quantum physics on a whiteboard. 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. If quantum was not referred to in the post-evaluation session, we prompted them by asking what can you tell me about quantum?

For the atom drawing, students were given paper and pencils and asked to draw what they thought an atom looked like. In some classes, students did this on a tablet drawing program. 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 a narrative framed around the FLEET research problem of digital technologies' unsustainable rise in energy consumption. As part of a critical thinking exercise, students were asked to consider the implications of not being able to generate enough energy to meet digital technologies' demands and what we could do to help solve the problem.

Students in years 4-7 typically struggled to make a connection between the electrical energy used by their digital devices and how electricity was generated, and its link to issues such as pollution and climate change. Most students had heard of climate change but did not readily connect it to the energy consumption of their devices. Once this connection was understood, students could think about solutions. Students from years 8-9 could more readily make the connections between the energy consumption of digital devices and climate change, but their solutions were typically different from the younger students.

Year 4-7 students typically considered socio-cultural solutions to the increasing energy demand from digital technologies, such as switching off lights and reducing the time spent playing their gaming devices or watching streaming services on TV. Older students perceived technological advances as having a greater potential to solve the problem. They discussed using more renewable energy or finding novel ways to generate more energy. Typically, at this stage of the workshop, few students of any age mentioned developing technologies that would use less energy as a solution.

Three broad solutions were presented to students: renewable energy (research to find new ways to generate renewable energy and improve existing technologies); developing algorithms to improve the efficiency of computations, especially in areas such as AI; and reducing the energy consumption of computations. More details were given about FLEET's research here, and the workshop activities and student discussions were linked to FLEET's research and the broad 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 electrical energy. 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 conceptualise 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 and role-playing the electron cloud model

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, this model is the one that students are 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 were asked to select an atom from one of the first four on the periodic table and then asked how many protons and neutrons we needed to make one. 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 emphasised 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 was 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, specifically the nature of the electron.

We did a small demonstration to help reinforce the role of electrons and protons. We rubbed a balloon 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 the balloon would initially repel the cup and then sometimes attract the cup. Based on their knowledge that like charges repel and opposite charges attract, we asked students what was happening. We then broke off a piece of the styrofoam cup and tested the charged balloon against that. The piece of foam is attracted to the balloon, but as noted, the balloon can repel the foam cup. We got the students to develop hypotheses explaining what was happening and how they might test their hypotheses.

Constructing circuits

Students were introduced to a circuit and what is necessary to make one work. We also describe the role of the electron in generating current here. It is emphasised 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 an LED work. We emphasised that it is not the flow of electrons that is electricity or what turns on the light, but for the purpose of primary students, the explanation given is that it is the flow of electrons that enables the generation of the electrical energy that we use to do work. No electron flow; no electrical energy is generated.

We explained to students how to construct their graphite circuit and asked them to consider the following questions that were part of a worksheet each student completed as part of the activity:

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 asked 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 who play the role of atoms in the lattice and students who play the role of electrons. It is based on Activity 7, from the FLEET Schools resource, Electricity, conductors and insulators. The student electrons were given a hat with several pipe cleaners stuck in it. The pipe cleaners represent the energy of the electrons.

The student electrons were asked to pass through the student lattice. A FLEET member acted as the battery and applied a small amount of continual force to the student electrons 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 extra jiggling meant they also generated extra heat. The electron continues to pass through the lattice until it runs out of pipe cleaners (energy).

Students were asked what they would need to change about their circuit to ensure the electrons could continue to move – not run out of energy. Typically, there was discussion and prompting before the students said to use a bigger battery to give the electron more energy. To represent an electron in a circuit attached to a bigger battery, another hat was placed on the student electron’s head with about double the amount of pipe cleaners than the first hat. The FLEET member acting as the battery applied more force to the student electrons' back, making them move faster through the lattice. This time, the electron made it much further through the atomic matrix. When questioned, students also understood that because the electrons had much more energy to lose, more heat was generated due to the even greater amount of energy transferred to the atoms in the lattice.

FLEET facilitated a discussion about the sustainability of 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 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 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 the necessary current and, therefore, the electrical energy. See the post-evaluation comments and worksheet responses that suggest students understood that resistance is heat and wasted energy.

Post-evaluation/reflection

The post-evaluation and reflection involved repeating the brainstorm and draw-an-atom activity. Students also completed the last question in the worksheet about resistance: Why do you think the LED gets dimmer the further it gets from the battery (or the longer your circuit is)?

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 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. The questions also reflect questions posed in the initial critical thinking discussion about FLEET's research and the implications of not being able to generate enough energy to meet demands from digital technologies. These additional prompts are also part of students' reflection to help reinforce their learning. Time constraints in at least half of the workshops we conducted meant the post-brainstorm was often rushed with minimal if any, time to prompt students about how they value digital technologies and whether they have shifted their thinking about the relevant research to help solve the problem. See Table 1.

Table 1. Typical pre- and post-brainstorm responses to the question: what comes to mind when you think of electricity

Typical pre-brainstorm responses	Typical post-brainstorm responses
• **What is electricity**: Static electricity, lightning, circuits, wires, energy, power • **What uses electricity**: Light, phones, technology • **What generates electricity**: Solar panels, wind turbines, batteries • **Tech components**: conductors, circuits, wires and stuff • **Sciency connections**: positive and negative, electrons • **Thinking quantum**: Einstein, black holes, dark matter, Antman, Marvel, really tiny	• **Thinking quantum:** Electron waves; protons, neutrons, electrons; phonons; sound waves; quantum – at the size of an atom, Positive proton attraction – electrons are drawn toward protons; neutrons, 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, Heat = resistance, Electrons still have energy (when there is no resistance), Moving electrons=electricity • **Digital impact**: FLEET making materials that save energy; Better conductors = less wasted energy; Making materials with no resistance; Resistance is

	wasted energy, 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 • **Sciency connections:** 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

While there is some overlap with the pre- and post-workshop brainstorm themes, the responses under each theme differed. The responses shift from mostly single-word responses to more in-depth explanations or conceptualisations of electricity and energy. For instance, the post-workshop brainstorm responses for the theme, Thinking quantum, shift from the big picture popular science topics (black holes, wormholes, string theory and Antman) to a more in-depth consideration of the quantum nature of electricity and energy (moving electrons=electricity; circuits have wasted energy from them; wasted energy is heat; electrons are waves; resistance is when atoms attract the energy from the electrons).

Draw an atom

There is a distinct shift in students' interpretation of the atom. Before the workshop, students' conceptualisation is largely of the classic Bohr model where electrons represented as particles are in distinct orbits around the nucleus. Others draw abstract blobs or something that resembles a virus. Pre-workshop drawings typically lack any labelling of protons, neutrons and electrons. In the post-atom drawings, students' conceptualisation 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. Electrons are often described and drawn as waves. Protons, neutrons and electrons are often labelled. See Figures 3-5.

