Light-Emitting Diode (LED) Module

Forefronts of Research Educational Modules (FOREM)

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Objective: Discover functional properties and physical characteristics of LEDs; explore the mechanisms behind these characteristics; learn about uses and advantages of LEDs.

The LED is a device that uses the junction between a p-type and n-type semiconductor (the p-n junction) to convert electric energy to light and back. A semiconductor is a material that behaves as an insulator at low temperatures and as a poor conductor (with relatively high resistance) at higher (room) temperatures. This special electric property is due to a structure in the energy of electrons in the material, in particular, an energy difference between valence and conduction electrons. While the details of this energy structure is only understood properly within quantum theory of solids and beyond the scope typical high school physics, we can see its effects and understand some of its features with simple hands-on activities using LEDs. This module of activities employs an inquiry-based mode of learning to introduce students to the basic function of LEDs, some of its properties, e.g. its nonlinear I-V curve, and its underlying physics. It also connects to foundational subjects of high school physics, such as energy conversion, and the history and practice of science exemplified by the invention of LEDs, as well as energy efficiencies of modern materials technology.

Conceptual Framework:

1. In a circuit, the LED passes the current only in one direction because its resistance depends on the direction it connects.
2. LEDs can act as a signal light; this was one of their earliest uses.
3. The resistance of LED depends on the voltage; the I-V curve is nonlinear. It is characterized by an onset voltage.
4. LED consists of a p-n junction between p-type and n-type semiconductors.
5. The brightness and color of the light produced by LED depends in a special way on temperature. This is the result of its p-n junction.
6. LED converts electric energy to light and back.
7. LED are many times more cost-effective and energy-efficient than incandescent light because they use less power, last longer, and can be made cheaply.

List of Activities and Material

<u>Class 1</u> (60 minutes)
Activity 0. Opening Discussion (10 minutes)
Activity 1A. Lighting an LED, compare to incandescent light (15 minutes)
Activity 1B. Testing the unidirectional characteristics of LED (35 minutes)

<u>Class 2</u> (60 minutes)
Activity 2. Doing things with LED: Traffic Light (15 minutes)
Activity 3. Measuring the LED I-V curve (45 minutes)

<u>Class 3</u> (60 minutes)
Activity 4A*. LED under a microscope (25 minutes) – or –
Activity 4B*. Temperature dependence of intensity and color of LED (25 minutes)
Activity 5. Energy conversion in LED (25 minutes)
Activity 6. Summary: LED efficiency (10 minutes)

<u>Home activities</u>
Home activity 1. History of LED
Home activity 2. Semiconductors
Home activity 3. LED technology

<u>Material and equipment needed</u>

- Various LED lights, such as small battery operated ones, as well as LED circuit elements with connectors, and with various colors (red, green, yellow);
- Incandescent light, a small size that can be submerged in a Styrofoam cup, as well as one that can be part of a circuit;
- 100 Ohm resistor;
- 3V battery packs;
- voltmeters;
- ammeters;
- three-way switch;
- variable resistor or resistor-ladder (need a range of voltages from -3 V to 3 V);
- magnifier;
- microscope;
- silicone or baby oil
- Styrofoam cups;
- hot water;
- water-ice mixture;
- dry ice;
- liquid nitrogen (may be skipped);
- tongs for holding;
- safety gloves and goggles

<u>Class 1</u>

60 minutes

Activity 0. Opening Discussion
Time: 10 minutes
Material: LED light.

1. Hold up an unlit LED and ask the class if they know what it is. They will probably not be able to recognize it in this form. You can give them a hint: a version of it won the 2014 Nobel prize in physics for its creators.
2. (After it is revealed that it is an LED:) where they may have seen or heard about them before? Some common uses: display screens, lights on their phones, TVs, Christmas lights, etc. They are everywhere including the ball drop in Times Square.
3. What does LED stand for? Light Emitting Diode, which leads to the first activity.

Activity 1A. Lighting an LED, compare to incandescent light
Time: 15 minutes
Material: red LED; incandescent light; 100 Ohm resistor; 3V battery pack; voltmeter.
<u>Challenge</u>: Light the LED!

