Lesson 4: How does an antenna transfer energy to matter at a distance?

Previous Lesson *We produced waves with a spring and developed a model for how they transfer energy. We used a simulation to plan and carry out investigations to make claims about how various wave properties affect energy transfer. We developed a mathematical model of the relationship between some of these properties.*

This Lesson

Investigation

2 days

We decide to investigate how moving electrons in an antenna cause energy transfer. We use and evaluate different representations of electromagnetic radiation propagating through space. We read about how a vibrating charged particle generates electric and magnetic fields, and use a wire and compasses to observe this interaction. We use our ideas to develop a mechanistic explanation for electromagnetic radiation, and use that to predict interactions with matter inside the microwave oven.

Next Lesson *We will argue for, plan, and carry out investigations to determine what happens to the energy transferred by two forms of EM radiation when they reach and interact with the materials in the microwave oven door and walls. We will develop a model to explain the results of our investigation, and generate new questions.*

BUILDING TOWARD NGSS

HS-PS2-5, HS-PS4-1, HS-PS4-2, HS-PS4-3, HS-PS4-4, HS-PS4-5, HS-ESS2-4

What students will do

4.A Use and ask questions about multiple models of electromagnetic radiation to refine a mechanistic explanation for patterns of energy transfer through changing electric and magnetic fields, applying empirical evidence from an in-class investigation. (SEP: 1.4, 2.4; CCC: 1.5, 2.2; DCI: PS4.B.1)

4.B Examine smaller-scale mechanisms of changing electric and magnetic fields to construct an evidence-based explanation about energy transfer through electromagnetic radiation. (SEP: 6.2; CCC: 2.2; DCI: PS4.B.1)

What students will figure out

- Moving electrons create electric fields that change.
- These changing electric fields, in turn, create changing magnetic fields, which generate changing electric fields again. This wavelike cycle continues, resulting in the formation of electromagnetic radiation.

- Electromagnetic radiation can travel through empty space without needing matter to move through.
- The energy in changing electric and magnetic fields spreads out as waves travel, becoming weaker the farther they go.

Lesson 4 • Learning Plan Snapshot

Part	Duration		Summary	Slide	Materials
1	3 min		**NAVIGATE** Summarize the Lesson 3 exit ticket responses to highlight the importance of investigating energy transfer from the antenna in the microwave oven.	A	M-E-F poster (from *Earth's Interior Unit*)
2	6 min		**EXPLORING STATIC FIELDS** Map the parts of the Radio Waves and Electromagnetic Fields PhET Simulation https://phet.colorado.edu/sims/cheerpj/radio-waves/latest/radio-waves.html?simulation=radio-waves to the parts in the microwave oven system, and identify evidence of energy transfer in the simulation.	B-D	computer with internet access, Physical Wave Properties poster (from Lesson 3), M-E-F poster (from *Earth's Interior Unit*)
3	5 min		**IDENTIFY EVIDENCE OF ENERGY TRANSFER TO DEVELOP AN INITIAL ENERGY TRANSFER MODEL** Share ideas about energy transfer in the system. Develop an initial energy transfer model to identify parts of the system that require further investigation.	E	Energy Transfer from an Antenna poster, markers
4	10 min		**IDENTIFY PATTERNS IN DIFFERENT PARTS OF THE SYSTEM** Use a handout and computer to answer prompts about an assigned simulation setting in groups.	F	*Static Field Visualization*, *Arrows and Line Field Visualization*, or *Full Field Visualization*, computer with internet access
5	11 min		**DEBRIEF OBSERVED PATTERNS** Complete the handout's Summary Table in groups. Revise the Energy Transfer from an Antenna poster and identify limitations of the model to motivate the reading about the electric field.	G-H	*Static Field Visualization*, *Arrows and Line Field Visualization*, or *Full Field Visualization*, Energy Transfer from an Antenna poster, Physical Wave Properties poster (from Lesson 3)
6	10 min		**READ ABOUT LIGHT WAVES AND NAVIGATE** Read about light waves and answer the questions in the reading.	I-J	*Light as a Wave*
					End of day 1
7	2 min		**NAVIGATE** Use the exit tickets and a Turn and Talk to orient to where we left off.	K	*Light as a Wave*

8	5 min		**MAKE SENSE OF CHANGES IN MAGNETIC FIELDS** Discuss the model of electric and magnetic fields from the reading. Make sense of the representations used in the second simulation to show the fields' direction and magnitude.	L-N	*Light as a Wave*, computer with internet access
9	4 min		**MAKE SENSE OF CHANGES IN THE ELECTRIC AND MAGNETIC FIELDS** Compare the field representations we have used in the context of energy transfer in the system. Motivate using physical equipment to further our understanding.	O	Electric and Magnetic Fields Visualization
10	14 min		**CONDUCT A DEMONSTRATION OF CHANGING ELECTRIC FIELDS CAUSING CHANGES IN MAGNETIC FIELDS** Test the relationship between electric and magnetic fields with a demonstration in a Scientists Circle.	P-R	Changing Fields Demonstration
11	10 min		**DISCUSS REVISIONS OF THE ENERGY TRANSFER MODEL** Turn and talk about revisions to the energy transfer model based on new evidence and science ideas. Record definitions in Personal Glossaries.	S-T	Energy Transfer from an Antenna poster
12	6 min		**ADD IDEAS TO THE PROGRESS TRACKER** Add the first entry to *Progress Tracker*.	U	*Progress Tracker*
13	4 min		**NAVIGATE** Complete an exit ticket.	V	8.5" x 11" paper

End of day 2

Lesson 4 • Materials List

	per student	per group	per class
Electric and Magnetic Fields Visualization materials			• computer with internet access
Changing Fields Demonstration materials			• hand-crank DC generator • homemade generator tube from *Electricity Unit* (magnet wire wrapped around paper tube • ends sanded) • 4-6 compasses • 4-6 alligator clips
Lesson materials	• *Static Field Visualization* • *Arrows and Line Field Visualization* • or *Full Field Visualization* • computer with internet access • *Light as a Wave* • science notebook • *Progress Tracker* • 8.5" x 11" paper		• M-E-F poster (from *Earth's Interior Unit*) • computer with internet access • Physical Wave Properties poster (from Lesson 3) • Energy Transfer from an Antenna poster • markers

Materials preparation (45 minutes)

Review teacher guide, slides, and teacher references or keys (if applicable).