Students' pre- and post-drawings of the atoms

Pre-evaluation atomic drawings

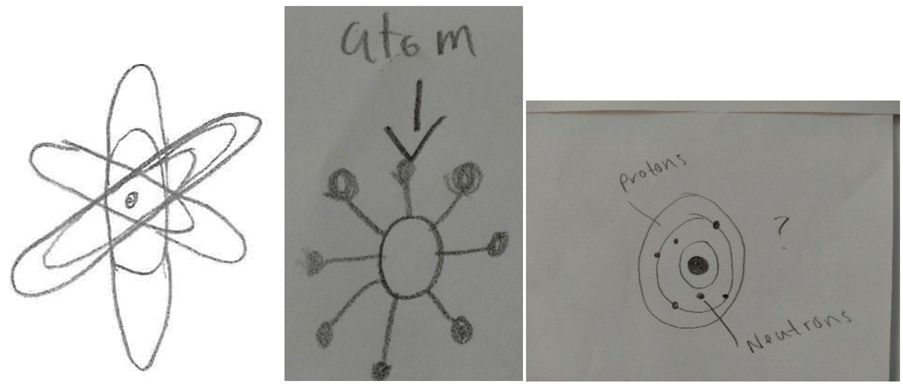
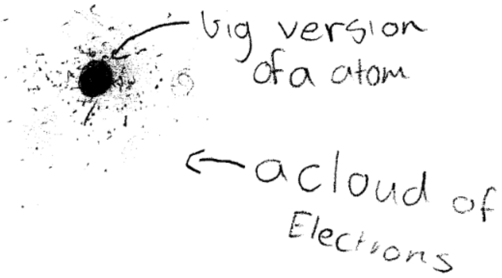


Figure 3. Typical students' conceptualisation of the atom in the pre-evaluation activity. The unlabelled Bohr atom (left) was one of the more common conceptualisations. The virus particle (middle) was also common. A small proportion of students represented electrons as a particle – again in distinct orbits around a nucleus (right)

Post-evaluation drawings



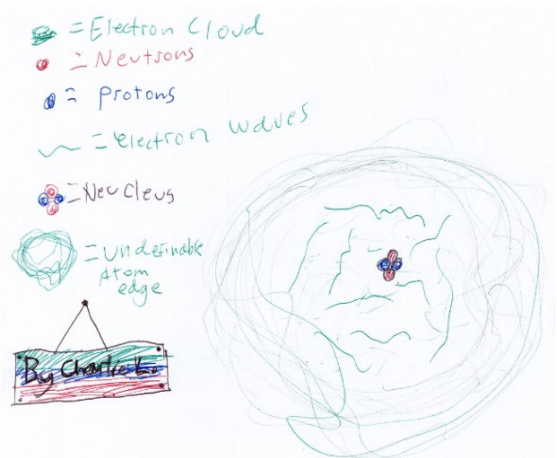


Figure 4. By the end of the workshop, students shifted their conceptualisation of the atom to one more representative of the quantum model that showed electrons as a cloud, often describing the electrons as waves. Drawings typically labelled the protons, neutrons and electrons.

Worksheet

Student responses on their worksheets support the other post-evaluation activities that indicate they have begun understanding what happens in circuits at a quantum level. All students noticed that their LEDs got dimmer the further it was from the battery. While there were some misconceptions, their responses to why this was happening showed that students have begun to conceptualise that electrons have energy and their flow through a circuit generates electrical energy, and as they flow through the circuit, they lose energy, which means there is less electrical energy generated to make their LED work. Some students describe the electrons' energy being transferred or lost to the atoms in the lattice and that this is resistance and generates heat. See Table 2.

Table 2. Student worksheet responses to the question, why does your LED get dimmer the further it is from the battery

Theme	**Theme/sub-theme description**
Energy lost Most students could describe the reason for their LED getting dimmer was because energy was being lost somehow. Student responses fall under four sub-themes: Electrons are losing energy; Electrons transfer their energy to atomic lattice - including the role of phonons;	**Electrons are losing energy (N=27)** The electrons will get tired and the electrons will run out of energy or 'die' The LED grew dimmer because the electrons lose energy the further it travels down the graphite

Electrons losing their energy as heat; and Energy just being lost. Most understood that it was the electrons losing energy, some with a more in-depth understanding than others. As noted in the right-hand column, some students understood that the energy was lost as heat, transferred through to the atomic lattice, or with 1 student even describing that this energy transfer occurred via phonons. While student responses are conceptually correct, a small number describe energy being lost along the circuit, but often with an unclear description of what that energy was, where it came from or how it was lost, though one student did describe the energy being lost through resistance.	When the electrons travel further they lose energy and can't travel as far 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 **Electrons transfer their energy to atomic lattice - including the role of phonons (N=11)** 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 Electrons are lost by getting used by atoms and the electrons lose their energy The LED dims because the negatively charged particles (electrons) lose electricity to the atoms of the conductor 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 Our experiment showed the atom would take more energy so the electrons would slowly lose energy. **Electrons losing 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 **Energy just being lost (N=9)** The further away it [LED] is, the more energy it needs to spread out Running a marathon – loses energy over time 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

	The further the LED moves from the battery, the more energy is lost through resistance and there is less energy to power the LED.
It is something about the conductor (N=2) Students understood that their conductor affected the brightness of their LED, specifically that if there was break in the conductor the LED would not work, or that if they made the graphite thicker the LED would work better.	The stronger and darker the lines the brighter the LED
Misconception (N=11) There were a small number of misconceptions about what was causing the LED to get dimmer	The further away, the less electrons 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 LED gets dimmer because the battery's current is trying to travel further It gets dimmer because a lot of electrons are lost along the way meaning there is less power

Students sometimes created images or wrote other comments in the margins or back of their worksheet that reflect their deeper understanding of the quantum circuit. See Figure 5 and examples of these comments from years 5 and 6 students below.

> Electron is a wave not a particle
>
> 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.

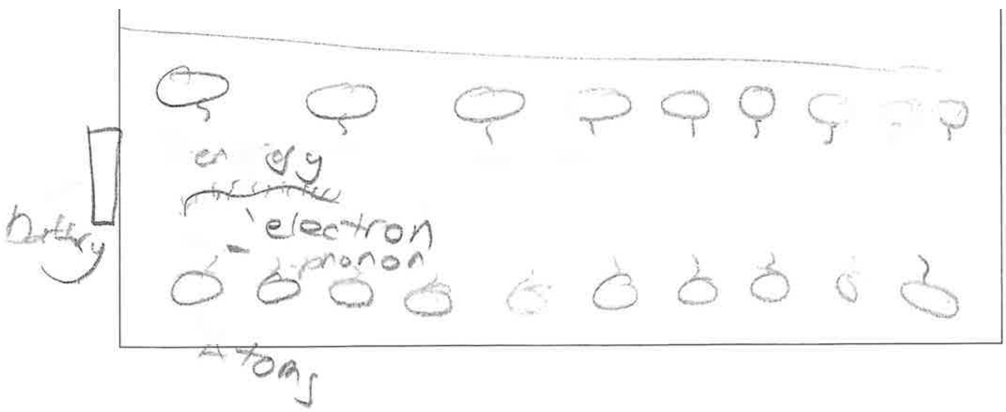


Figure 5. Image drawn in worksheet in response to the question, why do you think the LED gets dimmer the further it moves away from the battery? It depicts the electron

as a wave with a certain amount of energy and flowing through a circuit where it interacts with the phonons emanating from the atoms in the lattice. (Year 6 student)

Discussion

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 conceptualisation of how electricity and resistance work at the quantum level. Second, students, to varying extents, started to think critically about the increasing energy consumption of digital technologies and the implications this has for society.

Understanding quantum

Alongside students' increased understanding of electricity, conductors and insulators, the results strongly suggest that students can conceptualise the quantum nature of the atom, at least at a qualitative level. Students started to think about and attempt to articulate how electrons act like waves. While students depicted electrons as clouds and waves, we can only speculate about the level of student understanding that the electron's position is based on probability rather than existing only as a particle in a precise and measurable point in space. Based on answers to question 2 in the worksheet, most students understood that electrons (behaving as a wave) lose their energy as they flow through a circuit, with a large proportion of those students understanding that the energy was lost to the atomic lattice, which generates heat. They understood that this energy loss 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 they go 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

Some students, however, had the misconception that the electrons had to reach and pass the LED to transfer their energy to the LED and make it work. Some thought needs to be put into how to correct this.

Further, the additional student comments and images in worksheets 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 that enables the electrons to flow through a circuit, and the flow is enabled by the electrons being repelled from the negative end of the battery and attracted to the positive end.

