TEACHER ANSWER KEY

Exploring Planck's Law

Note: This worksheet is designed to be exploratory and as such should be considered a formative assessment and lens into student progress and thinking. Although "correct" answers are provided below, if using this worksheet for a grade, that grade should be based on effort/completion.

This activity was designed to be completed using the following PhET simulation:
http://phet.colorado.edu/en/simulation/blackbody-spectrum

The simulation allows you to select a temperature and uses Planck's Law to plot the blackbody curve (emission spectrum) associated with that temperature as a function of the wavelength of the electromagnetic radiation. Try changing the temperature (by either dragging the knob or typing a number into the box) and observe how the emission spectrum changes.

Note: you may need to rescale the axes, using the magnifying glass icons to zoom in and/or out, to be able to read the plot at certain temperatures.

Once you have established some familiarity with the simulation…

COMPARING SPECTRA FROM DIFFERENT OBJECTS:
The cartoon thermometer on the right indicates the approximate temperature of the Sun, a light bulb, an oven, and the earth. Use the simulation to answer the following questions.

1. How are the spectra produced by the light bulb and the oven **similar**? List as many ways as possible

- the overall shape of the distribution of intensity vs. wavelength is similar
- both have a wavelength that corresponds to an absolute maximum in intensity
- these absolute maxima in intensity both occur in the infrared range (wavelengths longer than visible light)
- intensities for both approach zero for sufficiently small wavelengths
- intensities for both approach zero for sufficiently large wavelengths
- both plots of intensity skew positive, i.e., the right tail is longer

2. How are the spectra **different**? List as many ways as possible.

- the magnitudes of the intensities are substantially different, and the spectrum for the light bulb has greater overall intensity compared to the oven
- the wavelength of the maximum intensity for each is substantially different
    - $\lambda_{max} \approx 1\ \mu m$ for the light bulb
    - $\lambda_{max} \approx 4\ \mu m$ for the oven
- the maximum intensity for each is substantially different
    - $I \approx 3\ MW/m^2/\mu m$ for the light bulb
    - $I \approx 0.002\ MW/m^2/\mu m$ for the oven

(this could all be stated qualitatively without including the actual quantitative values)

3. Explain the relevance of the position of the rainbow relative to the spectra.

The rainbow illustrates the wavelengths of visible light.

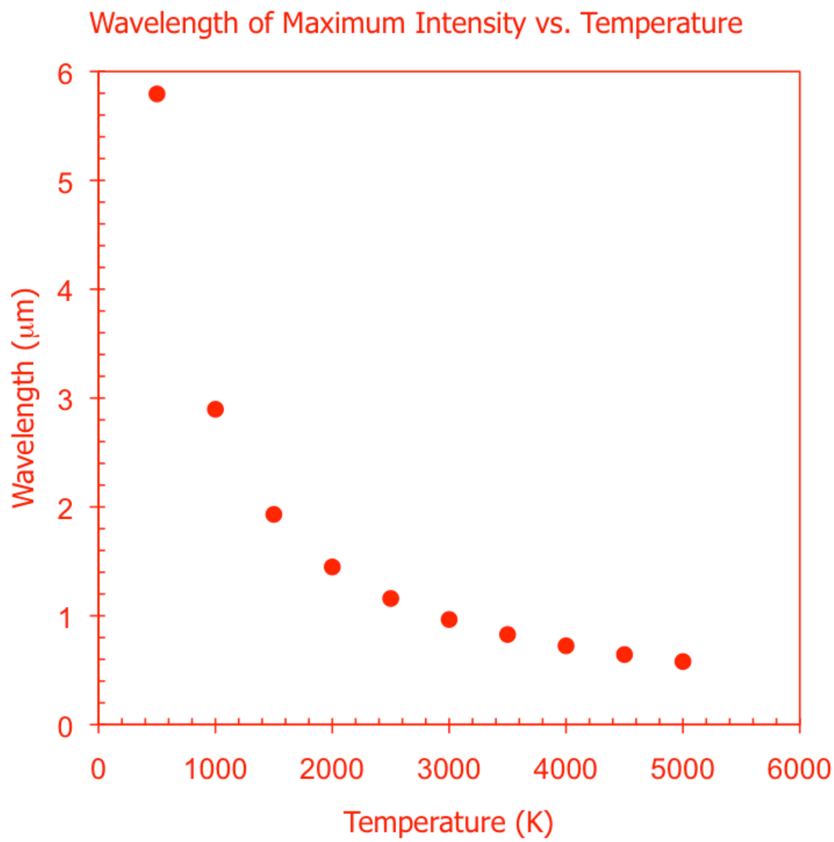
DETERMINING THE RELATIONSHIP BETWEEN TEMPERATURE AND PEAK WAVELENGTH:
You should have noticed that both the intensity and the distribution of the spectrum change drastically with changing temperature (i.e., it was necessary to zoom both axes in order to see the spectra). Use the simulation to determine the relationship between the wavelength of the maximum intensity (λ_{max}) and temperature (T). You may use the space below to construct tables and/or sketch plots.