Make copies of handouts and ensure sufficient copies of student references, readings, and procedures are available.

Three-hole-punch all handouts so they can be added to students' notebooks.

Hang the M-E-F poster (from *OpenSciEd Unit P.2: How forces in Earth's interior determine what will happen to its surface? (Earth's Interior Unit)*) where students can see it. If you are teaching this unit without having developed this resource yet, we recommend creating one as described in *Earth's Interior Unit*.

Hang the Physical Wave Properties poster created in Lesson 3, so students can reference it while using the new simulation.

Check ahead of time to ensure these links work and will project:

- https://phet.colorado.edu/sims/cheerpj/radio-waves/latest/radio-waves.html?simulation=radio-waves
- https://www.openscied.org/general/fieldsthroughspace/
- https://youtu.be/TKkJx7i-Mvs

When reading through the Electronic Exit Tickets students completed at the end of Lesson 3, look for mechanistic explanations about how energy transfers from the magnetron to the food inside the microwave oven. This means looking for cause-and-effect reasoning, changes in matter that might occur as energy transfers, and/or forces acting on parts of the system. You will use these ideas to navigate into this lesson.

Prepare chart paper for the poster you will make in this lesson:

- Energy Transfer from an Antenna

Day 2: Changing Fields Demonstration

- **Group size:** Whole class.
- **Setup:** Check 4-6 compasses ahead of time to ensure they all point in the same direction (which does not necessarily need to be north). One tube with wire wrapped around it should be free of magnets so it can be used as a coil of wire. If you have the materials from *OpenSciEd Unit P.1: How can we design more reliable systems to meet our communities' energy needs? (Electricity Unit)*, you can use a wire-wrapped tube and homemade generator from those. Otherwise, see *Teacher Generator Instructions* for details on how to construct this equipment. As an alternative demonstration, you may show https://youtu.be/TKkJx7i-Mvs.
- **Storage:** All materials can be stored and reused indefinitely.

Lesson 4 • Where We Are Going and NOT Going

Where We Are Going

This lesson is designed to coherently build ideas related to the following disciplinary core idea:

- **PS4.B.1 Electromagnetic Radiation.** Electromagnetic radiation (e.g., radio, microwaves, light) can be modeled as a wave of changing electric and magnetic fields~~ or as particles called photons~~. The wave model is useful for explaining many features of electromagnetic radiation~~, and the particle model explains other features~~. (HS-PS4-3)

In this lesson, students explore how moving charged particles can cause energy transfer from an antenna to distant electrons. They identify patterns of moving electric fields from an antenna and examine smaller-scale mechanisms of electric and magnetic field interactions to explain how energy is transferred through electromagnetic radiation.

Note that this is students' first opportunity to develop a wave model of electromagnetic radiation. The goal of exploring electromagnetic radiation using various visualizations is to help students develop a model of a wave of changing electric and magnetic fields that doesn't necessarily look like a traditional wave-like representation, but like an oscillation of electric and magnetic fields that travels through space. They will evaluate the usefulness of this model to explain different phenomena in upcoming lessons.

Students encounter or co-develop definitions for the following words in this lesson: *electromagnetic waves* and *electromagnetic radiation*. **Do not** post any words or ask students to add them to their Personal Glossaries until after the class has developed a shared understanding of their meaning.

Where We Are NOT Going

This lesson does not explicitly focus on how electromagnetic radiation transfers energy to food. In the upcoming lessons, students will explore how electromagnetic radiation interacts with matter.

LEARNING PLAN for LESSON 4

1 · NAVIGATE

3 min

MATERIALS: M-E-F poster (from *Earth's Interior Unit*)

Orient the class to where we left off. Say, *I went through your Electronic Exit Tickets, and I found different ideas about how energy transfers from the magnetron to the food inside the microwave oven.* Share some of the main answers from the exit tickets.

ADDITIONAL GUIDANCE	When reading the Electronic Exit Tickets, look for mechanistic explanations about how energy transfers from the magnetron to the food inside the oven. This means looking for cause-and-effect reasoning, changes in matter that might occur as energy transfers, or forces acting on parts of the system. Suggest that we keep in mind whether these explanations are supported by evidence.

Motivate the use of a simulation. Say, *I have a simulation that shows an antenna transferring energy outward through space, just like the antenna in the microwave oven.* Present **slide A**. Elicit students' responses to the prompt as shown in the table below.

Suggested prompt	Sample student response	Follow-up question
What kinds of things would you like to see in the simulation that could help us figure out how energy transfers from a microwave oven's antenna into food?	Some representation of energy moving through space. A particle-level view. I want to see what the antenna is made of.	*Would you be interested in seeing energy or forces represented as well? Why or why not?* *What scale would you like to see represented, and why?* *How could that help us understand how energy transfers?*

2 · EXPLORING STATIC FIELDS

6 min

MATERIALS: computer with internet access, Physical Wave Properties poster (from Lesson 3), M-E-F poster (from *Earth's Interior Unit*)

Map 2-3 parts of the simulation to parts of the microwave oven. Present **slide B**. Mention that the image on the slide shows a screenshot of the simulation we will use. Remind students that radio waves are a type of electromagnetic radiation, which can give us some ideas about how microwave radiation transfers energy.