In summary, the data shows that primary students can conceptualise 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.

Critical thinking

Compared to other themes in the post-brainstorm activity, few responses indicated students' critical thinking about quantum technologies and electricity. The comments that suggest critical thought are largely about making materials or finding technologies that use less energy or have no resistance. One student made the connection between low energy electronics and climate change.

> FLEET making materials that save energy
>
> Better conductors = less wasted energy
>
> Making technology that will use less energy
>
> Making technology to stop climate change

In summary, students improved their literacy relevant to circuits and quantum physics. To different extents, students could think critically about the implications of digital technologies and their energy consumption of the research being done to help solve the problem. This outcome, however, was not as definitive as quantum literacy.

A broader, deeper understanding of physics as a career and discipline

This outcome was only properly evaluated when the John Monash School students participated in the Future Electronics elective. Evaluation of the elective quite definitively shows that students typically gained a new perception of physics and its value.

Public events Melbourne Knowledge Week 2021 and 2022, Sydney Science Trail 2023

Introduction

FLEET developed the interactive exhibits for public events to achieve the following outcomes:

- An appreciation/awareness of the purpose and value of FLEET research and physics generally.
- An increased public awareness of the increasing demand for and energy consumption of computation and its implications.
- Public thinking critically about the meaning and value of FLEET research.
- Primary and secondary students with a greater interest in and awareness and appreciation of physics
- FLEET researchers with improved communication skills and a greater understanding of audience values and perceptions of physics/FLEET research

Key findings

- The FLEET exhibit's visitor experience was overwhelmingly positive. Visitors learned a bit about physics and how it is applied to solve real-world problems.
- Visitors gained an awareness and appreciation for the purpose and value of FLEET's research. Their initial awareness of FLEET's research problem was typically low or non-existent.
- Visitors thought critically about FLEET's research and research problem and what constitutes public good outcomes for this research.
- People emphasise two different approaches to solving FLEET's research problem: a perception that technology will be the key driver in solving the problem and cultural or socially focused solutions.
- All visitors desired a sustainable and socially responsible digital future.
- FLEET outreach volunteers developed skills in communicating complex science to diverse non-scientific audiences. They gained a new perspective and understanding of the public as an audience, realising that this is an equally crucial skill and one that enables more effective communication. They saw value in communicating with the public and the skills they gained from the experience.

Method

A pre-evaluation survey, exit survey, mind maps and observation were used to collect data for these events. Thematic analysis of the data was used to understand whether we achieved the above objectives of raising awareness of FLEET's research and research problem and to get the public to think critically about the value of FLEET research, its value and our problem of the unsustainable energy consumption of digital technologies. Some descriptive statistical analysis was done on the quantitative data from the surveys.

Pre-evaluation short survey

A one-question survey on a laminated A3 paper was placed on a visible wall. The public was asked to contribute to the survey upon entry to the exhibit and before any engagement. Using a 5-point Likert scale to assess awareness, the public was asked to indicate their level of awareness of the following statement:

The demand for computation is increasing by 70% each year. Digital technologies use about 10% of global energy, doubling every decade.

In the 2021 Melbourne Knowledge Week (MKW) event, the following additional 5-point Likert scale question was asked, which was dropped for the following Melbourne Knowledge Week and Sydney Science Trail (SST) events because it was considered to not contribute anything of value to understanding the event's impact relative to our objectives.

2021 Melbourne Knowledge Week extra pre-evaluation survey question: What is your level of concern about the facts in this (above) statement?

Mind map

One of the post-evaluation activities asked the public to contribute to a mind map. At the first Melbourne Knowledge Week and Sydney Science Trail, this involved large sheets of Butchers paper on a wall.

At the 2022 Melbourne Knowledge Week, we took advantage of the glass walls enclosing our exhibit booth and used coloured paint pens to create the mind map directly on the wall. See Figure 6.

The mind maps at all three events contained the prompt: Digital technology uses lots of energy.

Following visitor engagement with FLEET volunteers, where the public had an opportunity to interact with the demonstrations, such as the levitating superconductor and converse with FLEET volunteers about our research and the research problem we are trying to solve, visitors were asked to contribute their thoughts to the mind map. Visitors were simply asked what the statement, Digital technology uses lots of energy, meant to them. The public's contribution to the mind map allowed them to reflect and think critically about their engagement with FLEET and then record this on the map.

Figure 6. A mind map was created with paint pens on the glass wall. Melbourne Knowledge Week 2022

Observation notes

Observation notes were also made on some of the more interesting conversations or points that were being raised continually by members of the public. Data from these notes is integrated into the analysis of the mind map data.

Exit survey

As visitors exited the exhibit, an online exit survey was conducted to understand further visitor perception of FLEET research, the research problem and how they interpreted their engagement with the FLEET exhibit. The selection of participants was random and based on a FLEET member being free to alert people leaving the exhibit of the survey and encouraging them to complete it. The survey was online and available to complete upon leaving using a FLEET laptop. Visitors could also take a QR code with them and complete it at a later point in time. The survey questions were refined slightly with each event to improve the rigour. This limits the ability to compare all data. Question 2 is the only question examined from all three exit surveys. Question 6 from MKW 2022 was dropped from the SST survey because it was considered a 'Dorothy Dicks' question, and again, it did not add any value to understanding the impact relative to our objectives. It is not examined in this report. Questions 6 and 7 from SST 2023 are also not examined in this report, as there are no comparable questions from MKW 2022. All questions used for the Melbourne Knowledge Week and Sydney Science Trail events are listed below for reference.

Exit survey questions

2021 Melbourne Knowledge Week (MKW)

1. Write one new/interesting thing I learned from this experience with FLEET today.
2. On a scale of 1 - 5, How has your appreciation and awareness of physics changed after your time with FLEET?
3. Only if you want to. Provide other comments about your engagement with FLEET

2022 Melbourne Knowledge Week

1. Participant's age
2. Write one interesting thing you remember from your experience with FLEET.

The demand for computation is increasing by 70% each year. Digital technologies use about 10% of global energy, doubling every decade. In the context of this problem, indicate your level of agreement/disagreement with the following statements:

3. My experience today has changed my understanding of society's use of digital technology
4. Low-energy technologies are unlikely to make a difference in the lives of ordinary people
5. I am unconcerned because there is always a technological solution to problems, such as the energy consumption of digital technologies
6. Public money spent on research that could reduce the energy used in digital technologies is well worth spending

Sydney Science Trail 2023 (SST)

1. Participant's age
2. Write one interesting thing you remember from your experience with FLEET.

The demand for computation is increasing by 70% each year. Digital technologies use about 10% of global energy, doubling every decade. In the context of this problem, indicate your level of agreement/disagreement with the following statements:

3. My experience today has changed my understanding of society's use of digital technology
4. Low-energy technologies are unlikely to make a difference in the lives of ordinary people
5. I am unconcerned because there is always a technological solution to problems, such as the energy consumption of digital technologies
6. My awareness of the applications of quantum physics has increased
7. What three words would you use to describe this experience with FLEET?

Results from the pre-evaluation survey, mind map, observation and comparable exit survey questions are presented next.

Results

Pre-survey. Level of awareness (N=167)

There was a low level of public awareness about the facts in the statement, The demand for computation is increasing 70% yearly. Digital technologies use about 10% of global energy, doubling every decade.

From a sample of 167 people, 60% of the public were either completely unaware or only slightly aware that digital technologies consume so much energy. Only 19% considered themselves extremely or moderately aware. See Table 3 and Figure 7.

Table 3. Combined MKW/SST data pre-survey data from the question to assess public awareness of the facts in the statement, The demand for computation is increasing 70% each year. Digital technologies use about 10% of global energy and this figure is doubling every decade.