Pose the challenge. Students should put the LED in a circuit with the resistor and the battery in an attempt to get it to light. Whether or not they are successful they should draw circuit diagrams and write out the details of their circuit. At this point, the teacher could use a temporary symbol for the LED in the circuit, such as –(LED)– or something similar. The groups that were not successful should discuss with those that were and compare their differences. Encourage the students to think through the following steps:

a) *Observe*: the LED is or is not lit;
b) *Communicate*: report the set up you used to your peers;
c) *Critique*: what differences are there between different setups?
d) *Conjecture*: what setup would light the LED?

After each group has successfully lit their LED, regroup and discuss. The objective here is to realize that the orientation of the LED will decide whether or not it will work. Ask the students to compare this with an incandescent light. They can do this from prior experience or by repeating the circuit with an incandescent light instead of the LED.

Conclusion: Unlike incandescent light, LED light only glows when connected to the DC power source in a certain direction. It will not glow in the opposite direction.

Activity 1B. Testing the unidirectional characteristics of LED
Time: 35 minutes
Material: two LEDs; 100 Ohm resistor; 3V battery pack.
<u>Challenge</u>: What causes an LED to only light when connected in a certain direction?

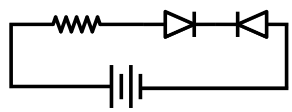
Pose the challenge. Collect ideas and conjectures. Two possibilities may be presented by the students (other possibilities might arise; collect all ideas and do not evaluate).

P1) Low resistance in one direction, and very high resistance in the other;

P2) Dependence on the direction of current.

Replace the temporary symbol for the LED with the standard one for a diode (–▷|–) showing the directionality of its function. Group students to discuss the possibilities. Ask: how can these ideas be tested?

Evaluate the proposed tests. Are they viable? Ask the students to communicate, critique, and conjecture ideas that might suggest a proposal to be right or wrong, based on prior knowledge. Participate and moderate the discussion. Use the board to facilitate the discussion. You may decide to pursue a test proposed by the students; ask them what material may be needed. If material is hard to obtain or not available at the moment, ask them to think about their proposals to pursue in the future. You may present the schematic below. What should happen if the LED is working on either mechanism?

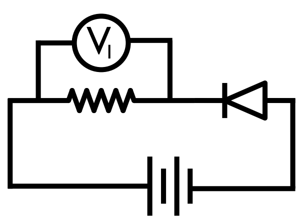


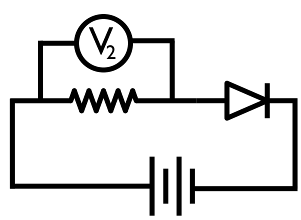
Note: In this circuit: if the resistance in one direction is higher than the other (P1), neither LED should light up because at least one of the LEDs will have a high resistance and will prevent current from flowing at all. However, if the lighting depends on the direction of the current (P2), one LED will light up and other will remain unlit since current will be flowing in the circuit.

Connect up the circuit as shown in the diagram and see which one lights.

Conclusion: One side has "infinite" (very large) resistance.

<u>Follow-up</u>: Using the circuit of the Activity 1A, attach a voltmeter to the resistor. Ask: How would the voltmeter readings compare if P1 is correct? How would they compare if P2 is correct? Can this be used as a test of these possibilities? Is our conclusion correct?





Note: If P1 is correct, the resistance in the two circuits must be different and voltmeter should show a different voltage drop across the resistor. If P2 is correct, however, the volatges must be the same.

Class 2

60 minutes

Activity 2. Doing things with LED: Traffic Light

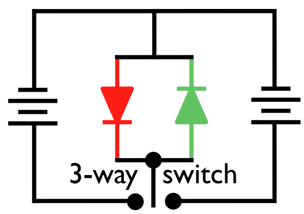
Time: 15 minutes

Material: red LED; green LED; two 3V battery packs; three-way switch.

Challenge: make a traffic light controlled by a switch.

Pose the challenge. Group students to come up with a design. They should record their designs using a circuit diagram. Ask: communicate and critique your designs with your peers. Test and reevaluate.

You may want to leave this activity open ended at this point and discuss it at the opening of the next class as a follow up. This would allow the students to continue thinking about the material beyond this class. Either at this point or the beginning of next class, you can present the following circuit design.