Point out that what is shown are electric fields, and that this option has been clicked in the toolbar on the right. Elicit 1-2 ideas in response to the prompts:

- *What do you notice?*
- *How does this compare to the microwave oven?*
- *What can we tell about the matter in the antenna from this image?*

Listen for students to suggest the following: ✱

- All arrows around the electron point toward it.
- The magnitude of the arrows decreases over distance.
- Both systems have an antenna.
- There is an electron in the antenna in the simulation and at least one (actually many) electrons in the antenna of the magnetron.
- The electrons vibrate inside the magnetron antenna.

Consider forces acting on charged particles. Present **slide C**. Point out that now what is shown are the forces on the electron in the antenna, and that this option has been clicked in the toolbar. Pose the first prompt on the slide:

- *What do you notice?*

Listen for students to notice:

- The arrows point away from the electron now.
- The magnitude still decreases with distance from the electron.

Say, *In Earth's Interior Unit, we figured out that energy transfers through forces.* Point to the M-E-F poster to support this idea. Then say, *But there is a large distance between the objects in the system in the simulation*. Elicit 1-2 ideas in response to the second prompt:

- *How close does electron 2 need to be to feel a force from electron 1?*

Listen for students to suggest that an electron would need to be in location B to feel any force, as shown by the arrows on the simulation. The labels B, C, and D are provided to help students be more specific when they talk about distance from the antenna.

Switch back and forth between **slide B** and **slide C** to help students see the change in orientation of the force arrows. Note that the red arrow shows "force on an electron from electron 1" and the green arrow shows "electric field from electron 1".

✱ ATTENDING TO EQUITY

Supporting emergent multilinguals: It can be very helpful for all students, and particularly emergent multilinguals, to express their ideas using nonverbal forms of communication. Use students' arm motions as a check for how well they are understanding and appropriating frequency and amplitude to make sense of particle motion.

Consider frequency and amplitude. Present **slide D**. Say, *We noticed that electrons in the magnetron's antenna move up and down, or vibrate. The simulation allows us to control the vibration of the first electron--specifically, to change the amplitude and frequency of the motion. Let's think back to the Wave on a String simulation to remember what amplitude and frequency are.* Point to the Physical Wave Properties poster.

Ask students to move their arm up and down to imitate the movement of the electron in the transmitting antenna. Then ask them to change the motion to indicate changes in frequency and amplitude, as prompted on the slide. Look for them to move their arm faster for increases in frequency, and higher and lower for increases in amplitude.

Suggest that we quickly test these ideas with the actual simulation to see if we are right about how the motion of the electron will change.

3 · IDENTIFY EVIDENCE OF ENERGY TRANSFER TO DEVELOP AN INITIAL ENERGY TRANSFER MODEL

5 min

MATERIALS: Energy Transfer from an Antenna poster, markers

Identify evidence of energy transfer in the system. Present **slide E**. Remind students that matter changes are often evidence of energy transfer. Elicit 1-2 ideas in response to the first prompt:

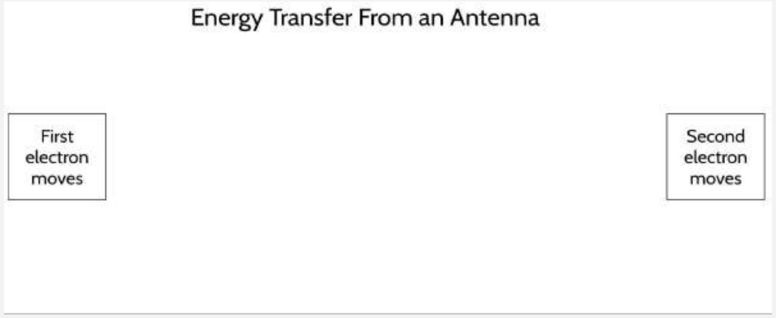
- *What evidence do we have of energy transfer?*

Listen for the following ideas:

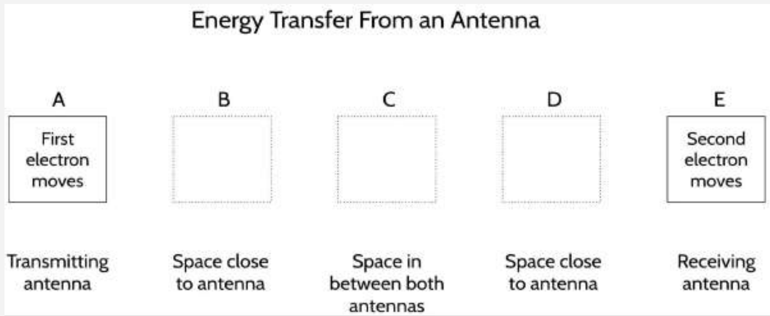
- The second electron starts moving a little after the first electron starts moving.
- The motion of the first electron seems to be connected to the motion of the second electron.
- The higher the frequency or amplitude of the first electron, the higher the frequency and amplitude of the second electron.

Ask, *So what can we say about energy transfer? Let's model what we know so far.*

Develop an initial model. Use student ideas to develop an initial model of the system on the Energy Transfer from an Antenna poster. Begin by drawing two boxes that represent the two electrons.



Propose that we concentrate on various parts of the system to understand how energy is transferred. Add letters (A-D) to label these different areas.



Motivate using the simulation to fill in the gaps in our understanding. Suggest that we use the different visualizations in the simulation to identify the changes in these different locations that can help us explain how energy transfers from the transmitting antenna.