Not at all aware	Slightly aware	Somewhat aware	Moderately aware	Extremely aware	No opinion
51	50	32	22	10	2

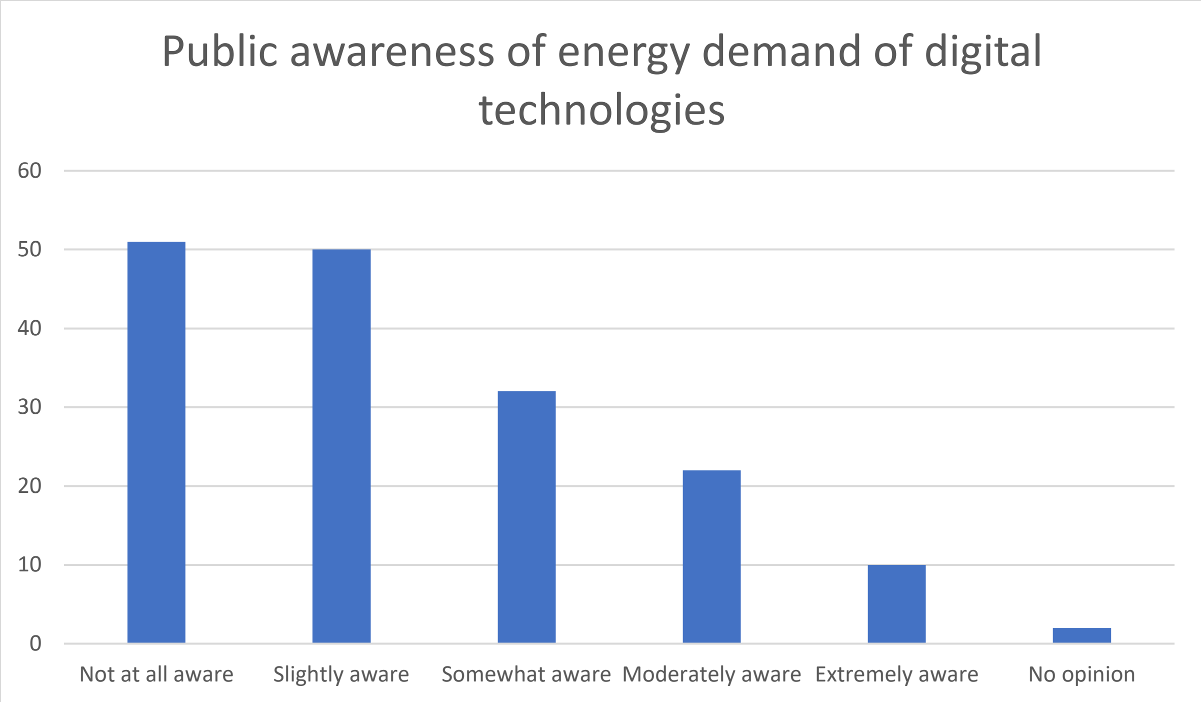


Figure 7. Outcomes from pre-entry survey to assess public awareness about facts in the following statement: The demand for computation is increasing 70% each year. Digital technologies use about 10% of global energy and this figure is doubling every decade.

Mind maps

The mind map was used to encourage critical thinking about the value of FLEET's research and its research problem: the unsustainable energy use of digital technologies.

While there were minor differences in themes between each event evaluated for this report, four core themes emerged from the combined data underpinning the overwhelming desired outcome for participants: a recognised need for a sustainable digital future. The different themes reflected different views on the means to achieve this sustainable digital future motivated by different concerns, hopes, and values.

The four core themes to emerge and that are examined in more detail below are the following:

- Rethinking digi tech values
- Environmental, social and governance (ESG)
- Research and Development (R&D)
- Dialogue

Consistent among all themes was critical thought about the value of FLEET (or similar) research and the means to achieve a sustainable digital future.

The themes and their relationships are modelled in Figure 8. Public quotes below that are in square brackets are observation comments noted in our record book. Other comments are from the mind map.

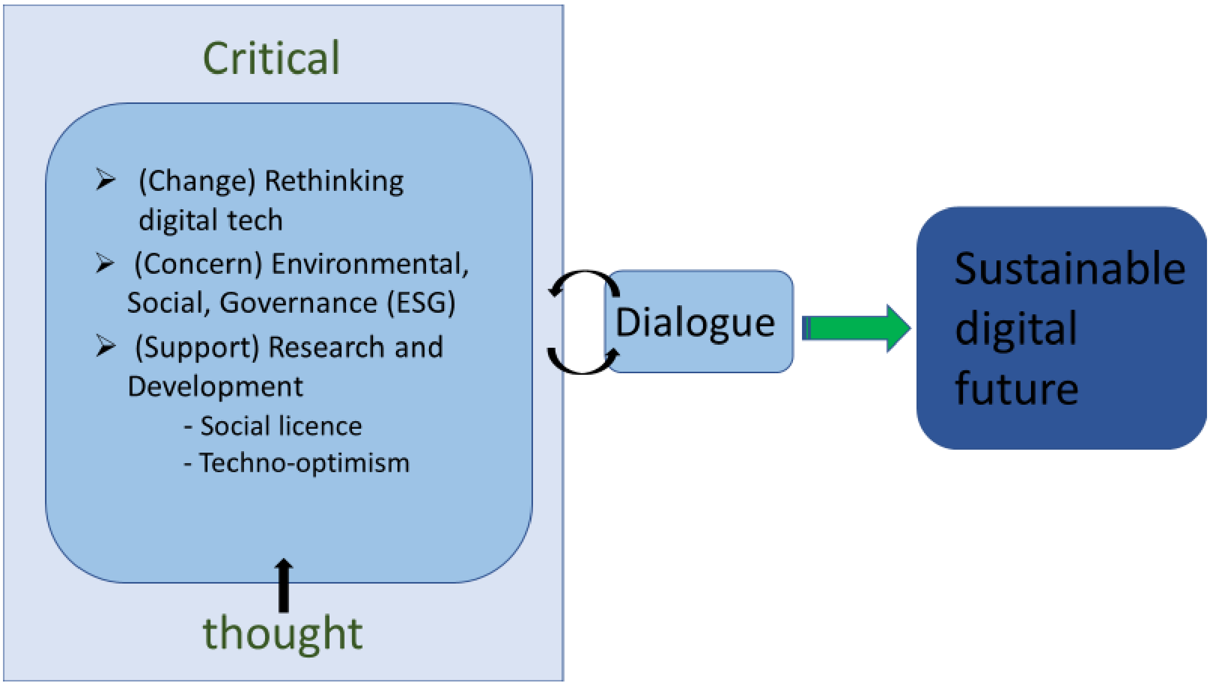


Figure 8. Thematic modelling of the core themes to emerge from the mind map and observational data from Melbourne Knowledge Week (2021-22) and the Sydney Science Trail (2023).

Theme: Rethinking digi tech values

This theme conceptualises the public's perception of a need for change: change in how we value digital technology and a consequent need for behaviour change; a need to change the standard economic models that focus on growth; and change to how we make decisions to enable a more sustainable digital future.

> It is important [but] you do not really need it to survive.
>
> Technology isn't necessary for survival.
>
> Degrowth and development of systems with longevity
>
> New economic models
>
> Just use what you need to survive – nothing else
>
> More 'green' political decisions
>
> We need to sacrifice convenience and achieve change in behaviour.
>
> Digi-tech is a great innovation but we use too much. Do we really need all this? What is really essential. Digi-watches that monitor our health and dial 000 are essential.

Theme. Environment, Social, Governance (ESG)

This theme reflects concern about what we do and how we do it regarding the environmental, social and governance (ESG) aspects of developing a sustainable digital future. The overall concern was a need for responsible innovation and the requirement for a social licence to operate that included the ethical and sustainable sourcing of the material needed for the technologies, control (for example, AI and data privacy), and equitable access to technologies, with the latter being a dominant concern.

