

# Student Understanding of Blackbody Radiation and Its Application to Everyday Objects

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**Abstract:** The Physics Education Group at the University of Washington is examining student understanding of blackbody radiation. Results from interviews and questions administered in sophomore and upper-division courses indicate that traditional instruction on blackbody radiation often does not help students apply the concepts and mathematical formalism to real-world objects. We are developing an online homework that approaches blackbody radiation from a phenomenological viewpoint, rather than from an idealized formalism. Initial use suggests that this homework helps students understand, for example, how the spectrum of an incandescent light bulb changes with temperature. Moreover, students who have worked through the homework also seem able to provide more robust answers during interviews than students who have not. However, we find that students continue to struggle with the concept of blackbody radiation. Additional research is needed to be able to design more effective instructional materials.

**Keywords:** physics education research, student understanding, quantum mechanics, modern physics, online homework, blackbody radiation

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## INTRODUCTION

The explanation for blackbody radiation helped lay the foundation of quantum mechanics. It is taught in many modern physics courses as a way of bridging the gap between classical and quantum models. It is often taught together with other fundamental experiments such as the photoelectric effect, Compton scattering, and the Bohr model in order to motivate the necessity for quantization. Some previous research has been conducted on student understanding of these topics, but very little on blackbody radiation [1–3]. These other experiments draw on ideas that are familiar to students from introductory courses (electric circuits, momentum conservation, and atomic structure), while blackbody radiation is arguably more abstract.

Blackbody radiation is commonly introduced in the context of a theoretical black box that is both a perfect absorber and perfect emitter of radiation, from which the Planck distribution is derived [4]. Homework and exam questions are often highly quantitative, requiring the use of formulae that may not be well-motivated to students, such as the Stephan-Boltzmann Law and Wien's Displacement Law. The light emitted by stars is the most commonly presented context, despite the existence of numerous everyday objects that may be approximated as blackbodies, such as light bulbs [5]. Since it is not taught from this perspective, it is perhaps not surprising that students struggle to connect blackbody radiation to everyday real-world objects.

Our current research is intended to identify the specific ideas with which students have difficulty. We

are also developing curriculum to improve student understanding of this topic, targeted at students who have completed or are at the end of introductory physics. The approach and methods used have been described in other papers from the Physics Education Group at the University of Washington [6].

This paper is divided into three parts, each focusing on a different population of students. Part I discusses results from early interviews with sophomore modern physics students. Part II reports on findings from questions administered online to juniors and seniors. Part III describes how the research has guided the development and assessment of an online instructional homework for students in a sophomore modern physics course. All data is from students enrolled in courses that are part of the physics major degree program at the University of Washington.

## PART I: STUDENT INTERVIEWS

Early in this research we conducted interviews with four students in their second year of instruction in physics. They had previously completed a full year of introductory physics, which included some basic quantum mechanics. They had also completed a one-quarter traditional (non-interactive) course on modern physics that also included some introductory quantum mechanics. The one-hour interviews were conducted during the quarter immediately following the modern physics course.

## Methods

In the first half of the interview, we described a theoretical device that could detect electromagnetic waves emitted from an object, and could measure the intensity emitted at any frequency. The students were asked to describe what this detector would measure from various objects, such as colorful books and people. They were also asked whether their answers would change if the lights in the room were turned off.

The second half of the interview focused on having students predict the graph of intensity versus frequency for an incandescent light bulb at different levels of illumination. If the students did not bring up the term blackbody radiation, the interview concluded with a question about how it related to the interview context.

## Results

Despite the fact that blackbody radiation had been covered in class and on exams, students failed to recognize its relevance to the interview context. Students could not identify that all objects emit radiation which depends on their temperature; for example, they described objects at room temperature as not emitting any radiation other than reflected light and drew incorrect spectra for incandescent light bulbs. Students also failed to use correct and consistent labels for the axes on their graphs.

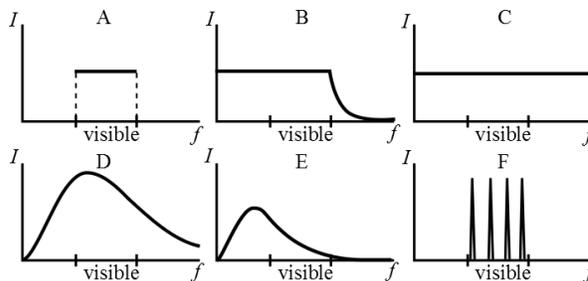
Additional common difficulties included a tendency to confuse frequency and wavelength and an inability to locate different parts of the spectrum on their graphs (*e.g.*, visible and infrared). Students also could not identify the quantity represented on the vertical axis of the graph. Only one student connected blackbody radiation to this topic, even after the term was brought up by the interviewer.

