CLEARING THE AIR

Using probeware and online simulations to understand the greenhouse effect

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This article describes a lesson on the greenhouse effect in which students explore blackbody radiation and Wien's law (Figure 1). The lesson, which has been tested in a variety of high school physics classrooms, uses probeware and online simulations and combines two well-established instructional strategies: the 5E Learning Cycle (Bybee et al. 2006) and the Prediction-Observation-Explanation (POE) demonstration (White and Gunstone 1992). This collection of activities is appropriate for either physics or Earth-space science courses.

As demonstrated by Wagoner, Liu, and Tobin (2010), many classroom investigations intended to demonstrate the greenhouse effect do not. Most of these flawed demonstrations compare either covered and uncovered containers of air or containers of air with containers of other gases. An actual greenhouse and most classroom demonstrations of the greenhouse effect work by trapping absorbed radiative heat *from a light source* (e.g., the Sun) by preventing it from leaving the structure through convection. The real greenhouse effect, however, happens when so-called "greenhouse gases" in the atmosphere (e.g., water vapor, carbon dioxide, methane) absorb outgoing radiation *from the Earth,* regardless of the presence of convection. A greenhouse is, in fact, not a very good model for the greenhouse effect.

Rye, Rubba, and Wiesenmayer (1997) suggested it is especially important to address this difference between incoming solar radiation and outgoing terrestrial radiation in relation to greenhouse gas absorption and the greenhouse effect, a study corroborated by Henriques (2002), who recounted student misconceptions about the greenhouse effect. This article's collection of classroom activities addresses such misconceptions by having students explore blackbody radiation and Wien's displacement law. Students applying these concepts discover that the constituent gases of the troposphere respond differently to different wavelengths of radiation, and this affects the surface temperature of the Earth.

Below, the lesson is presented using the five Es: engage, explore, explain, elaborate, and evaluate. The lesson may take one or two class meetings, depending on the directions students take in the "explore" section. If needed, parts of "elaborate" could be assigned for homework. The activities align with the *Next Generation Science Standards* (NGSS Lead States 2013) (see box, pp. 52–53).

Engage

The lesson opens with a POE demonstration using a stack of glass plates to model the greenhouse effect (materials list, Figure 2, p. 54). The teacher should set up the demonstration about an hour ahead of time to allow the system to equilibrate, but if time is short, can use screen-grabs of probeware output at equilibration instead of live output. As shown in Figure 3 (p. 54), students observe a stack of three glass plates with a surface temperature probe atop each plate placed under a light source. The teacher projects or writes the following question on the board, along with a hand-drawn schematic for reference (numbering the plates 1 through 3, starting with the top plate):

Which plate will have the highest surface temperature? Why?

- The plate closest to the lamp (1)
- The middle plate (2)
- The plate farthest from the lamp (3)

FIGURE 1

Core concepts.

Blackbody. An idealized body that completely absorbs all radiant energy incident upon it and emits electromagnetic radiation, called "blackbody radiation," according to Planck's law.

Blackbody radiation. The radiation emitted by any object may be approximated as blackbody radiation, i.e., electromagnetic radiation that has a specific spectrum and intensity that depends only on the temperature of the object and follows Planck's law.

Greenhouse effect. The process by which outgoing terrestrial radiation is absorbed by atmospheric gases, such as carbon dioxide, methane, and water vapor, and is reradiated in all directions. Since the troposphere (the lower level of the atmosphere) is essentially transparent to incoming solar radiation, without this effect, the average surface temperature of the Earth would be too cold to support life as we know it. The greenhouse effect should not be confused with global warming, which refers to the enhancement of the natural greenhouse effect due to increased greenhouse gas concentrations.

Planck's law. The empirically derived relationship between the temperature of an idealized object and the energy distribution of electromagnetic radiation it emits.

Wien's law. There is an inverse relationship between an object's temperature and its peak wavelength of emission. More specifically, the intensity of blackbody radiation per unit wavelength reaches its maximum at the wavelength λ_{max} given by

$$\lambda_{\max} = \frac{b}{T}$$

where T is the absolute temperature of the emitting body in kelvin (K) and b = 2897 μm*K is a constant of proportionality called Wien's displacement constant.