Activity 3. Measuring the LED I-V curve

Time: 45 minutes

Material: variable resistor or resistor-ladder (need to get a good range of voltages from -3 V to 3 V); LED (red, green); 3V battery pack; voltmeter; ammeter.

Challenge: What is the resistance of the LED?

Give a short recap of what was learned in the last class: we guessed and tested that the LED has a different resistance depending on the direction of current. Ask a question to pique the students' curiosity; for example: is it possible that the LED has a variable resistance in general? What could it depend on?

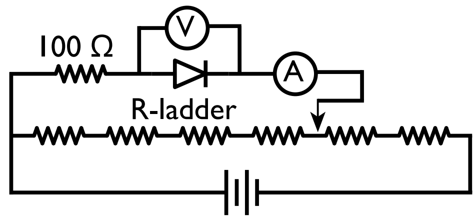
Pose the challenge.

Remind the students that we measure resistance as the ratio of changes in voltage to changes in current. So we need to measure what's called the "I-V curve" of the LED. Before getting started with the measurement, ask what this curve could be like. Group the students and ask them to make guesses for the shape of the I-V curve. Discuss these shapes. Compare to the I-V curve of a normal resistor (a simple line). This will be their *conjecture*.

Ask them to think about how they can measure the I-V curve. What do we need? Do we have the right material and equipment?

Through this discussion, the idea should emerge that we need to vary the voltage and measure the current through the LED or vice versa. Instead of stating this, try to moderate the discussion so the student can arrive at this. If they have already seen this before, refer them to previous knowledge.

One way to vary the voltage is to use a resistor-ladder in the following circuit.



The voltage across the LED branch of the circuit is the same as between points *a* and *b*. By moving these points to cross different number of resistors in the ladder we can divide the potential of the battery. This circuit is simple enough that some students might guess it or you may have already used it before. If not, you can present the circuit; but try to have a few minute of guesswork before presenting the final diagram.

At this point we have gone through communication, conjecture, and some critique to respond to the challenge. Ask the groups to perform the measurement, note down their results, make notes of the intensity of the color, and plot the I-V curve on (a graphing) paper. This may take some time because they need to take several data points. Allow enough time. You may want to divide the red and green LEDs among different groups to speed up the collection of data (some groups measure the red and some the green LED).

Question: What does the graph tell you?

From the graph you can see an asymmetrical I-V curve, meaning this is a non-ohmic device. What happens as the voltage increases in the direction matching the LED? How do the I-V curves for the green and red LEDs compare?

Students will make observations, communicate their results, and offer explanations. Note these explanations and discuss. Note that there is a turn-on voltage that is higher for green than red. We know voltage is related to energy. What happens at higher voltage? Does the color change? Does the brightness change?

Conclusion: there is a minimum voltage that is needed to light the LED, but if you apply more voltage we don't get a higher energy color, we just get more of the same color (higher intensity).

Follow-up: Color is related to the frequency of light. Voltage is related to energy, so having a minimum voltage for a given color is a relationship between energy and frequency. This is a result of quantum theory. The brightness, not its color, of light depends on how much power is given to the LED. Present this information. Ask what the students think the minimum voltage would be for a *blue* LED. More or less than the one for red and green?

The materials used in LEDs are semiconductors that have excess electrons (n-type) or a deficiency of electrons (p-type). The energy difference across a p-n junction produces the minimum voltage; the value depends on the material. The energy difference energy difference needed to create blue light was so difficult to find a material for that its discovery won a Nobel prize in 2014. This could be presented in class or assigned as home research (see below).

Class 3

60 minutes

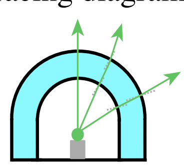
The focus of this class is two-fold: the underlying physics and structure inside the LED; and the energy function of LED. Depending on how much is available, one of activities 4A and 4B may be chosen. If there is more time, another class may be added to do all activities, as well as some of the previous follow-ups and home activities (see below).

Activity 4A*. LED under a microscope
Time: 25 minutes
Material: LED (with clear plastic); magnifier; microscope; water; silicone or baby oil.
Challenge: What does the LED look like inside?

Pose the challenge. Collect ideas how to look inside the LED. This can be done with the whole class as a conversation. Some students may observe by looking more closely at the LED that it is hard to see inside because of the plastic dome covering. Maybe a magnifier might help? What else? A microscope?