Say, *The simulation has a few different visualizations for an electric field, or the force an electron would feel from electron 1. Within your group, try splitting up to record observations for different visualizations, then get back together to make sense of what you saw separately. This will feel like a Jigsaw, but each person is looking at different settings on the simulation.*

4 · IDENTIFY PATTERNS IN DIFFERENT PARTS OF THE SYSTEM

10 min

MATERIALS: *Static Field Visualization*, *Arrows and Line Field Visualization*, or *Full Field Visualization*, computer with internet access

Assign simulation settings. Present **slide F**. Put students into groups of three. Tell them each member will be responsible for exploring one visualization and sharing their findings with their group.

Distribute a handout to each student that corresponds to the visualization they were assigned:

1. *Static Field Visualization*
2. *Arrows and Line Field Visualization*
3. *Full Field Visualization*

Review the task on the slide:

- *Load the simulation.*
- *Adjust it to the menu settings described in Part 1 of your handout.*
- *Fill in Part 1 to describe the changes you notice in different parts of the system.* ✱

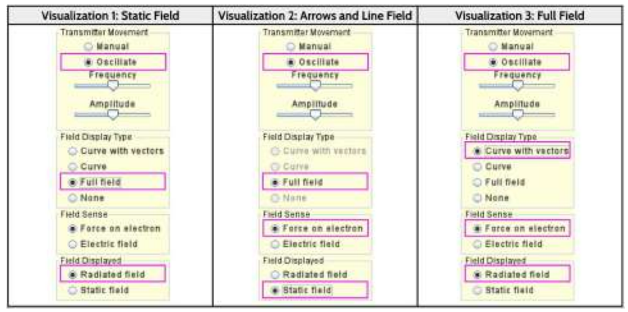
✱ ATTENDING TO EQUITY

Supporting emergent multilinguals: Encourage students to record observations and ideas using linguistic modes (e.g., written words) and nonlinguistic modes (e.g., drawings, graphs). This is especially important for emergent multilingual students because making connections between written words and nonlinguistic representations helps to generate richer explanations of scientific phenomena.

- *Consider what your visualization shows clearly and what seems unclear.*

Identify initial patterns. Distribute computers with access to https://phet.colorado.edu/sims/cheerpj/radio-waves/latest/radio-waves.html?simulation=radio-waves to each student. Give them 10 minutes to work on the simulation and fill in Part 1. Later, they will use their responses to fill in Part 2 with their Jigsaw group. The three visualizations look different, but for the Jigsaw discussion to be robust, it's important that students study the one they were assigned.

Radio Waves Visualization simulation action:



PhET Interactive Simulations

Students will use the simulation individually using different visualizations, as assigned.

ASSESSMENT OPPORTUNITY

What to look for/listen for in the moment:

Visualization 1: Static Field

- Shows that the static electric field changes in magnitude and direction near the antenna. Energy decreases because the field decreases.

Visualization 2: Arrows and Line Field

- Shows that the radiated electric field changes in magnitude and direction near the antenna, and that this change moves away from the antenna like a wave in a wavy line pattern. Energy decreases because the arrows get shorter.

Visualization 3: Full Field

- Shows that the radiated electric field changes in magnitude and direction near the antenna, and that this change moves away from the antenna, sort of like ripples in a pond. Energy decreases because the arrows get shorter. (SEP: 2.4; CCC: 1.5; DCI: PS4.B.1)

Limitations of Visualizations

- Visualization 1 shows no explanation for why electron 1 causes electron 2 to move.
- Visualizations 2 and 3 show no explanation for why the radiated field goes away when electron 1 stops moving.
- None of the visualizations explain why the electric field "radiates", or why a changing electric field causes a change in an electric field nearby. (SEP: 2.4; DCI: PS4.B.1)

What to do: Walk through the classroom as students complete Part 1 of their handout. If they appear confused about what to write down (especially for Visualization 1), emphasize that part of what they will bring to their Jigsaw group is what the simulation does **not** show. Encourage them to record even very basic observations, such as "electron moves" and "field changes".

The sample responses in the *Field Visualization Key* show prompts you can use when you see how students are integrating evidence, cause and effect, and ideas about energy transfer to make sense of the patterns they observe. The goal is to elicit ideas that can help them integrate these dimensions into a more sophisticated mechanism of energy transfer through changing fields.

Building toward: 4.A.1 Use and evaluate multiple models ~~and ask questions~~ to identify patterns of changing electric fields that can provide evidence for causality in explanations of energy transfer through electromagnetic radiation as the interaction of changing electric and magnetic fields. (SEP: ~~1.4,~~ 2.4; CCC: 1.5, 2.2; DCI: PS4.B.1)

5 · DEBRIEF OBSERVED PATTERNS

11 min

MATERIALS: *Static Field Visualization*, *Arrows and Line Field Visualization*, or *Full Field Visualization*, Energy Transfer from an Antenna poster, Physical Wave Properties poster (from Lesson 3)

Transition to small-group discussion. When a few groups are ready to share their individual findings with each other, present **slide G**.

✱ Read the protocol aloud:

- *Each person gets up to 1 minute to summarize the answers to Questions 1-4 from your assigned field visualization.*
- *With your group, complete the summary table: Question 5 in Part 2.*
- *Use your team's Summary Table to answer Questions 6-8 in the handout.*

ASSESSMENT OPPORTUNITY

What to look for/listen for in the moment: As you walk around the classroom, pay attention to how students integrate the different dimensions to make sense of energy transfer as they answer Questions 5-8 in Part 2 of their handout. See the *Field Visualization Key* for sample responses.

Question 5: See the example of a filled table.