Students draw the schematic and write in their notebooks their predictions (including an explanation) individually, while the teacher circulates to answer any questions about the experimental setup, reminding students that no answers are wrong at this stage. Students may get up to observe the plate system. Next, the teacher asks the students to share their predictions through a poll (e.g., using a show of hands, a service such as polleverywhere.com, or clickers). The teacher explains that the question of which plate is hottest is tricky and then asks for volunteers to make arguments for the three possible responses.

Connecting to the *Next Generation Science Standards* (NGSS Lead States 2013).

Standards
HS-ESS2 Earth's Systems
HS-ESS4 Waves and Their Applications in Technologies for Information Transfer

Performance Expectations
The materials/lessons/activities outlined in this article are just one step toward reaching the performance expectations listed below.
HS-ESS2-4. Use a model to describe how variations in the flow of energy into and out of Earth's systems result in changes in climate.
HS-PS4-4. Evaluate the validity and reliability of claims in published materials of the effects that different frequencies of electromagnetic radiation have when absorbed by matter.

Dimension	Name and NGSS code/citation	Specific Connections to Classroom Activity
Science and Engineering Practices	**Analyzing and Interpreting Data** • Analyze data using tools, technologies, and/or models (e.g., computational, mathematical) in order to make valid and reliable scientific claims or determine an optimal design solution. **Developing and Using Models** • Use a model to provide mechanistic accounts of phenomena. (HS-ESS2-4) • Develop a model based on evidence to illustrate the relationships between systems or between components of a system. **Using Mathematics and Computational Thinking** • Use mathematical representations of phenomena or design solutions to describe and/or support claims and/or explanations.	Students analyze an online simulation of blackbody spectra to determine the relationship between the temperature of a body and its wavelength of maximum electromagnetic emission (Wien's law). Students relate a physical model, consisting of a lamp shining down on glass plates stacked on a table ("the plate model"), to the Earth's troposphere (lower atmosphere) to provide a mechanistic account of the greenhouse effect. Students look for patterns in the data collected using the blackbody spectra simulation to obtain a mathematical model of the relationship between wavelength of maximum intensity and temperature for blackbodies (Wien's law). Students apply a mathematical relation (Wien's law) to explain essential features of the greenhouse effect.
Disciplinary Core Ideas	**ESS2.D: Weather and Climate** • The foundation for Earth's global climate systems is the electromagnetic radiation from the Sun, as well as its reflection, absorption, storage, and redistribution among the atmosphere, ocean, and land systems, and this energy's re-radiation into space. (HS-ESS2-4)	Students discuss the similarities and differences between the electromagnetic radiation emitted by the sun and the Earth, noting overlap in wavelengths emitted and wavelengths absorbed/transmitted by atmospheric greenhouse gases.

Common Core State Standards Connections (NGAC and CCSSO 2010)

Mathematics

MP.2 Reason abstractly and quantitatively. (HS-ESS2-4)

MP.4 Model with mathematics. (HS-ESS2-4) Students look for patterns to determine the appropriate mathematical relationship to model the connection between the temperature of a blackbody and its wavelength of peak emission.

	PS4.B: 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. • When light or longer wavelength electromagnetic radiation is absorbed in matter, it is generally converted into thermal energy (heat). Shorter wavelength electromagnetic radiation (ultraviolet, X-rays, gamma rays) can ionize atoms and cause damage to living cells. (HS-PS4-4)	Students use the wave model to observe that wavelengths of electromagnetic radiation vary depending on the temperature of an emitter and that this is useful in understanding the differential absorption of terrestrial versus solar radiation by the atmosphere. Students examine absorption spectra for greenhouse gases in the Earth's troposphere, noting that greenhouse gases warm the Earth because they preferentially absorb longer wavelength electromagnetic radiation (outgoing terrestrial radiation, versus incoming solar radiation).
Crosscutting Concepts	**Systems and System Models** • Models (e.g., physical, mathematical, computer models) can be used to simulate systems and interactions—including energy, matter, and information flows—within and between systems at different scales. • Models can be used to predict the behavior of a system, but these predictions have limited precision and reliability due to the assumptions and approximations inherent in models.	Students use an online simulation that models emission spectra of blackbodies at various temperatures, as well as a physical model ("the plate model"), to explore the interactions between the Earth, the atmosphere, and the Sun, and to provide a mechanistic explanation for the greenhouse effect. Students consider both the usefulness and limitations of the physical "plate model" in understanding the Earth-atmosphere-Sun system.