> At what cost – have we got the balance right (cost/benefit)?
>
> [It is also the minorities and marginalised affected negatively.]

> …who has access? If malicious actors take control, then what?
>
> What do we have to mine to make the digital technologies?
>
> - not just the battery, but all components
>
> How much is my job affecting the environment?
>
> Social license, social inequity
>
> Concerned about slavery in supply chain/mining of materials
>
> Coded bias - AI and racial discrimination. Lack of representation
>
> Greater sustainability, less mining, more even society
>
> Innovation forward and negative impact backwards

Or this recollection from a FLEET volunteer and their conversation with a member of the public.

> [One memorable chat I had was about whether technology was 'natural' or not, and whether we should be sacrificing some of the convenience technology brings, to try and lower the amount of energy we require. Because we don't need the technology to live and the further it advances the more energy it demands. The conversation progressed to contemplating human nature, whether people would make these sacrifices, and how we could limit people's access to technology without impinging on their human rights. As for whether technology is natural or not, we discussed that the smart human brain was able to develop technology, so is that not a natural consequence of our crazy natural human brain? If our brains were able to develop technology, hopefully they are clever enough to also figure out how to solve the energy problems that arise from it.]

Theme. Research and Development (R&D)

Three sub-themes emerged from the data to describe general support for research and development of low-energy electronics. There was general support for FLEET research (or any research aiming to develop low-energy electronics), but some people attached ESG-related caveats to that support. A third theme reflects a proportion of people who, while typically maintaining some level of concern about the problem, possess an optimism that technology will solve the problem. The three sub-themes are examined below.

Sub-theme: Support for FLEET research: Overall, there was support for the type of research FLEET is doing to develop low-energy electronics. Such research is considered an important investment, and international collaborations are needed. One comment was that public demand will outpace any policy and that it will be the private sector that will finance and lead the research in this space.

> Discovery. Bringing new technology for material used with saving energy
>
> Investment and support in research
>
> Increased use of technology can reduce fossil energy use
>
> Increase efficiency
>
> [We need to] find more efficient process such as coding that requires fewer computations.
>
> I think the idea [energy efficient electronics] is very useful and we must save lots of energy.

While there were a couple of comments that reflected a concern about our economic models and a need to change this, there were also participants (two of whom identified themselves as economists) who raised questions about the cost of not doing the research and how we value the investment. Similar support came in the form of a critical economic analysis and return on investment in this research.

> [What is the opportunity cost if we don't do this (FLEET) research and someone else discovers it? Even if someone else discovers it first, if we have the local expertise, we have the base for local production. But if we don't have the local expertise, we will have to import everything.]

> [How do we measure the value of innovation investment, eg patents, the value of jobs, etc?.]

> I think the idea [making digi-tech use less energy] is very good.

Sub-theme: Support with caveats: While there was optimism and interest in FLEET research and support was positive, it was for many participants, provisional on the social and environmental implications of the research. FLEET's research should be transparent and open to scrutiny, provide benefits and do no harm, be socially equitable, and maintain or improve lifestyles without compromising the environment. This applied to FLEET's research and the technologies it might be applied to. This included using more renewable energy or researching novel technologies such as using the waste heat from computing as an energy source. Nuclear was also a definitive option for one person. The following comments were attached to support for the research.

> Greater sustainability, less mining, more even society

> Environment-friendly society without compromised lifestyle

> Open access and duplication of effort

> Innovation forward and negative impact backwards

> Data Centres
> -Need for green surplus renewable energy

Sub-theme: Techno-optimists: While not as apparent or dominant as other themes, the techno-optimists appeared at all three events. It was most prominent in the data from the Sydney Science Trail, which may reflect the greater number of secondary students who visited FLEET's exhibit compared to the two Melbourne Knowledge Week events. That is, FLEET's experience in workshops with secondary students has found their first response to solutions to solve FLEET's research problem is a technical fix. See two student comments below.

> Can we collect the wasted energy, the heat?

> I believe that digital tech will outrun the production of energy and we will need energy efficient materials to conserve energy.

The theme generally reflects people's optimism that technology will find a solution to the unsustainable energy use of digital technologies, a perception that as an individual I do not need to make any change because research and technology will solve our problems.

While positive about FLEET research, one member of the public with an engineering background saw greater potential in how we can use renewables in energy production. They could not see humans changing their behaviour regarding their digital requirements. A second individual saw this increasing computational demand as an opportunity rather than a problem. While concerned about the energy consumption of computation, they were optimistic about the ability of research to find solutions and that the 'problem' was a driver of innovation and solutions.

Theme. Dialogue

Greater dialogue is connected to all the above three themes. There was a perception that dialogue was necessary to facilitate greater awareness and reflection on this issue. Others perceived a need to change the discourse to how we negotiate our growing reliance on digital data. That is, participants thought that the public appeared to be fixated on all the potential benefits and scary things that can result from digitalisation and greater computing power (e.g., AI, driverless cars) without understanding or being aware of the issues that underpinned the narrative FLEET presented about the technology's unsustainable energy consumption. This was one of their rationales for greater community discussion. As noted, there was a relatively low initial awareness of the increasing energy demand for computation and the associated costs, which prompted some comments that this needs to be discussed at a societal level.

> Advancement of knowledge. Awareness of connectivity use
>
> Community discussion re: ICT, ethics and development roadmap
>
> Teach young people about strategies for developing renewable energy

Critical thought

A large proportion of the mind map and observational comments are examples of critical thought about the value of the research (How do we measure the value of innovation investment, e.g., patents, the value of jobs, etc.) and the means to achieve a sustainable digital future (At what cost? Have we got the balance right—cost/benefit?).

Exit survey

The following are the combined responses from the Melbourne Knowledge Week (2021, 2022) and Sydney Science Trail (2023) exit surveys. For this report, we have not considered the age range, which was question 1. There were 40 exit survey responses from the three public events.

Survey question 2: Write one interesting thing you learned from your experience with FLEET?

The following four themes emerged from this question:

- Valuing research effort
- Learning physics
- ESG concerns
- Critical thought

Each theme is examined in more detail below

Theme: Valuing research effort

Reflecting on the mind map sub-theme, R&D support, respondents' comments were indicative that people recognised and placed some value on the scientific efforts to develop technology that could improve the energy efficiency of digital technologies. This perception extended to the potential of FLEET to help solve the increasing computational demand and energy consumption issue, and that such research had social benefits.

> The possibility of no resistance currents for operating tech in the future
>
> Topological conductors, and about other areas of research that are currently being undertaken in the energy conservation space.
>
> I am glad to hear about the research being done…
>
> [Recalling] the need for low energy electronics
>
> [Recalling] importance of quantum physics for more sustainable future
>
> Amazing potential new material can save power

Theme: Learning physics
Respondents noted as their 'interesting thing' that they had learned something about physics, and that it was a thought-provoking and engaging experience. For instance, participants recalled learning about topological insulators, electrical resistance, electricity, 2D materials and that resistance = heat.

> I learnt why our computers and phone heat up.
>
> [You] demonstrated what lightning (electricity) is for my children aged 7 and 5. It helped my earlier explanation of the difference between coal and green energy is. Very enjoyable and well explained demo.
>
> Didn't know graphene was one atom thick
>
> Bismuth Ferrite is a promising material for low energy electrics.
>
> The more efficient my technology parts get, the less cooling my PC needs.
>
> The presentation was excellent and the talk was fantastic. They really connected with my students found where they were at and continued on to their learning.