Do you notice any patterns? What is the mathematical relationship between T and λ_{max}?

Students may use a table and/or graph to examine patterns. Typical student answers will not come out as cleanly as below, since making measurements using the imprecise scale/ruler tools in the phet simulation introduces error. Also, they will choose what temperatures to test, so the table and graph below are just examples.

The goal is for students to discover the <u>inverse relationship</u> between the wavelength of the maximum intensity (λ_{max}) and the temperature (T).

T (K)	λmax (μm)
500	5.79
1000	2.90
1500	1.93
2000	1.45
2500	1.16
3000	0.97
3500	0.83
4000	0.72
4500	0.64
5000	0.58



Although students are not expected to find this equation on their own, the ultimate form this relationship takes is given by:

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

where b = 2897 μm/K is a constant of proportionality (Wien's displacement constant).

TEACHER ANSWER KEY

The "Plate Model" of the Greenhouse Effect

The "Plate Model," a system that consists of three glass plates stacked on top of each other under a bright light bulb, can be useful for providing insight about the troposphere (the lowest portion of the Earth's atmosphere) in a laboratory setting. Specifically, the plates model the way the troposphere responds to incoming solar radiation and outgoing terrestrial radiation.

The "Greenhouse Effect" is a process by which outgoing terrestrial radiation is absorbed by atmospheric gases, such as carbon dioxide, methane, and water vapor, and is re-radiated in all directions. Since the troposphere is essentially transparent to incoming solar radiation, without an atmosphere, the average surface temperature of the earth would be too cold to support life as we know it.

The following questions were designed to help you relate the plate system to the Earth's atmosphere and apply what you have learned about blackbody radiation in order to build a conceptual understanding of the important elements of the greenhouse effect.

1. 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).

The students should be able to identify the following connections between the model and target systems:
- lamp = sun
- desk = earth
- plates = atmosphere

A more specific explanation (not expected from the students here, but for the teacher's benefit) is that the plates model the troposphere, i.e., the lowest portion of the Earth's atmosphere. Like greenhouse gases, glass preferentially absorbs infrared radiation and tends to be transparent to visible light. Like the real earth and sun, the emission spectra of the table and the lamp are well-separated in the electromagnetic spectrum, with the former emitting primarily at infrared wavelengths and the latter at visible wavelengths. Because of this, the plates (atmosphere) preferentially absorb the *upward* radiation, from the table (earth). This is why the plate closest to the table absorbs the most radiation and is the warmest—as the upward radiation passes through and is partially absorbed by each plate, less and less is transmitted up to the next plate to be available for absorption.

2. 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).

An ideal student answer would include the following points:
- there is an inverse relationship between temperature and wavelength of peak emission (Wien's Law; stated in either words and/or equations)
- the temperatures of the earth and the sun are (very) different
- because of the difference in temperature of the earth and sun, the two emit at (very) different wavelengths (could deduce this from Wien's Law and/or refer to the emission spectra figure)
- the gases that make up the troposphere preferentially absorb infrared radiation, i.e., radiation emitted by the earth (refer to absorption spectra of CO_2 and water vapor)

3. What properties of the "Plate Model" make it analogous to the earth-atmosphere-sun system? Why?

An ideal student answer would include both of the following facts:

- glass (like greenhouse gases) preferentially absorbs infrared radiation while remaining largely transparent to visible light
- the temperature of the lamp and the desk are very different, and thus emit radiation at different wavelengths

This 1) differential absorption of wavelengths of radiation along with 2) the separation in emission spectra is what is responsible for the greenhouse effect.

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

This is meant to be open-ended, and any response that demonstrates that the student is thinking critically (i.e., reasonably and logically) is acceptable.

Common and acceptable student answers often note that the geometry is not accurate (e.g., this is basically a 1D model and the earth is 3D, the plate and lamp are quite close compared to the earth and sun), that the plates are solid and the atmosphere is a fluid, that surface of the earth is not uniform and does not look like a table, the sun and the light bulb are not producing the same spectrum, etc. Even with these limitations, the model helps us understand how the lower atmosphere produces a greenhouse effect that keeps the earth habitably warm, by differentially absorbing outgoing (terrestrial/desk) radiation in preference to incoming (solar/lamp) radiation.

Some additional areas of usefulness and limitation are discussed below for the benefit of the teacher, but are not expected from the students.

Usefulness:

Despite its simplicity, this model captures the first order physical phenomena responsible for the greenhouse effect. It allows us to examine and test certain hypotheses in an easy to alter table-top experiment, e.g., what would happen to the surface temperature if we changed greenhouse gas concentrations (i.e., added or removed additional plates).

Limitations:

This three plate model is an oversimplification of the structure of the true atmosphere, providing an incomplete model of the troposphere (the layer of the atmosphere closest to the earth's surface) and neglecting the stratosphere and aloft. This model only includes static radiative effects, and does not include the effects of turbulent mixing or fluid flow that are prevalent in the troposphere.