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Exploring the greenhouse effect through physics-oriented activities

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Abstract

We are developing a new activity-based unit on global warming and the environment as part of the *Explorations in Physics Curriculum*. We describe the current status of this unit, which focuses on helping students understand the greenhouse effect and its relationship to global warming. We outline several problems encountered in testing the unit and share our ideas about how to improve it. These improvements include the introduction of the concept of dynamic equilibrium to help students understand global warming, population growth and other environmental phenomena.

(Some figures in this article are in colour only in the electronic version)

Introduction

In this paper we describe the *Explorations in Physics* (*EiP*) curriculum development project and present details about a new unit currently entitled *Energy, Fuels and Environment*. A major goal of this unit is to help students understand global warming and other environmental issues. It is designed for use in teacher preparation programs and general studies courses; however, the hands-on nature of the course has already inspired some students to pursue one of the sciences as a major. As part of our presentation of the unit we describe key activities designed to help students understand the greenhouse effect. We then summarize some of the problems encountered during classroom testing of the unit. Finally, we share our ideas for how we plan to revise the unit by introducing the concept of dynamic equilibrium—a concept we feel is essential for a more comprehensive understanding of global warming, population growth and other environmental phenomena.

The Explorations in Physics Curriculum

As part of the *Workshop Science Project*[1] we have been developing a series of activity-based *Explorations in Physics* units for non-science majors [1, 2]. The *EiP Curriculum* is part of an ongoing effort to increase the effectiveness of science education at the undergraduate level [3]. Each unit in the curriculum combines the use of guided-inquiry techniques with self-directed projects that help students acquire a more fundamental understanding of the nature of science. The goal of this curriculum is to change the focus of introductory science courses from covering a large number of topics (usually accomplished via lectures) to giving students experience with the process of scientific investigation. Students are encouraged to construct a consistent mental model of the

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Table 1. Sections in the Energy, Fuels and Environment unit.

Section[a]	Energy, Fuels and Environment	Hours
1	Societal issues via web search and ethical debate	2
2	Exploration of the greenhouse effect	6
3	Exploration of sources of carbon dioxide	6
4	Oceans and rain forests as moderators	4
5	Projects	~15

[a] Sections 1–4 involve core activities and section 5 is student projects.

concepts under study through direct observation and scientific reasoning.

We emphasize the development of a 'storyline' in each unit that directs students to connect specific activities to real-world phenomena. This provides a framework for students to develop their own scientific investigations that they complete during the project phase of the course. The core material in each unit is explored through a series of activities that students work through in small groups. These activities involve predictions, observations, measurements, analysis and reflections designed to guide the students through the process of scientific inquiry. The core material for a unit is typically followed by an extended student-directed project that draws on topics introduced in the core activities. Students meet in a laboratory setting equipped with computer tools for data collection, display and analysis as well as for web research.

The *EiP* units are designed to be completely independent of one another and can be introduced in any order. This flexibility allows instructors to design a course to match their particular needs and interests. Four units have already been published [4]. These include:

- Unit A: Force, Motion, and Scientific Theories
- Unit B: Light, Sight, and Rainbows
- Unit C: Heat, Temperature, and Cloud Formation
- Unit D: Buoyancy, Pressure, and Flight

Additional units under development are:

- Unit E: Energy, Fuels, and Environment
- Unit F: Sound, Vibrations, and Music
- Unit G: Magnets, Charge, and Electric Motors

In this article we share our experiences in developing, testing and refining the *Energy, Fuels, and Environment* unit at Dickinson College in Spring 1999 and again in Spring 2002. We will describe the current unit, describe some of the successful activities, pinpoint some of the problems with the unit and discuss some changes we plan to make.

The Energy, Fuels, and Environment unit

The *Energy, Fuels, and Environment* unit was designed to help students understand how the combustion of fossil fuels, which adds carbon dioxide to the environment, can contribute to global warming by means of the greenhouse effect. The unit was initially drafted by Nancy Devino, a former member of the Dickinson College Chemistry Department. The Unit was designed to cover approximately 30 to 36 hours of class time and is organized into five sections. The first four of these sections introduce core material and centre around guided activities (see table 1).