Theme: ESG - concerns
There were two sub-themes here: Environmental – computational energy demand, and social concerns about responsible innovation. Most responses under this theme reflect a recognition and concern for the amount of energy used by digital technologies.
Environmental - Computational energy demand: Respondents became aware for the first time of the increasing demand for computation and the associated energy requirements.

> We won't be able to support our energy demands for our devices in 10 years at the current rate the demand is growing.
>
> [recalling] how quickly the demand for electricity from computers will exceed our capacity to produce it.
>
> [unaware of] the amount of computing power being used
>
> A lot of coal is burnt for electricity" [Child less than 12 years old]
>
> We are pretty much at the limit of data storage with silicon - it is time to spin
>
> How the use of more efficient conductors can help solve the power crisis.

Social concerns – responsible innovation: There was only one response under this theme, but it reflects mind map and observational comments that suggest any research needs to be considered alongside its potential social cost.

> New materials will minimise energy use on digital tech but will still come at a cost (socially, environmentally)

Theme: Critical thought
This theme reflects how FLEET's engagement made the participants think critically, from a global perspective, about a problem they were either unaware of (which was most people) or had not considered in any depth before. Again, the responses reflect comments in the mind maps and observations where respondents largely thought critically about the social and environmental implications of the research and technologies resulting from that research, as well as about the potential solutions to these problems.

> The problems facing our planet in terms of energy consumption.
>
> New materials will minimise energy use in digital tech, but they will still come at a cost (socially and environmentally).

> The possibility of no resistance currents for operating tech in the future.
>
> How the use of more efficient conductors can help solve the power crisis
>
> In 10 years, we won't have enough power to meet the demand for computational energy - food for thought, how we consume and use computers, etc.
>
> Energy loss and thinking about research and innovation on new materials to help with reducing [energy loss].

There was some evidence of respondents critically reflecting on how their own behaviour or computational needs contributed to the problem of demand and energy use, which was something they had not previously considered.

> I never thought of the computation-electricity demand problem and how closely related it is to my technology needs. It is definitely an eye-opener.

A visual artist had similar thoughts. They worked in Virtual Reality and thought they did some "cool stuff", but until now had not considered the consequences of their own work's high computational demand, a demand that they acknowledged was only increasing. They now realized their footprint was "massive" and this concerned them.

A second individual worked in a data centre where their role was to "get more and more people to use the cloud". Until their engagement with FLEET, they had only vaguely thought about the implications of this and the impact their role had on social and environmental sustainability.

Survey question 3. My experience today has changed my understanding about society's use of digital technology

There was strong agreement among the survey respondents that their experience with FLEET changed their understanding of how society uses digital technology, with 32 of the 40 responding that they either strongly agree or agree that their understanding was changed. See Figure 9.

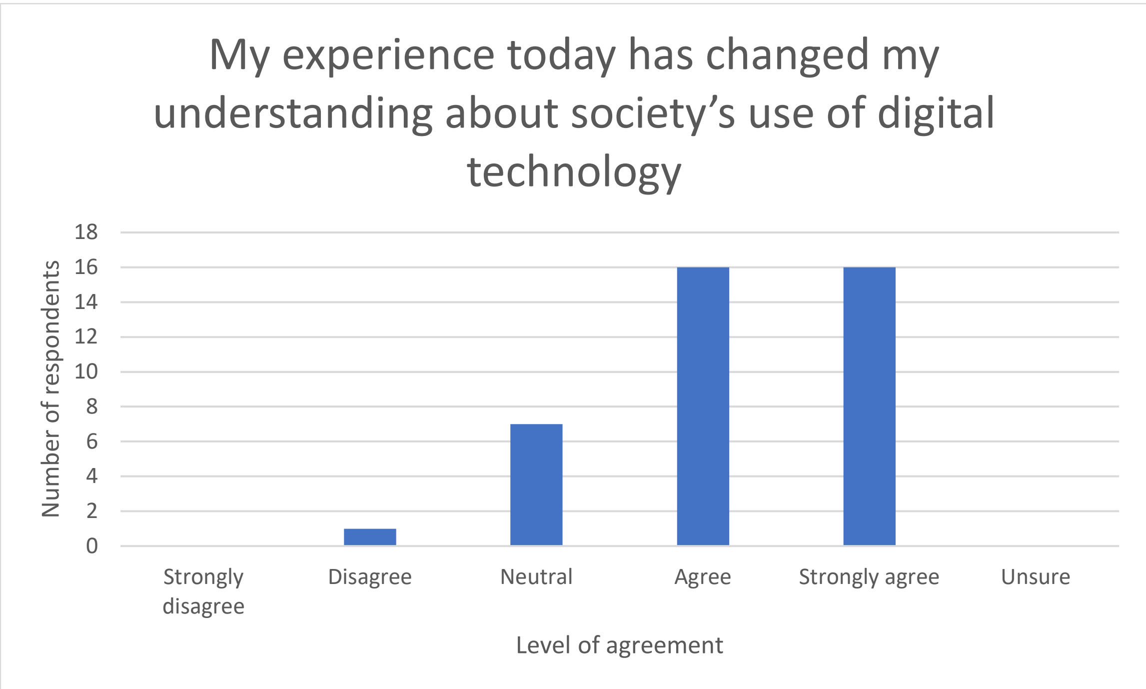


Figure 9. Exit survey response from Melbourne Knowledge Week (2021-22) and Sydney Science Trail (2023). Respondents' level of agreement with statement, My experience today has changed my understanding about society's use of digital technology.

Survey question 4. Low-energy technologies are unlikely to make a difference to the lives of ordinary people

The majority (70%) of respondents to this question think that low-energy technologies will have some impact on their lives. However, 18% still thought that such digital technologies are unlikely to make a difference to their lives. See Figure 10.

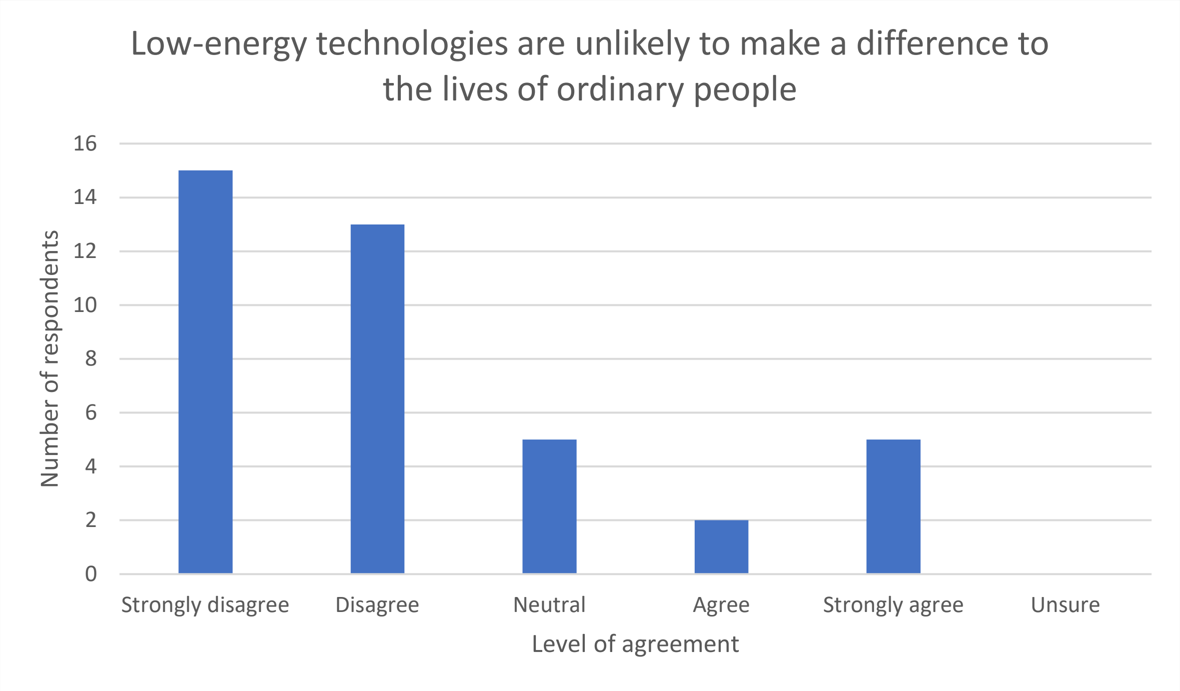


Figure 10. Exit survey response from Melbourne Knowledge Week (2022) and Sydney Science Trail (2023). Respondents' level of agreement with the statement, Low-energy technologies are unlikely to make a difference in the lives of ordinary people