Question 6: Based on the observations in Visualizations 1, 2, and 3, we can add "electric field changes" to locations B, C, and D. (Visualizations 2 and 3 showed patterns of changing arrows at C and D, but Visualization 1 showed nothing.) (SEP: 1.4; CCC: 1.5, DCI: PS4.B.1)

Question 7: Based on the observations in Visualizations 2 and 3, the radiated electric field goes away when the electron stops moving, but the static field stays there in Visualization 1. This tells us that the motion of the electron causes the field to radiate, but we don't know why. (SEP: 1.4; CCC: 2.2, DCI: PS4.B.1)

Question 8: Example questions:

- What causes radiated electric fields?
- How is a radiated field different from a static field?
- Why does a changing electric field at one location cause an electric field nearby to change also? (CCC: 2.2, DCI: PS4.B.1)

What to do: During this Jigsaw discussion, step back and listen to what students are sharing. Use this as a check for understanding of the main takeaways from the visualizations. If you don't hear many of these key ideas, be ready to ask guiding questions to help the class reach these conclusions together.

✱ ATTENDING TO EQUITY

Supporting emergent multilinguals: Quiet time before a discussion gives students an opportunity to prepare for it ahead of time. This strategy is particularly effective with emergent multilingual learners, who gain confidence from the additional time to organize their ideas before sharing them with others.

Pay attention to which groups have useful ideas so you can call on them during the whole-class share-out. If you hear something identified above, or see it written on a page, point it out to that group, and say, *Would you be willing to share that idea during our class discussion?*

Building toward: 4.A.2 Use and evaluate multiple models and ask questions to identify patterns of changing electric fields that can provide evidence for causality in explanations of energy transfer through electromagnetic radiation as the interaction of changing electric and magnetic fields. (SEP: 1.4~~, 2.4~~; CCC: 1.5, 2.2; DCI: PS4.B.1)

Build understanding about observed patterns in the system. Present **slide H**. Summarize patterns across the locations labeled in the simulation by eliciting student ideas using the first prompt:

- *What patterns did we observe at B, C, D, and E?*

Listen for students to say they saw the electric field change at B, C, and D.

After a group shares a pattern at one location, ask the rest of the class whether they observed the same change with their visualizations. Summarize the pattern in the corresponding location of the model, such as "Electric field changes" in location B (near antenna 1). If there is no consensus, display the simulation using the three visualizations and direct students' attention to the location in question.

If students mention that the "Static Field Visualization" did not show any changes in locations C or D, ask them how they resolved those differences. Ask, *What other differences did you see between the visualizations? How did your Jigsaw group resolve these differences?* Listen for them to say that nothing in one visualization contradicts another, but there seems to be a difference between the static field and the radiated field.

Highlight changes in the amount of energy transferred. Pose the slide's second prompt:

- *What can we conclude about how much energy transfers as the electric field radiates from left to right?*

Students may refer to this as "damping". If they did not notice this change in the amount of energy, display the simulation again using the "Arrows and Line Field Visualization". Then ask what the length of the arrows suggests about energy transfer.

Students may have noticed that the "Full Field Visualization" helps us make sense of this--because the energy is traveling in so many directions, the energy transferred in one direction has to decrease. If they do not, do not dwell on this point. They will have a chance to come back to this idea on day 2.

ADDITIONAL GUIDANCE	Use this as an opportunity to discuss the difference between static and radiated fields. Elicit student ideas using the following prompt: *Why do we think the Field Displayed is called radiated or static?* Listen for them to suggest that the static field only shows the forces acting in the proximity of electron 1, while the radiated field shows the forces moving away from electron 1.

Consider changes in the energy transfer model. Point to the Energy Transfer from an Antenna poster. Elicit student ideas using the slide's third prompt:

- *What changes can we make to our consensus model of energy transfer?*

Similarly to the protocol you used to capture the patterns in the system, invite a group to suggest a change to the model, and ask the rest of the class whether they agree that the change captures a pattern they saw in the simulation. If there is consensus, add this change to the model. If there is no consensus, display the simulation using the three visualizations, and ask whether it provides enough evidence to support the change. If there is no consensus after this, add a question mark on this part of the model and suggest we explore it later.

Repeat this process until the model captures all the new ideas shared by the class.

Elicit ideas about limitations of the model. Continue by asking students about the relationship between the observed patterns and energy transfer, using the fourth prompt:

- *What are the limitations of the simulation for explaining how the antenna transfers energy to other parts?*

Use the Physical Wave Properties poster developed in Lesson 3 to draw comparisons of energy transfer between the string and electromagnetic radiation. Point out that the simulation helped us identify the changes happening to transfer energy across the hand to the last particle on the string. Ask, *Does the simulation help us identify why we observe these changes across the system?*

Finally, elicit student ideas with the slide's last prompt:

- *What questions did the simulation raise for you?*

Listen for the class to recognize that the simulation does not show us why the field begins to radiate only when the electron begins to move. Transition to the next slide by saying, *It seems we need more ideas that can help us explain why the electric field radiates only when the charged particle moves.*

6 · READ ABOUT LIGHT WAVES AND NAVIGATE

10 min

MATERIALS: *Light as a Wave*

Introduce the reading. Present **slide I**. Tell the class that you have a reading that might help us answer some of our questions. Distribute *Light as a Wave* to each student. Review the task on the slide:

- *Part 1: As you read, draw a ⋆ next to:*
    - *a hypothesis that was tested*
    - *the result of that test*
- *Part 2: Underline all ideas that could help us explain why the electric field radiates only when charged particles move.*

Assign and collect the exit ticket. A few minutes into the reading, present **slide J**. Describe the task with the prompts:

- *Answer the questions in Part 1 of the reading.*
- *Turn in your reading to your teacher.*

Give students 10 minutes to read and answer the questions in Part 1. Make sure they write their name at the top of the reading, as you will collect it as an exit ticket. For now, tell them to ignore the questions at the end of Part 2. These will be used with a new visualization at the beginning of day 2.