In the first section, which addresses global warming as a scientific and political matter, students explore the issues through web research and discussion. Students are asked to contrast the views on the global warming issues expressed by environmental organizations with those presented by industry groups. This first section concludes with students making a list of concepts they will need to understand in order to begin making sense of the global warming debate.

The next section, on the Greenhouse Effect, is in many ways the most critical of all the sections. Here students make several observations to understand the key role of water vapour and carbon dioxide as absorbers of infrared radiation. We describe these activities in more detail in the next section of this article.

In the third section, students do several simplified calculations. They estimate the rate of carbon dioxide released to the atmosphere due to respiration by the world's human population. Then they contrast this with the amount of carbon dioxide released when the world's inhabitants drive cars. Students then make some crude measurements of the relative amounts of carbon dioxide released when butane and propane are burned as a function of the heat value of these fuels. They complete the section by discussing web data showing that US residents burn considerably more fossil fuels per capita than people in any other country.

In section 4 students do activities that demonstrate how carbon dioxide can be removed from the atmosphere by natural processes. These include measurements of carbon dioxide uptake in the photosynthesis of fresh leaves and the absorption of the gas by the surface of water.

In the final section students break into groups of three and choose hands-on projects that are either designed by them or suggested by us. The criteria for choosing suggested projects are nicely summarized in an article by Mark Lattery [5], who has used some of our units at the University of Wisconsin at Oshkosh. Some projects students have done as a capstone experience for this unit (see figure 1) include:

- How exercise affects human CO_2 emission.
- The effects of light intensity and colour on plant photosynthesis and respiration.
- Plant growth rates and the addition of nitrogen and CO_2 to the atmosphere.
- The impact of temperature on aquatic plant photosynthesis and respiration.
- Exploring the effects of global warming on ocean levels.

Sometimes the outcomes of projects catch students by surprise. For example, one student who took our course because she was an ardent environmentalist chose to study plant growth as a function of the carbon dioxide level in the air. She was amazed to find that green plants grow better when additional carbon dioxide is available to the plant. She thought this phenomenon was a myth perpetrated by industry.

Exploring the greenhouse effect

A major focus of the *Energy, Fuels and Environment* unit was to help students understand the greenhouse effect and its role in global warming. As is typical of the *EiP* units, we developed a set of activities to explore the greenhouse effect.

Figure 1. Top: a CO_2 sensor is used to measure the amount of carbon dioxide in a plant's environment. Bottom: students complete some last minute experiments as they prepare the oral presentation of their project.

The activities described below are designed to help support the standard model of the greenhouse effect. In this model, electromagnetic energy at visible wavelengths coming from the sun passes through the atmosphere and is absorbed by the surface of the Earth. This energy is then reradiated as infrared radiation that does not penetrate the atmosphere as easily. As a result, some of the energy from the sun is trapped in the Earth's atmosphere and serves to elevate the temperature at the surface of the Earth. Figure 2 illustrates this model. Students develop a background for understanding the greenhouse effect by engaging in activities that guide them to explore several key topics, including electromagnetic radiation, conversion of visible radiation to infrared radiation and selective absorption of infrared radiation.

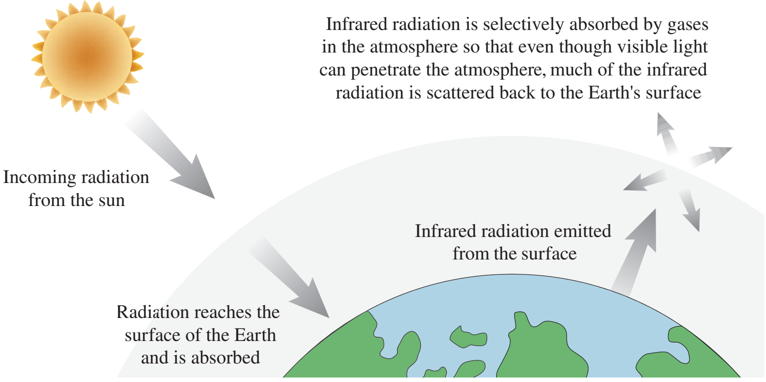

Figure 2. The greenhouse effect in the atmosphere.