## PART II: ONLINE QUESTIONS

### Methods

Based on the results of the interviews, we designed a sequence of questions on blackbody radiation to assess the prevalence and persistence of the difficulties we had identified. These questions were administered online to two different populations: 25 students at the end of their first quarter of junior-level quantum mechanics, and 15 students in a senior-level course on particle physics. All of these students had previously completed the modern physics course described above.

**Question 1:** An incandescent light bulb is turned on in a darkened room with no other sources of light. Which of the following graphs (see Fig. 1) best describes its electromagnetic spectrum? Explain.



**FIGURE 1.** Answer choices for the questions administered to upper-division students. Choices A-C were based on incorrect sketches made by students in interviews.

Choices A-C in Fig. 1 were based on sketches made by students during the interviews. They represent the idea that a light bulb emits the same amount of light at some subset of frequencies. Choice D is a blackbody curve with its peak in the visible spectrum, which would only be accurate for an object with a temperature similar to that of the sun. The correct answer (E) is a blackbody curve with a lower temperature than choice D, which has its peak located outside the visible spectrum. We included choice D to make it more difficult to select the correct answer with incomplete reasoning. Choice F is from an object with a discrete spectrum.

**Question 2:** The current through the light bulb is reduced to half its original value. Describe how the spectrum of the light bulb changes. Explain.

## Results

On question 1, most students (80%) chose one of the blackbody curves (D and E). However, fewer than half of the students explained their answer using the term blackbody radiation. On question 2, 65% of the students gave answers consistent with a decrease in intensity or brightness. However, only 35% described a change in the frequency distribution of the spectrum. Very few students gave any explanation for the cause of these changes, with only 15% specifying a decrease in temperature. The others identified no change, or did not reference intensity in their answers. Even for the correct answers, most explanations did not use scientific terms, including those associated with blackbody radiation, such as the quantitative laws discussed in the introduction.

## PART III: ONLINE HOMEWORK

To try to help students relate blackbody radiation to real-world phenomena, we designed a one-hour online instructional homework that was used in the sophomore modern physics course described in part I. In this homework, students considered blackbody

radiation phenomenologically. A total of 95 students completed the instructional homework, which was graded and returned with feedback.

The homework began with a question about the application of blackbody radiation to real-world objects (question 1 below). Then students were directed to an online PhET simulation on blackbody radiation [7,8]. The simulation displays a graph of the Planck distribution for a user-selected temperature, such as those associated with an oven, a light bulb, or the sun. We then asked students several more questions including questions 2 and 3 given below. In the last part of the homework, students viewed a video of an iron nail being heated, breaking, and then cooling down, with the associated blackbody curve inset in the video [9]. We also asked guiding questions about the video. The instructor told the students to read about this topic in the book, but did not lecture on it in class.

## Assessment

To measure the effectiveness of the online homework, we administered pre- and post-tests to the students. We also studied the responses students gave to the questions on the homework in order to assess and improve its potential for instruction. Lastly, we conducted three additional student interviews using the same protocol (described in part I) as for the students who received traditional lecture instruction. These interviews were performed the quarter immediately following instruction.

### Pretest

**Question:** Sketch a possible graph for the electromagnetic spectrum of an incandescent light bulb.

**Results:** Only 30% of the students drew something that might be interpreted as a blackbody curve. Very few students labeled the spectrum or explained how they arrived at their answer. These results were similar to those from the interviews.

### Online Homework

**Question 1:** Which of the following have spectra that may be well-approximated by a blackbody distribution: fire, an incandescent light bulb, a star, a fluorescent light bulb, an LED, and a tree? Explain.

**Results:** Student responses to this question were highly variable. Several students stated the idea that an object can only be approximated as a blackbody if it is or can get hot. Two typical explanations are shown below.