Connections to Nature of Science:

- Scientific knowledge assumes an order and consistency in natural systems.
- Laws are statements or descriptions of the relationships among observable phenomena.
- Theories and laws provide explanations in science
- Science knowledge is based on empirical evidence.

While looking for order and consistency in the online blackbody simulation, "the plate model," and the Earth-atmosphere-Sun system, students confront the definition of a scientific law and the importance of empirical evidence in the discussion of nature of science following the introduction of Wien's Displacement Law (which was discovered empirically before it was derived rigorously mathematically).

If no one volunteers, students are directed to do a think-pair-share, until every student can provide potential explanations for at least two of the options. This exercise helps uncover misconceptions without pointing fingers.

While every class is different, the most common misconception is that what matters most is a plate's distance from the light source, and therefore the top plate, closest to the lamp, will have the highest temperature. Students sometimes compare the plates to blankets, serving as insulators, which leads to one of two predictions: (1) the bottom plate will be warmest because the two plates above it keep it warm, or (2) the middle plate will be warmest, because it is insulated by the top and bottom plate. These explanations are sensible, given the students' prior knowledge, but incorrect. These misconceptions are similar to those students have about the atmosphere and the greenhouse effect (Henriques 2002).

Students observe the temperatures of the plates (Figure 4; the bottom plate has the highest temperature) and record observations in their notebooks, explaining how their explanations may have changed and providing reasoning for any discrepancies between their prediction and observation. At this point, the teacher should refrain from explaining the phenomenon or telling students whether their explanations are correct.

Explore

This phase requires enough computers so that all groups of students (three per group works well) have access to the blackbody spectrum simulation (see "On the web") from the Physics Education Technology (PhET) project (Wieman, Adams, and Perkins 2008). (While not ideal, if there is only one computer, the teacher could manipulate the simulation at the students' direction in a whole-class discussion format, while students record data and conclusions individually.)

The blackbody spectrum simulation uses Planck's law (Figure 1, p. 51) to model emission spectra for objects of various temperatures. The law, originally formulated by physicist Max Planck in 1900, gives the intensity radiated by a blackbody as a function of wavelength and temperature. In this simulation, students learn about the spectra emitted by the Sun, a lightbulb, an oven, and the Earth, adjusting the temperature to observe resulting changes in wavelength and intensity of the blackbody spectrum.

Students are given a worksheet full of questions entitled "Exploring Planck's Law" (see "On the web" for worksheet and answer key) and are encouraged to record their answers in their own words for reference and to be ready to explain their findings at the end of the activity. This worksheet is designed to be exploratory and should be considered a formative assessment and lens into student progress and thinking.

The worksheet includes the following prompts:

- How are the spectra produced by the lightbulb and the oven similar? List as many ways as possible.
- How are the spectra different? List as many ways as possible.
- Explain the relevance of the position of the rainbow relative to the spectra.

After students have compared spectra from different objects, the second page of the worksheet directs them to determine the relationship between the temperature of an object and the peak wavelength of its emission. Providing only blank space, instead of a table to fill in, promotes creativity and critical thinking. As students look for patterns to determine the mathematical relationship between temperature and peak wavelength (Wien's law; Figure 1, p. 51), the

FIGURE 2

Demonstration materials.