Electromagnetic radiation

Students began by observing visible and infrared light to appreciate that we are only able to see a small fraction of the electromagnetic radiation coming from the sun. They first looked at an infrared source with their eyes and then with a digital camera. They saw nothing with their eyes because the human eye is not sensitive to infrared. However, the infrared source was clearly visible through the camera since the CCD in the camera is very sensitive to infrared radiation.

Following this activity, we demonstrated how visible and infrared light are related. First, a digital camera was used to take a picture of a rainbow generated by a prism. Then, without changing the system, an infrared pass filter was placed in front of the digital camera and another picture was taken. These pictures are shown in figure 3. Together, the pictures clearly indicate that there is radiation 'beyond' the red that is sensed by the camera but not the human eye.

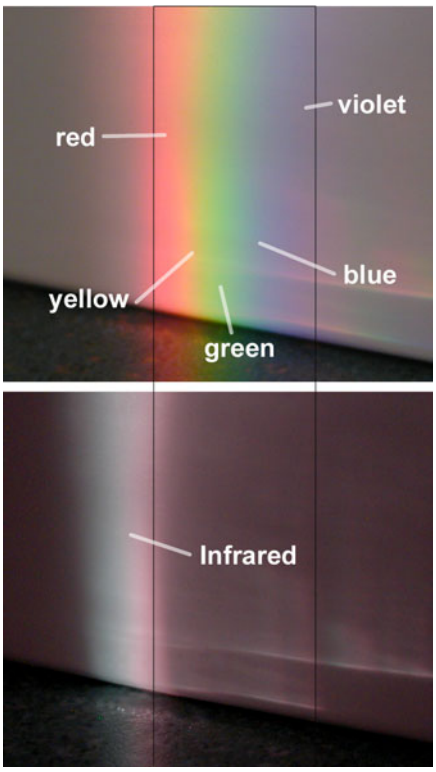

Figure 3. Images of a rainbow generated by a prism. The top image was taken without a filter, while the bottom image is taken with a Hoya R72 infrared pass filter that screens out almost all of the visible while passing the near infrared. The infrared band in the upper picture is not clearly visible because this picture was taken with a shorter exposure so that the visible rainbow would not be overexposed.

Conversion from visible to infrared radiation

We designed the next activity to investigate what happens to electromagnetic radiation incident upon the surface of the Earth. The surface of the Earth was modelled by a plastic bin filled with either gravel (to represent land) or water (to represent the oceans). Each student group prepared two identical bins (containing either gravel or water). One of the bins was illuminated for several minutes with a desk lamp to simulate the irradiation of the Earth's surface by the sun. The other bin served as a control and was not illuminated. Students observed that the desk lamp gave off both light and heat. After the desk lamp was turned off, students made observations of each bin. They observed that while they could feel ‘heat’ coming from the bin that had been illuminated, they felt no heat coming from the bin that was not illuminated. They also observed that they could not see any light coming from either bin. Finally, they used a broadband (visible to 40 μm) infrared sensor, obtained from PASCO Scientific, to measure the amount of far-infrared radiation coming from each of the bins. They noted that the bin that had been illuminated emitted more infrared radiation. The purpose of this activity was to show that visible light coming from the desk lamp (sun) could be absorbed by the Earth (gravel or water) and emitted later as infrared radiation. Another goal of this activity was to establish the idea that surfaces with a higher temperature emit more infrared radiation.

Selective absorption of infrared radiation

In the next activity students investigated the selective absorption of infrared radiation by water. The purpose of this activity was to observe that some substances can efficiently absorb infrared radiation even though they are virtually transparent to visible radiation. In this activity an infrared source and an infrared sensor were lined up on opposite sides of a glass beaker. The reading on the infrared sensor was measured as more and more water was added to the beaker. The apparatus used to make these measurements is shown in figure 4. A graph of this infrared intensity is shown in figure 5.