*“Blackbody distributions are dependent on high*

*temperatures.”*

*“The others would not have a high enough temperature to show up in blackbody radiation.”*

**Question 2:** (a) Estimate what percentage of the energy emitted by a light bulb is in the form of visible light. (Students were shown a graph consistent with the temperature of a light bulb.) (b) Is a light bulb an efficient or an inefficient source of lighting? Explain.

**Results:** Almost all students reasoned correctly that the light bulb was an inefficient source of visible light, by estimating what fraction of the area under the curve fell within the visible spectrum. Most students (65%) gave essentially correct explanations such as the one below, although many tended to use words such as non-visible rather than infrared.

*“A light bulb is ... inefficient ... because the majority of the radiation is in the infrared spectrum which we cannot see.”*

About 15% of students, such as the one below, confused or did not distinguish between heat and infrared light.

*“... more than 80% of the energy emitted is in the form of heat and not light that we can see.”*

**Question 3:** Some night-vision goggles can be used to distinguish objects in complete darkness (with no external sources of light). Using what you have learned, identify the conditions under which night-vision goggles can be used to distinguish between two different objects.

**Results:** About 60% of students answered this question correctly. However, only 40% of them identified a *difference* in temperature between the objects as a critical feature to be able to distinguish the objects; the remaining 20% did not include temperature in their reasoning. These incomplete responses, such as the one below, focused on a difference in frequency or intensity without identifying the underlying cause.

*“The different objects must emit light at the different frequencies (or energies) so that they exhibit different colors and are therefore recognized distinctly from each other.”*

**Summary:** The results from the online homework are encouraging. Many students seemed to learn some of the fundamental properties of blackbody radiation from the simulation and exercises on the online homework. However, it is clear that many students fail to apply the correct reasoning to account for all consequences of blackbody radiation.

## Exam

The following free-response exam question was asked approximately one week following the completion of the homework.

**Question:** Three identical incandescent light bulbs (A, B, and C) are illuminated such that the total power emitted by bulb A is equal to the combined total power emitted by bulbs B and C. Draw a graph of intensity versus frequency for bulb A and a similar graph for bulb B. Describe any differences between the graphs and explain your reasoning.

**Results:** Students who drew any curve for bulb A consistent with a blackbody curve were counted correct. Responses were only considered correct with correct reasoning if they also identified both of the important differences between the two graphs: the curve for bulb B should be shifted down in frequency (the temperature is lower) and have less total intensity than bulb A. Table 1 shows the pretest and exam results. There is a clear improvement in the ability of students to apply blackbody radiation to light bulbs, although there is room for improvement in their ability to give complete explanations.

**TABLE 1.** Comparison of student responses on pretest and midterm exam questions.

Correct ...	Pretest (N=94)	Exam (N=107)
Blackbody curve*	30%	80%
with explanation	<5%	20%
Change in intensity	N/A	85%
Shift in frequency	N/A	40%
Shift in temperature	N/A	30%

\*Includes all curves consistent with blackbody radiation

## Interviews

Interviews with students who completed the online homework indicate a more thorough understanding of blackbody radiation than the students who received only traditional lecture instruction. A full quarter after completing the homework, the students we interviewed were able to draw and explain blackbody curves for real-world objects, extending beyond the light bulb context they had studied. They made direct references to the simulation used in the homework and gave more complete reasoning when changes were made to a system. However, many students still had difficulties relating frequency, wavelength, intensity, and temperature for blackbodies.

## CONCLUSION

Our findings indicate that after traditional instruction, a majority of students do not associate blackbody radiation to real-world objects. Without

instruction explicitly devoted to making these connections, many students fail to apply blackbody radiation beyond the framework within which it is studied. Even students who recognize that blackbody radiation may apply to everyday objects often do not use the formalism they have learned correctly, and often fail to identify one or more of the important features of these phenomena.

Evidence from students who completed our online homework suggests that emphasizing the more qualitative properties of blackbody radiation can help students answer qualitative questions. In particular, interviews with these students reveal that they were significantly more capable of relating blackbody radiation to everyday objects, and more likely to use blackbody radiation as an explanation of physical phenomena, than students who had received traditional instruction.

Future research and curriculum development by our group is aimed at extending the ideas in the online instructional homework to the classroom. This will take the form of an interactive lecture that will allow students to discuss their ideas with each other to form a more robust model of blackbody radiation as it relates to the real world. It will also help students bridge the gap between classical and quantum mechanics, which is the primary motivation for introducing this topic to modern or quantum physics courses.

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