ALTERNATE ACTIVITY	If you are running short on time, assign this reading as home learning, and start the class next time with **slide L**.

End of day 1

7 · NAVIGATE

2 min

MATERIALS: *Light as a Wave*

Briefly orient students to where we left off. Present **slide K**. Say, *Last time, we used a radio wave simulation to help identify patterns of changing electric fields from two antennas, and we hoped the reading could help us better explain these patterns.*

Return the reading exit tickets from last class, *Light as a Wave*. Have students turn and talk about the prompts on the slide (**not** the questions in the reading):

- *What patterns from our work with radio waves did the reading help us explain?*

- *What new patterns did we see?*

Walk around the classroom while partners discuss, and listen for the following ideas:

- It helped us explain why the electric field radiates only when charged particles move.
- As the electron wiggles, electric and magnetic fields are produced.
- We saw magnetic fields changing along with electric fields.

8 · MAKE SENSE OF CHANGES IN MAGNETIC FIELDS

5 min

MATERIALS: *Light as a Wave*, computer with internet access

Discuss noticings about electromagnetic field representation. Present **slide L**. Have students turn and talk about the prompts on the slide:

- *What do you notice in this diagram from the reading?*
- *What would change if you could animate the drawing?*
- *How would this animation look for just one arrow?*

Walk around the classroom and listen for the following ideas:

- The fields are perpendicular to each other.
- Both fields travel as waves with the same wavelength.
- We should add perpendicular magnetic fields traveling alongside the electric fields.
- At every point, there will be two perpendicular arrows growing larger and smaller, and flipping directions at the same time.

Orient students to a new visualization. Present **slide M**. Say, *It's very hard to represent magnetic and electric fields together in a clear way. When physicists model them, sometimes they need to use arrows pointed "toward" or "away".* Introduce the notation shown in the slide, giving students some time to make sense of it.

Use the simulation to identify additional patterns. Display https://www.openscied.org/general/fieldsthroughspace/, introducing it by explaining that it represents both magnetic and electric fields, using the symbols we just discussed. Suggest we focus on the magnetic field.

Present **slide N**. Make changes to the simulation to allow students to make sense of the prompts on the slide. Though it is possible to go back and forth between the slide and the simulation, it is more convenient for students to see the simulation while they discuss the questions. To facilitate this, the Discussion Questions are shown at the end of Part 2 of *Light as a Wave*:

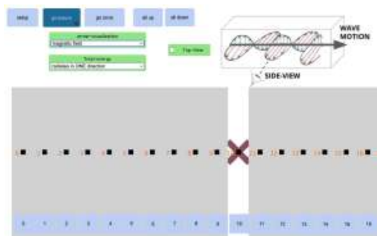
A. *What do you notice at one point in space? What would we see from a "Top view"?*

B. *What do you notice at two points next to each other? What would we see at all points in space?*
C. *What do you see when we select "Total energy radiates in ALL directions"? What does this suggest?*

Listen for the following ideas:

- The arrows point toward you and then away from you.
- The changes at one point are repeated at the next a little after.
- There are alternating patterns of X's and O's.
- The magnitude of the X's and O's decreases over distance if "Total energy radiates in ALL directions" is turned on. This means other energy is going in different directions, so the energy in one direction gets smaller.

Fields Through Space simulation action:



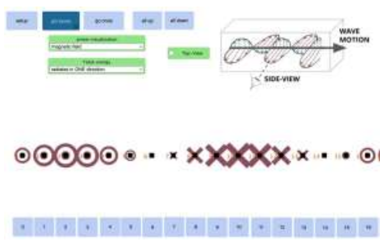
Open the simulation.

- Click **"Setup"** then **"Go/pause"**.
- Change **"Arrow-visualization"** to **"Magnetic field"**.
- Click ***one*** of the numbers at the bottom to remove the blinder from only that point in space.

To select **"Top-view"**, click the checkbox at the top. This will change the key image, and change the X's and O's to up/down arrows.

To show two points next to each other, click a second number adjacent to the first.

Fields Through Space simulation action:

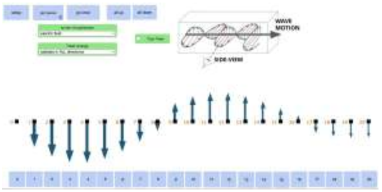


To show all points at once:

- Uncheck **"Top-view"** to go back to **"Side-view"**.
- Click the **"All down"** button to see all points in space changing at the same time.

Emphasize that each point in space is simply changing back and forth, if students seem to see "horizontal movement" (also called "wave speed").

Before checking **"Top-view"**, ask students to predict what they will see, referring to the red magnetic field and blue electric field arrows.

Fields Through Space simulation action:	Select **“Total-energy”** as **“Radiates in ALL directions”** to demonstrate an effect similar to “damping”--the arrows get smaller. Elicit student observations. Listen for them to suggest that energy traveling in one direction decreases with distance. 

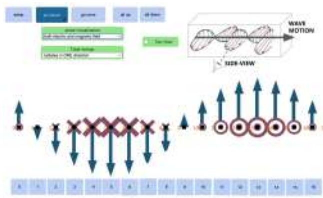
9 · MAKE SENSE OF CHANGES IN THE ELECTRIC AND MAGNETIC FIELDS

4 min

MATERIALS: Electric and Magnetic Fields Visualization

Compare field representations. Present **slide O**. Ask students to use the diagram on *Light as a Wave* along with their observations of https://www.openscied.org/general/fieldsthroughspace/ to turn and talk about the questions at the end of the reading:

- *How do electric and magnetic fields change as the wave travels?*
- *Is energy transferring through the electric fields, magnetic fields, or both? How do you know?*
- *What are the limitations of this model? What doesn't it show or help explain?*

Fields Through Space simulation action:	Leave the simulation set to **"All down"** so students can make sense of both arrows together.	