Group students so they can test which method works best to look inside the LED. After a few minutes, ask the groups to communicate their observations. The magnifier and the microscope would help, but there is still a challenge seeing clearly through the plastic dome. Why? Let students ask questions and conjecture ways to go ahead.

The difficulty is that the plastic dome distorts the path of light as it exits the covering. If geometric optics has been covered already, you can ask the students to think about the path of light rays. In any case, a ray-tracing diagram can help.



What can help? The clue here is the index of refraction of various parts. The more closely matched the index of refraction, the less the distortion in light ray paths. The index of refraction for the plastic covering is ~ 1.5. Submerging the dome in a liquid with a higher index of refraction can match the plastic dome and reduce distortion. Silicone or baby oil can help get a better view under the magnifier or microscope.

Ask the groups to record their observation and draw a sketch of the physical structure inside the LED. Compare to the structure in the incandescent light. Guiding question: In which part does the glow originate?

Conclusion: There is a sort of a junction inside the LED, sitting in a cone (this is a metallic reflector), and a glowing part on top.

Follow-up: What are the parts that make the junction? How is light produced in LED?

You can collect ideas/conjecture to answer these questions. Some may think the parts are metallic and light is produced by the hot metallic plates, similar to the incandescent light. If this is proposed, ask everyone to think and critique the idea. There are several reasons this may not be the case; for example, the resistance of the incandescent light increases with current as it gets hotter, while it decreases for the LED. A less technical reason is that LED lights consume much less energy and require much less currents to operate; at such low powers any metallic part won't get too hot to glow much. (This is of course why LEDs are much more efficient than incandescent lights.)

You can present the information about the material used in the LED again: p-n junctions of semiconductors. This was already mentioned in the Activity 3 and it is good to present it again.

Activity 4B*. Temperature dependence of intensity and color of LED

Time: 25 minutes

Material: Styrofoam cups; hot water; water-ice mixture; dry ice; liquid nitrogen; small LED light; small incandescent light; tongs for holding; safety gloves and goggles.

<u>Challenge</u>: How can we learn more about the physics of LEDs?

Pose the challenge. You may preface this challenge by recasting what we did in the previous activity as an exploration: we explored the physical appearance of the LED to learn about its function. This is quite a general approach to learning about how things work and how nature operates: probe the system, make observations, collect data, make guesses, tests those guesses, and repeat. This *is* science. How else can we probe the LED and learn about it?

Collect ideas. Discuss. If changing temperature does not come up, remind students that we know a material is an electric conductor or insulator by the way its resistance varies with temperature: as we lower the temperature, the resistance of a conductor drops, while the resistance of an insulator increases. Also remind the students that we still have not tested what materials make the junction inside the LED. Apart from temperature, other ways to probe the system is by applying a voltage (electric field), or a magnetic field, or pressure. All of these probes and more, e.g. radiation, are used by scientists to probe, experiment, and learn about material properties.

Deciding on varying temperature as a way to learn more about the LED, proceed to put LEDs in different environments with different temperatures and observe the color and intensity of its glow. Ask students to record their observations and communicate. How do these findings compare to the incandescent light?

SAFETY NOTE. Contact with hot and cold liquids and objects can cause irreparable injury. Hot water, dry ice, and especially liquid nitrogen must be handled with extreme care while wearing safety gloves and goggles. You may want to perform these experiments yourself and have the students observe. Another idea is to perform them in a safe environment beforehand and record a video to show in class.

Note: The onset voltage decreases and the color of the glow shifts to lower frequency (higher wavelength) with increasing temperature. The intensity shows a more complex behavior: at lower temperature, it initially increases and then drops. This is due to a decrease in loss of electrons, which is then quenched by the falling density of electrons. This results in a variation of current through LED.

Conclusion: Temperature affects the color and intensity of light emitted by LED.

Activity 5. Energy conversion in LED

Time: 25 minutes

Material: LED (yellow); light source (flashlight); resistors; voltmeter; ammeter.

Challenge: What energy is converted in an LED?

Pose the challenge. Collect initial answers. It is anticipated that the initial answer is what is more or less obvious: electric energy is converted to light and heat. If this is all that is offered in answer, pose a follow-up question: Can it be the other way too?