The following materials are necessary for the opening POE activity:

- 3 glass plates
- 1 shop light or bright lamp
- 3 surface temperature probes (e.g., Vernier surface temperature sensors and Go!Link USB adapters)
- 1 laptop computer (must have at least 3 USB ports and LoggerLite pre-installed to use probeware)

FIGURE 3

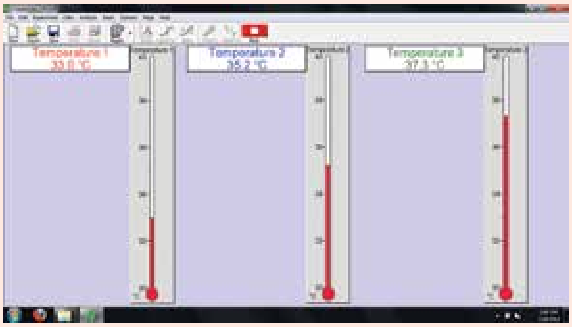
Demonstration setup.

Three glass plates are stacked under a bright lamp. A surface temperature probe is placed on each plate. The system remains untouched for one hour to equilibrate.

FIGURE 4

Demonstration temperature measurement.

Temperatures 1, 2, and 3 refer to the plate closest to the lamp (1 = top), the middle plate (2 = middle), and the plate farthest from the lamp (3 = bottom), respectively.



teacher circulates among them and evaluates their progress. Once groups have begun to notice the inverse relationship, the teacher begins a class discussion.

Explain

The class discussion addresses students' results from the Planck's Law Exploration, including discussing how the spectra of blackbodies with different temperatures were similar, how they were different, and the relationship between temperature and wavelength of maximum intensity (the worksheet key includes typical student answers and teacher expectations; see "On the web"). Only after the students have effectively discovered it themselves should the teacher introduce Wien's law. This is a good point to discuss the nature of science, specifically the definition of a scientific law and that scientific knowledge is based on empirical evidence (see box, pp. 52–53).

Next, students examine a plot of solar radiation and terrestrial radiation (Figure 5) and are asked to compare and contrast the incoming solar radiation spectrum (red curve) and outgoing terrestrial radiation spectrum (blue curve) in a whole-class discussion. The teacher could begin the discussion with a broad question about Figure 5, such as "How does the spectrum of incoming solar radiation compare to that of outgoing terrestrial radiation, and how does that relate to what we've learned so far?" Sometimes student-to-student discussion about the red and blue curves and the relevance of Wien's law takes off from there; other times it needs more scaffolding (e.g., "What does this plot represent? What are the axes? What is the red line? The blue line?"). Through this discussion, students should conclude that since the surfaces of the Earth and Sun have very different temperatures, Wien's law dictates that their emission spectra are well-separated in the electromagnetic spectrum.

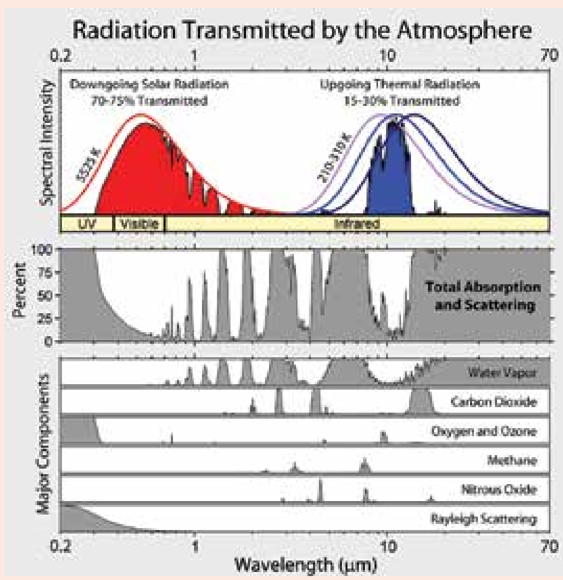
The teacher should make sure to point out the absorption spectra for various greenhouse gases shown in the figure, specifically noting that the greenhouse gases predominantly found in the troposphere (water vapor, carbon dioxide, and methane—three of the major components shown in Figure 5) preferentially absorb infrared radiation and tend to be more transparent to visible light (i.e., the plot of absorption and scattering for each includes multiple maxima in the infrared range but is minimal in the visible range). Probing questions guide students to connect the spectra of incoming solar radiation and outgoing terrestrial radiation (top half of Figure 5) to what they have learned about Wien's law and then to note that different gases emit and absorb characteristic frequencies of light (bottom half of Figure 5).