Give partners a couple of minutes to explore these questions before inviting them to share. Listen for the following ideas:

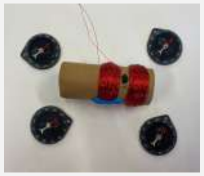
- The magnitude of both fields increases and decreases at the same time.
- This suggests energy transfers in both fields.
- We cannot change frequency or amplitude directly with this simulation to study how these variables affect energy transfer through magnetic and electric fields.
- We don't see why changing electric fields cause changing magnetic fields or vice versa.
- If both fields change at the same time, how can energy transfer from one field to the other?

Motivate using physical equipment to aid our understanding. Ask, *Could it be useful to use physical equipment to observe whether changes in electric fields can cause changes in magnetic fields, and how?* Accept 1-2 ideas and then say, *I've got some materials that generate electric and magnetic fields. Let's try it out and see if we can fill in some gaps in our understanding.*

10 · CONDUCT A DEMONSTRATION OF CHANGING ELECTRIC FIELDS CAUSING CHANGES IN MAGNETIC FIELDS

14 min

MATERIALS: Changing Fields Demonstration

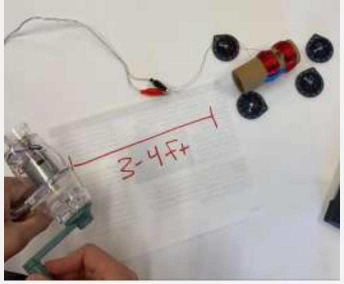


Form a Scientists Circle and introduce the demonstration. Present **slide P**. Show the class the materials we can use to test the relationship between electric and magnetic fields. Elicit student ideas using the prompt: ✱

- *How could we use this equipment to investigate how changes in electric fields affect magnetic fields or vice versa?*

Accept all ideas, but listen for students to suggest placing compasses near a wire and connecting the system to electricity.

Present **slide Q**. Describe the demonstration you can carry out with the materials, mentioning the direction of the flow of electricity in the system when you connect it to a power source.



Elicit student predictions. Ask students to turn and talk about the prompt to make a prediction based on this system:

- **Generator, Wire Coil, Compasses:** *If changing electric fields cause changes in magnetic fields, then cranking the generator back and forth should...*
- **Wire Coil, Magnets, LED:** *If changing magnetic fields cause changes in electric fields, then moving the magnets inside the coil of wire should...*

Invite students to share their predictions. After a volunteer has shared, use the following prompts:

- *Does anyone else have a similar prediction?*
- *Who has a different prediction?*

Proceed with this protocol until you feel you have captured the predictions of all students.

Demonstrate changing fields. Present **slide R**. Carry out the demonstration with a generator connected to an empty coil of magnet wire, letting students observe the changes in the magnetic field registered by the compasses near the coil. Note that as you change the direction you are turning the generator's crank (clockwise versus counterclockwise), the direction of the current changes as well.

Carry out a second demonstration with a homemade generator, spinning the magnets quickly inside the coil connected to a bright red LED. Mention that as you spin the magnet, the direction of the magnetic field inside the coil changes as well. As an alternative demonstration, you may show https://youtu.be/TKkJx7i-Mvs.

✱ SUPPORTING STUDENTS IN DEVELOPING AND USING CAUSE AND EFFECT

In grades 6-8, students used cause-and-effect relationships to predict phenomena in natural or designed systems. In high school, they figure out that cause-and-effect relationships can be suggested and predicted for complex natural and human-designed systems by examining what is known about smaller-scale mechanisms within the system. Here, students examine what is known about electric field and magnetic field propagation through space (a small-scale effect) to explain how energy transfers from an antenna to distant charged particles (a large-scale system).

Make sense of observations. Elicit 1-2 ideas in response to each of the slide's prompts:

- *What happened when we used the generator to change the direction of the electric field in the wire?*
- *What happened when we used spinning magnets to change the direction of the magnetic field in the wire?*
- *How might this help us understand what is happening inside the cooking area of the microwave oven?*

Listen for these ideas:

- When the direction of the electric field in the wire changed, so did the direction of the magnetic field.
- When the direction of the magnetic field changed, so did the electric field inside the coil of wire, which pushed electrons and lit up the LED.
- The electric field in the magnetron changed, which causes changes in the magnetic field, causing further changes to the electric field.
- When the generator stays still, the compass stays still as well.

Say, *Let's see how we can revise our model in light of the evidence and new ideas we have.*

11 · DISCUSS REVISIONS OF THE ENERGY TRANSFER MODEL

10 min

MATERIALS: science notebook, Energy Transfer from an Antenna poster

Discuss revisions of the energy transfer model. Present **slide S**. Ask students to use evidence and their new ideas to turn and talk about how we would need to change the model in the Energy Transfer from an Antenna poster to show:

- *How do changes at one place cause changes at other places in the system?*
- *How does the vibrating electron at A cause energy to transfer?*
- *What do we call this system of changing electric and magnetic fields?*