Survey question 5. I am unconcerned because there is always a technological solution to problems such as the energy consumption of digital technologies

While there is some spread across the levels of agreement suggesting diverse views, the majority (65%) of respondents disagree with the idea there is always a technological solution to problems such as the energy consumption of digital tech, which suggests they believe we cannot rely entirely on science to fix such problems. This reflects discussions and commentary that social solutions must be considered alongside technical ones. It also reflects the small but significant number of mind map and observation comments from people who were optimistic about the ability of technology to find a solution.

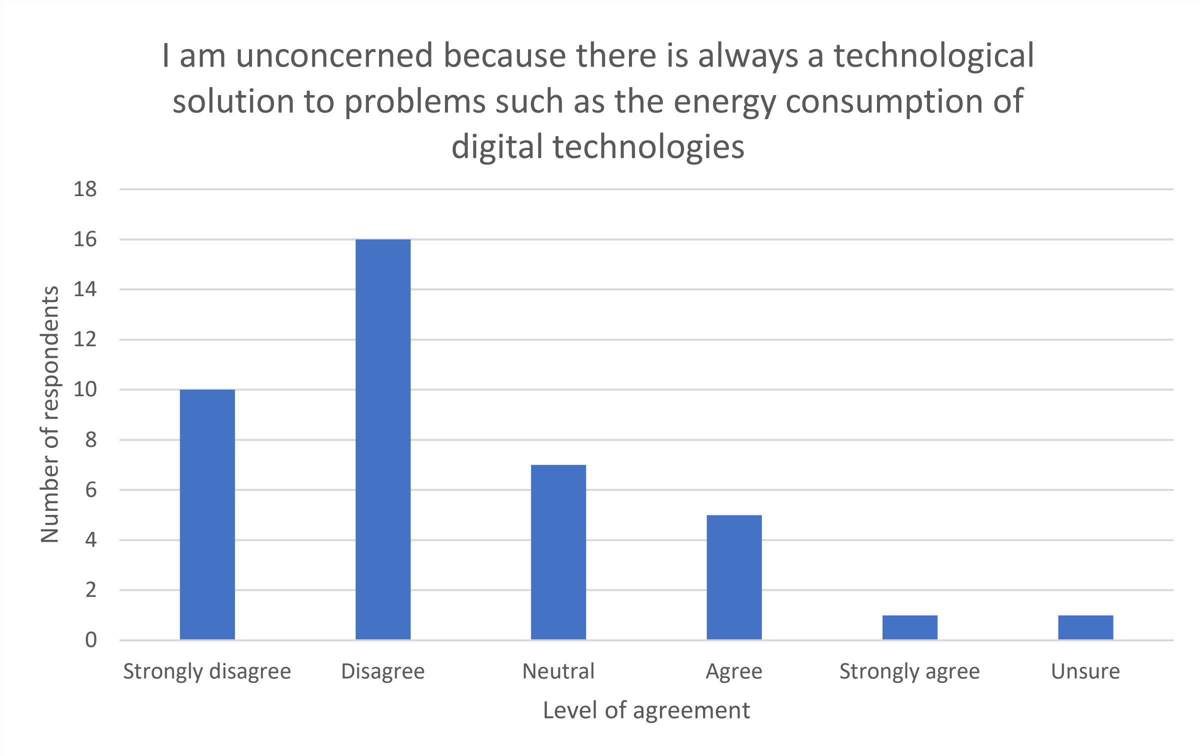


Figure 11. Exit survey responses from Melbourne Knowledge Week (2021-22) and Sydney Science Trail (2023). Assessment of the level of agreement to the statement, I am unconcerned because there is always a technical solution to problems such as the energy consumption of digital technologies.

FLEET volunteer impact

FLEET had up to 12 volunteers helping during any of the three events evaluated in this report.

FLEET's objective for volunteers conducting outreach is to improve researchers' communication skills, including understanding audience values and their perceptions of physics/FLEET research.

To help understand the volunteers' experience and the impact relative to the above objective, FLEET asked their thoughts on the open-ended questions below.

Volunteer survey questions

1. In terms of the value you got from volunteering at [event], can you tell me about your experience?

2. How did volunteering at [event] contribute to your skill set as a scientist?

3. What did you learn about the public's perspective on FLEET or your own research?

4. How, if at all, did this awareness of the public's perception of FLEET/your research make you think about the role of communication/engagement and how you communicate to others outside your area of research expertise?

Their responses to the above questions were thematically analysed and presented below. The following three core themes emerged from their responses:

- Understanding the public
- Enjoying Conversations, connecting
- Sci Comm skills

Themes

Understanding the public

This theme is based on volunteers getting a new and broader understanding of how the public perceives their research, which helped them reflect on and shift how they communicate their research to the public. Further, volunteers learned that although the public is largely unaware of and lacks an in-depth understanding of FLEET's science, they are actually interested in and appreciate the research. Two sub-themes, 'social perspective' and 'communication urgency', indicate specific aspects that volunteers learned about the public they engaged with that affected how they engaged with the public and their perceived value of public engagement. The following volunteers' survey responses below reflect this.

> I learned just how inaccessible our work can be to the general public sometimes, and how important it is to strip it back and talk about the overarching goal (devices that use less energy). People don't really even know that research centres like FLEET exist.
>
> … people are quite interested in what we do, in spite of their knowledge being in general very limited.

Sub-theme: Social perspective: Volunteers learned that the public can perceive their research and its value differently from how they themselves perceive it. They learned they have to put their research into a social context to more effectively engage the public because the public typically puts greater emphasis on the implications of their science than on the science itself. To some extent, this forced volunteers to reflect on what that might mean for how volunteers communicate in outreach, but it possibly gave them a different perspective on their own research.

> [Volunteering] also helped me view my research from a different, broader perspective. People bring up relevant social aspect issues about our research that I don't usually consider.
>
> Most people are not really aware of our general motivation, the energy crisis brought on by IT. When made aware, they usually are supportive of our research. But they are also concerned about the ethics and sustainability of our proposed solutions. A lot of people had a basic understanding of electricity from high school but did not realise how it relates to the energy problem.
>
> I was somewhat surprised by the concern people had for computer energy consumption. It's generally not broadly advertised, but it seems this issue resonates with many people.
>
> I think the thing that stuck with me the most is that I've never actually thought about the source of the materials we use, and the environmental and societal impact of mining those materials. It's easy to focus only on the research questions and not realise what other people (stakeholders) are concerned about…

Sub-theme: Communication urgency: Volunteers learned that their audience was largely unaware of FLEET's research problem and that to garner social licence for their research, they perceived an urgent need to engage the public more effectively and frequently.

> We still need to do more to communicate the energy problem better. Everybody is aware of the climate change crisis, but a lot of people don't know the wide range of research being done to help solve the problem outside of green energy. People can't be supportive if they don't know we exist.
>
> We get so caught up in getting the work done that we forget that our work is supposed to impact the world in some way, and for people to care about that we need to be able to communicate our work to the general public.