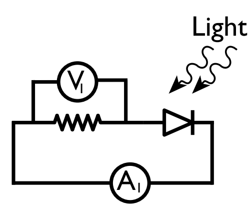
Note that many processes in nature can go both ways. For example, a pendulum can swing back and forth, or a ball thrown up will reach a maximum height and fall down; in both cases, kinetic energy is converted to potential energy and back. However, some processed only or mostly proceed in just one way. For example, once you open an air-tight container, the air rushes into the container and will not leave without being pumped out; similarly, if a hot or cold object is placed in the room, it will gradually cool down or heat up to room temperature. In these cases, the thermal energy in the container or the objects is exchanged with the environment and turns into kinetic energy. This could be an introduction to think about the challenge.

It is not easy to answer this challenge without detailed knowledge of the physics of LEDs. However, we can test our answers. Form the following hypothesis:

H) The LED converts electrical energy to light and back.

We can see the first part of H is true from previous experiments of connecting LED to a batter and seeing it glow. How can we test the second part of H?

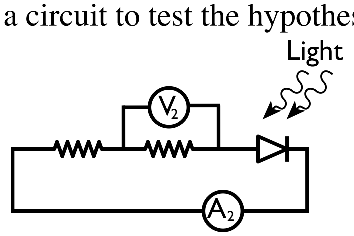
Collect ideas. Students will be communicated their thoughts. After collecting ideas, ask them to offer critiques of the ideas and decide on a way to test. You need to be prepared to some extend to play this part as it unfolds. You may offer guidance and participate in the evaluations of ideas. If no viable experiments are offered, you may make a suggestion. A possible outcome is shown in the following circuit diagram:



Once one or two designs are chosen, group the students to perform the experiments. Ask them to record their observations and communicate their results. What is the answer?

Conclusion: The LED also converts light energy to electric current, like a solar cell.

Follow-up: What kind of power source is the LED? Discuss this question and come up with possible hypothesis. Two possibilities are: a constant-voltage source; or a constant-current source. Design a circuit to test the hypotheses. For example:



Activity 6. Summary: LED efficiency
Time: 10 minutes
Material: commercially available LED and incandescent lights.
Challenge: Which one would you buy, incandescent or LED light?

Pose the challenge. Collect answers. Ask what the reasons are for these answers.

Take a few seconds to pause. Ask what information is needed to answer this question. Collect ideas. Which variables are important? Note the cost of light bulbs, how long they last, how much energy they consume. What else? Aesthetics? The color and feel of the light?

Research on the internet or present these values: a pair of 60-watt incandescent light bulbs is sold for ~ \$3, consuming 60 watts of power each, generating 635 lumens (unit of brightness) and lasting 3000 hours. A pair of 60-watt-equivalent LED light bulbs is sold for ~\$2, consuming 9.5 watts of power each, generating 840 lumens, and lasting 11000 hours. How much more cost-effective is the LED light?

Answer: (840 lumens/635 lumens)×(11000 hours/3000 hours)÷(9.5 watt/60 watt) ÷(\$2/\$3) ≈ 45 times more cost-effective.

Home activities

The following home activities can be assigned to individual or groups of students. They can be assigned at various stages, or all at once in the first class. For example, they can be assigned to three different groups who will then share their results in an additional class, 20 minutes each.

Home activity 1. History of LED

Ask student to research LEDs and write a page (500 words) about their discovery, physics, and history. Provide some guiding questions, e.g.: Who invented the first LED? Who made the first visible light LED? What color of LED was the hardest to find? Why?

Some possible resources: Wikipedia article on LED; description material for 2014 Nobel prize in physics (Nobel website); google search with queries "LED history," "LED physics," "LED Nobel prize," etc.

Home activity 2. Semiconductors

Ask student to research semiconductors and write a page (500 words) about their discovery, physics, and history. Provide some guiding questions, e.g.: Who first described semiconductors? What is the defining property of a semiconductor? What physics is needed to explain their properties? What are the technological uses of semiconductors? What properties make them useful?

Some possible sources: Wikipedia article on semiconductors; description material for 2000 Nobel prize in physics (Nobel website); google search with queries "semiconductor technology," "semiconductor physics," "semiconductor Nobel prize," etc.