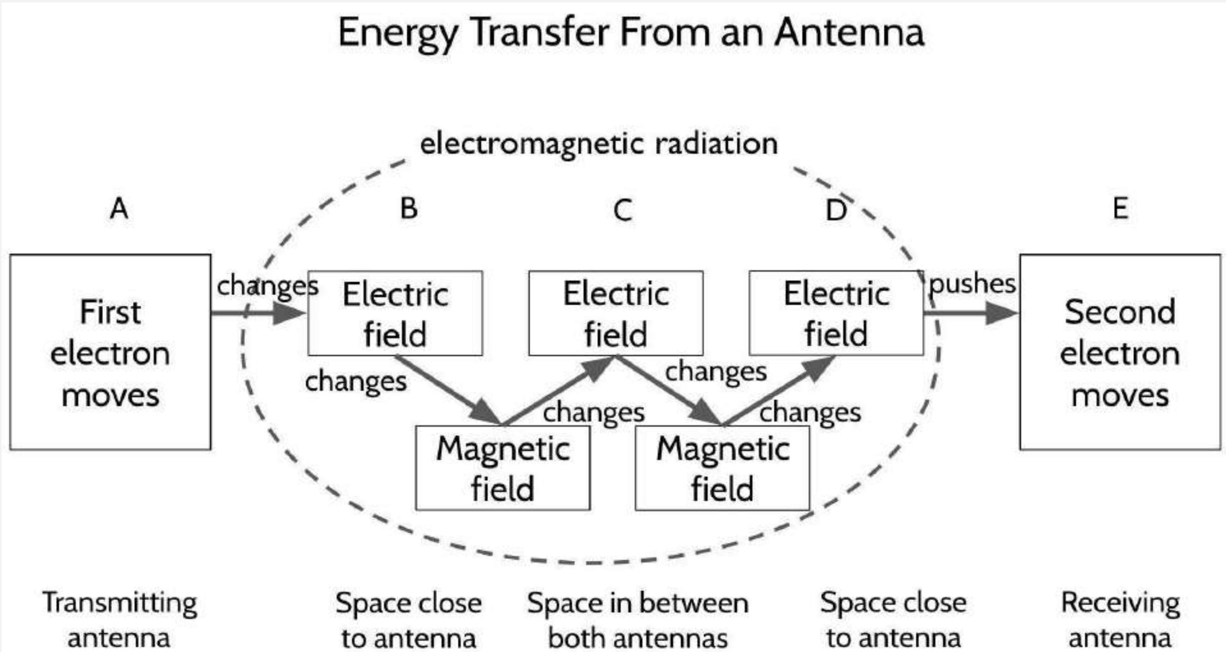
Give partners a few minutes to discuss these changes before inviting them to share. Listen for the following ideas:

- We should add changing magnetic and electric fields as the mechanism behind energy transfer.
- The vibrating electron changes electric fields, which changes magnetic fields, and so on.
- "Electromagnetic radiation" is what we call this system of changing fields.

✱ SUPPORTING STUDENTS IN DEVELOPING AND USING CAUSE AND EFFECT

This is an opportunity to help students recognize the complex cause-and-effect relationship that explains why electromagnetic waves travel through space without a medium. When building this explanation, it is not important to decide what happens first when the electron moves: changing electric fields or changing magnetic fields. In this case, the vibration of

Revise the consensus model on the poster. Record student ideas on the poster. Your finished model may look something like the example below. ✱ Once you have a useful model of changing fields, say, *We identified "electromagnetic radiation" as being important as soon as we read the Microwave Oven Manual. Are we ready to describe what that is now?*



charged particles causes changes in both electric and magnetic fields that propagate to space. Invite students to use the language of cause and effect in their explanations.

ASSESSMENT OPPORTUNITY

What to look for/listen for in the moment:

- Add changing magnetic fields as part of the mechanism that can help explain how energy transfers through electromagnetic radiation. (SEP: 6.2; CCC: 2.2; DCI: PS4.B.1)
- Describe energy transfer using cause-and-effect language that connects changes in electric and magnetic fields and the difference in motion of both electrons. (SEP: 6.2; CCC: 2.2; DCI: PS4.B.1)
- Call this system of changing magnetic and electric fields as electromagnetic radiation. (DCI: PS4.B.1)

What to do: If students feel stuck, use these prompts to elicit additional ideas that might help them move forward:

- *Can we explain why the electric field radiates only when the first electron moves?*
- *In the string, energy was transferred through fields between moving particles. How is energy transferred through electromagnetic radiation?*
- *Can we explain the delay in the motion of the second electron?*

Building toward: 4.B Examine smaller-scale mechanisms of changing electric and magnetic fields to construct an evidence-based explanation about energy transfer through electromagnetic radiation. (SEP: 6.2; CCC: 2.2; DCI: PS4.B.1)

Add entries to Personal Glossaries. Present **slide T**. Give students a couple of minutes to record definitions for *electromagnetic radiation* and *electromagnetic waves* in their Personal Glossaries using words or pictures.

12 · ADD IDEAS TO THE PROGRESS TRACKER

6 min

MATERIALS: *Progress Tracker*

Introduce and add to the *Progress Tracker*. Present **slide U**. Distribute the *Progress Tracker* to each student. Remind the class that throughout this course, we have kept track of our thinking using a Progress Tracker. Explain that the tracker is not intended to be a record of the "right" answers--it is a record of our changing thinking over the course of a unit, and should be a place where students feel comfortable reflecting on what they do not know or do not yet understand.

Tell students they can use drawings and words to fill in each column independently or to answer the three table prompts at once.

13 · NAVIGATE

4 min

MATERIALS: 8.5" x 11" paper

Assign and collect an exit ticket. Distribute a piece of paper to each student. Present **slide V**. Read the directions aloud:

- *Use words and/or pictures to make a prediction about what microwave radiation would do when it encounters matter.*

Give students the remaining time to complete this task. Collect these exit tickets as they leave.