Enjoying Conversations, connecting

This theme contains two components: a volunteer's joy in engaging and connecting with interested members of the public about their research and the fact that such conversations enable them to reconnect with the reasons they do science and reinforce the value of their work.

> I found particular value in meeting people from very different backgrounds (government workers, teachers, business people etc.) and from different age groups. I found it useful in learning to listen to what people are asking and having a conversation at a level they are comfortable with.
>
> I enjoyed speaking with the people that stopped by, both the kids and their parents.
>
> Volunteering for MKW or outreach in general helps renew my passion in science, seeing the excitement and wonder that people have towards science reduces the feeling of being burnt out that the PhD process brings.
>
> Seeing other people's interest in our work helps remind me of why I'm doing this research and keeps my passion in science alive.

Sci Comm skills

Volunteers appreciated and acknowledged the opportunity to develop skills in communicating complex science to the non-scientist.

> …The questions they [public] asked definitely helped me think about how I can engage with the public in a way that resonates with their interests.
>
> It was definitely beneficial for my scientific communication skills, having to communicate my research / physics concepts to different levels. But I also found it useful to revisit some more 'basic' scientific concepts which I don't work with regularly. We get so used to doing the same thing every day in our research, I sometimes forget the basics I learned in undergrad.
>
> It helped improve my communication skills, specifically in terms of communicating with the general public. It also helped refresh my knowledge and understanding of general physics, as demonstrating and explaining basic physics principles outside of my research required me to remember and understand things I learned in undergrad or high school but can't say I really understood.
>
> Working at Melbourne Knowledge Week has made me realize I still need to practice a lot, though there were a lot of questions from the public that were more technical than I expected.
>
> What I learnt is that sometimes it's fine to just straight up leave out information if it helps get the message across. You don't have to explain the entirety of something for someone to get to grips with why it's useful/important in the wider scope.

Outreach impact for volunteers

There was a strong alignment in the themes that emerged from the volunteer responses across the three events. Together, the data suggests that volunteers get a new perspective and understanding of the diverse public audiences they are communicating with. Volunteers were confronted by a public who often placed meaning and value on FLEET research that was unexpected or that volunteers had not previously considered. Alongside developing the skills to communicate complex science to a non-scientific audience, FLEET volunteers began to understand their audience – their values, worldviews, how they interpreted their research, what value they placed on it, and why. Understanding your audience is an equally crucial skill that enables more effective communication.

This, along with their enjoyment of connecting with their audience about their research, reinforced the value of communicating with the public and that their research has value and meaning.

Discussion

The visitor experience of the FLEET exhibit was overwhelmingly positive. Visitors learned a bit about physics (even quantum physics) and how it is applied to solve real-world problems. They gained an awareness and appreciation for the purpose and value of FLEET's research and thought critically about FLEET's research and research problem.

The strong socio-cultural means to achieve a sustainable digital future raised by the public, which includes, to some extent, students, reflects a broader conceptualisation of public good than the narrow economic national security lens outlined in Australia's quantum strategy.

New Awareness

Before they engaged with FLEET, most people had minimal or no awareness of the problem regarding the unsustainable energy consumption of digital technology. Their experience with the FLEET exhibit had a strong impact on their awareness and, indeed, understanding of society's use of digital technology and the potential implications of this use. The mind map data and exit survey data indicate that visitors used this new awareness and understanding to think critically about the value of FLEET's research and research problem.

Critical thought and the goal of a socially responsible digital future

While in principle people supported and valued FLEET and similar research they raised questions and concerns about the means of how we might achieve the goal of a sustainable digital future. Participants had environmental, social and governance concerns relevant to the research and potential applications of that research, and they questioned how they themselves and society valued digital technologies and our increasing reliance on it.

People put emphasis on two different approaches to solving this problem: a perception that technology will be the key driver in a solution to the problem and cultural or socially focused solutions, with the majority of people putting greater emphasis on the latter.

The tech-fix approach included developing and implementing low-energy electronics but also greater use of renewable energy sources. The cultural approach involved a shift in how we value digital technology. People questioned what digital technologies have a socially responsible function and what were potentially frivolous desires. The emphasis for this approach was to consider what digital technologies we could do without to reduce energy consumption and ensure a shift toward a more socially responsible digital future. There was also a strong concern about the source and use of the materials that enabled low-energy electronics. Any innovation in this space will need a social license to operate.

The exit survey data supports this dichotomy to some extent. Survey respondents showed mixed levels of agreement regarding the ability of a technical solution to solve a problem. While most people did think that low-energy tech would make a difference, there was still some level of disagreement with this statement.

Both approaches aimed for a sustainable and socially responsible digital future. Each person reiterated that reducing digital technology's energy consumption was necessary, and the solution must be sustainable. People just placed different emphases on the acceptable means to achieve that goal.

FLEET volunteering

FLEET Volunteers gained a new perspective and understanding of the public as an audience, which enabled them to become more effective communicators. They saw value in communicating with the public. There was reinforcement that their research has value and meaning, and all volunteers who responded reported that such experiences improved their communication skills, skills they placed a high value on.

Outreach impact - overview

This section examines whether FLEET has achieved its outreach objectives for its two key audiences: school students and the general public.

Objectives

The goals for students were improved science literacy, a broader and deeper understanding of physics as a career and discipline, and the ability to think critically about FLEET's research, its value, and our problem of the unsustainable energy consumption of digital technologies. For the public, it was improved awareness of FLEET research and the research problem and the same critical thinking outcomes as students.

Students

Our comparison of pre-and post-evaluation data consistently showed a shift in how students perceived and understood the core topics they were introduced to, including quantum physics, which was indicative of improved science literacy. The data for critical thinking was not as strong, but it was clear that a significant proportion of the students did think critically about the unsustainable energy consumption of digital technologies, the implications of FLEET research and potential ways to solve the problem.

See the separate report on the impact of the John Monash Science School-FLEET future electronics unit, which examines the effect of the unit on students' understanding of physics as a career and discipline.

Public

It is apparent that the public who engaged with FLEET at outreach events has become more aware of digital technologies' unsustainable energy consumption and has begun to think critically about this problem and what constitutes public good outcomes to achieve a sustainable digital future.

The public evaluation emphasises the varied lenses through which we perceive science and our different relationships with science, which in turn reflects the different conceptualisations of what constitutes public good, a conceptualisation that, except for a couple of economists that visited FLEET's exhibit, appears to be in contrast to the goals in Australia's National Quantum Strategy. Continued engagement and dialogue about the increasing energy consumption of digital technology is crucial because of the identified low public awareness and because once the public becomes aware, there is a strong call for effective dialogue about acceptable ways to solve this problem.

Further, to ensure there is social license for any quantum-based research, any public dialogue should aim to build trust and help understand the different interpretations of public good and what are acceptable directions and outcomes of any research.

ARC research impacts

Part of the Australian Research Council's Centre of Excellence final reporting requirements asks Centres of Excellence to show how they produce social and cultural benefits for the community. FLEET considers that they have produced impact through benefits to social-informed decision-making and a social-enhanced skill base.

The evaluation data in this report show that we have increased awareness of a social problem that FLEET's research is helping find solutions to. This awareness initiated critical thinking about their research and what constitutes public good outcomes. The public that FLEET engaged with now has the capacity to make informed decisions and engage in a critical dialogue to inform research direction and ensure acceptable solutions to a more sustainable digital future.

The experience of doing outreach has provided FLEET volunteers with a greater understanding of the research ecosystem, developed their communication skills and helped build motivated and confident science leaders with highly developed research and translation skills, deep insight into the value and social implications of their research, and their ability to have constructive dialogue about this with diverse audiences that will help build the social and cultural capital required for valued and trusted scientific research in Australia.

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