Elaborate

It turns out that clear, colorless glass, much like greenhouse gases, preferentially absorbs infrared radiation and tends to be transparent to visible light. With this in mind, students are asked to turn back to their notes from the POE activity ("Engage" section) and to reevaluate their final explanations, appending their new thoughts. Next comes another whole-class discussion about the scientifically accepted explanation for the temperature distributions of the plates shown in Figure 4. If students do not bring it up naturally, the teacher should ask how what they have learned about Wien's law, blackbody radiation emission spectra, and absorption spectra relate to the plate model. This is where the class makes the connection

FIGURE 5

Atmospheric transmission.



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between the plates and the greenhouse effect explicit. Following the discussion, the students revisit their individual explanations and append any additional ideas they now think are important. The plate closest to the table absorbs the most radiation and is therefore the warmest. This is because the table primarily emits infrared wavelengths and the lamp primarily emits visible wavelengths of electromagnetic radiation, and the glass plates preferentially absorb infrared radiation.

Students work through the final activity individually, following "The Plate Model of the Greenhouse Effect" section of the worksheet (see "On the web"). They draw connections between the plate model from the POE at the beginning of the lesson and everything they have learned about blackbody radiation through the rest of the lesson, relating the plate system to the greenhouse effect. This tangible application of Wien's displacement law highlights the usefulness and limitations of the plate model. The worksheet answer key (see "On the web") provides expert explanations (for the teacher's benefit) to the following prompts:

Q. Explain how the Plate Model relates to Earth and its atmosphere (e.g., What does the lamp represent? What do the plates represent? What part of the model corresponds to the Earth?).

A. lamp = Sun; plates = atmosphere; table = Earth

Q. What is Wien's law and why is it relevant to a discussion of the greenhouse effect? Use evidence from the lesson to support your claim (e.g., absorption and emission spectra).

A. There is an inverse relationship between temperature and wavelength of peak emission, and this is relevant because the temperatures of the Earth and the Sun are (very) different and the gases that make up the troposphere preferentially absorb radiation at wavelengths emitted by the Earth.

Q. What properties of the "plate model" make it analogous to the Earth-atmosphere-Sun system? Why?

A. An ideal student answer would include: (1) glass (like greenhouse gases) preferentially absorbs infrared radiation while remaining largely transparent to visible light, and (2) the temperature of the lamp (Sun) and the table (Earth) are very different, and thus emit radiation at different wavelengths.

Q. How is the model useful? What are the limitations of the model?

A. This is meant to be open-ended, and any response that demonstrates that the student is thinking critically is acceptable. The worksheet key includes common and acceptable answers (see "On the web").

Evaluate

The student worksheet "The 'Plate Model' of the Greenhouse Effect" (see "On the web") can be completed in class or as homework to serve as a summative assessment. It provides evidence of a student's ability to apply the target concepts (blackbody radiation, Wien's law, the greenhouse effect) and draw connections between the plate model and the atmosphere, demonstrating their understanding of the physical mechanisms underlying the greenhouse effect.

This lesson intentionally omits global warming but would be an excellent introduction to a larger unit on climate change (see "On the web" for another PhET simulation on the greenhouse effect). Specifically, one can think of increasing or decreasing greenhouse gas concentrations in the atmosphere as analogous to inserting or removing a plate in the plate model activity described in this article. ■

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On the web

Blackbody Spectrum simulation: *http://phet.colorado.edu/en/simulation/blackbody-spectrum*

"Exploring Planck's Law" and "The Plate Model of the Greenhouse Effect" worksheets: *www.nsta.org/highschool/connections.aspx*

The Greenhouse Effect simulation: *https://phet.colorado.edu/en/simulation/greenhouse*

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