Home activity 3. LED technology

Ask students to find, bring and/or describe any device or technology in their home or school environment that uses LEDs. How are LEDs used? What function do they perform? What conditions are they used in (temperature, lighting, wet/dry, etc.)? What is the benefits of LED use in these places instead of other options? Can you imagine any device that could use LEDs?

References:

[1] Gorazd Planinšič and Eugenia Etkina, "Light-Emitting Diodes: A Hidden Treasure," The Physics Teacher **52**, 94 (2014); doi:10.1119/1.4862113.

[2] Eugenia Etkina and Gorazd Planinšič, "Light-Emitting Diodes: Exploration of Underlying Physics," The Physics Teacher **52**, 212 (2014); doi:10.1119/1.4868933.

[3] Gorazd Planinšič and Eugenia Etkina, "Light-Emitting Diodes: Learning New Physics," The Physics Teacher **53**, 210 (2015); doi:10.1119/1.4914558.

Light-Emitting Diode (LED) Module

Forefronts of Research Educational Modules (FOREM)

Teacher Experience Survey

This survey takes about 5 minutes. It asks about your experience as a teacher in the LED module, a part of project FOREM. Your feedback will help us improve the modules and the project overall. Thank you for your participation.

1) Before this experience, how much did you know about LEDs?
   - ☐ In depth knowledge of their function and use
   - ☐ I knew about their use as well as a little about how they work
   - ☐ I knew about their use, but not much about how they work
   - ☐ I had heard about them, but not much more
   - ☐ Not at all
   - ☐ Other: ____________________________

2) After this experience, how much do you feel you know about LEDs?
   - ☐ In depth knowledge
   - ☐ I know about their use as well as a little about how they work
   - ☐ I know about their use, but not much about how they work
   - ☐ I know a little about them, but not much
   - ☐ Not at all
   - ☐ Other: ____________________________

3) "The activities were focused around a clear challenge or question."
   - ☐ Strongly agree
   - ☐ Somewhat agree
   - ☐ Somewhat disagree
   - ☐ Strongly disagree

4) "The activities encouraged and provided ample opportunity to express ideas, their evaluations, and communication."
   - ☐ Strongly agree
   - ☐ Somewhat agree
   - ☐ Somewhat disagree
   - ☐ Strongly disagree

5) How did this experience compare to your other teaching experience?

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   ____

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6) What were the strengths and weaknesses of this module? What can you tell us to improve the module?
Strength: ____

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Weakness: ____

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Improvement: ____

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Light-Emitting Diode (LED) Module
Forefronts of Research Educational Modules (FOREM)

Student Experience Survey

This survey takes about 5 to 10 minutes. It asks about your experience as a student in the LED module, a part of project FOREM. Your feedback will help us improve the modules and the project overall. Thank you for your participation.

1) Before this experience, how much did you know about LEDs?
   - ☐ In depth knowledge of their function and use
   - ☐ I knew about their use as well as a little about how they work
   - ☐ I knew about their use, but not much about how they work
   - ☐ I had heard about them, but not much more
   - ☐ Not at all
   - ☐ Other: ________________________________

2) After this experience, how much do you feel you know about LEDs?
   - ☐ In depth knowledge
   - ☐ I know about their use as well as a little about how they work
   - ☐ I know about their use, but not much about how they work
   - ☐ I know a little about them, but not much
   - ☐ Not at all
   - ☐ Other: ________________________________

3) "The activities were focused around a clear challenge or question."
   - ☐ Strongly agree
   - ☐ Somewhat agree
   - ☐ Somewhat disagree
   - ☐ Strongly disagree

4) "The activities encouraged and provided ample opportunity to express ideas, their evaluations, and communication."
   - ☐ Strongly agree
   - ☐ Somewhat agree
   - ☐ Somewhat disagree
   - ☐ Strongly disagree

5) "I feel I learned effectively through the cycle of inquiry and ideas."
   - ☐ Strongly agree
   - ☐ Somewhat agree
   - ☐ Somewhat disagree
   - ☐ Strongly disagree

6) Did you complete any of the home activities? ☐ Yes. ☐ No.

7) What were the best parts of your experience?

8) What were the worst parts of your experience?

9) How can this module be improved?

10) How did this experience compare to your experience in the rest of the class?

11) How did this experience compare to your experience in your other courses?