Students clearly observed that as more water was added (the thickness of the water increased) more infrared radiation was absorbed. At the same time the water remained transparent in the visible. The purpose of this activity was to draw an analogy between the addition of water to the beaker and an increase in the amount of H_2O or CO_2 in the atmosphere.

Modelling the greenhouse effect

After completing the activities described above, students were ready to understand the greenhouse effect. We completed this part of the unit with a culminating activity that we hoped would enable students to synthesize what they had learned from the previous activities into a coherent understanding of the greenhouse effect. This activity involved the direct observation of greenhouse behaviour in a paper cup. The idea behind this activity was to illuminate an environment with very little water vapour and

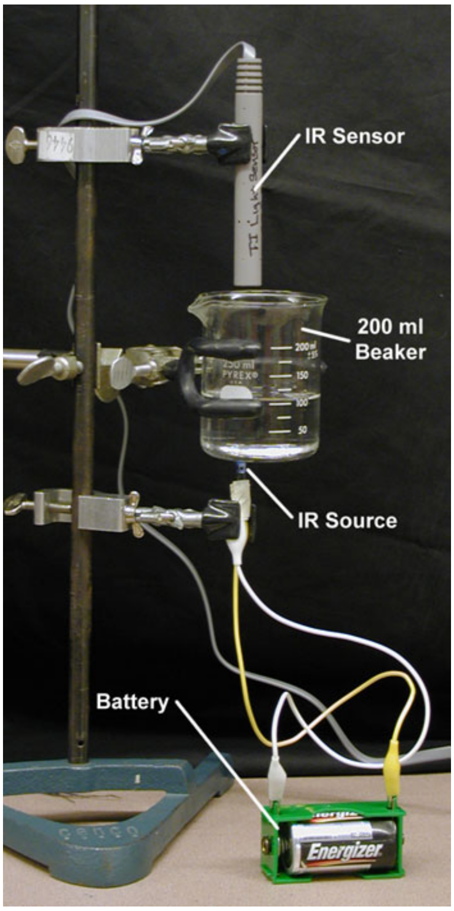

Figure 4. Apparatus used to measure infrared absorption by water.

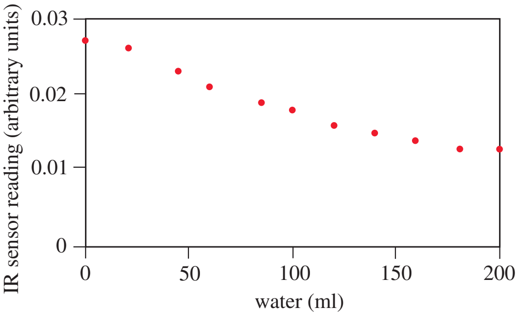

Figure 5. Measured infrared intensity versus water added to a 300 ml beaker. The amount of water added to the beaker is approximately proportional to the thickness of the column of water between the infrared source and the sensor.

an environment with lots of water vapour and compare the final temperature that each reached.

The students began by placing a small Ziploc bag containing a known amount of water inside a paper cup. The cup was then covered with plastic wrap and a temperature sensor was placed inside the cup. The cup was illuminated with a desk lamp and the temperature was measured. Eventually, when the system reached equilibrium, the students recorded the temperature inside the cup. The plastic wrap was then taken off of the cup, the Ziploc bag was opened and the plastic wrap was replaced. The purpose of this was to allow water vapour to fill the cup without changing the heat capacity of the environment. The cup was again illuminated and the temperature measured until equilibrium was reached. The students observed that the equilibrium temperature in the second case was higher than in the first case. The only thing that had changed was the presence of water vapour inside the cup. Despite the fact that this experiment worked flawlessly in class, *we found out later that the conclusions we had drawn were scientifically incorrect*. We will discuss this issue and other problems we experienced while testing this unit in the following section.

Problems identified during testing

We encountered a rather nasty problem in our section on the greenhouse effect. As we mentioned above, our interpretation of the culminating activity on the greenhouse effect was scientifically incorrect. Recall that in this activity students used a desk lamp to illuminate two cups containing a small amount of water. Both cups were sealed with plastic wrap. Students found that the cup containing water that could vaporize reached an equilibrium temperature that was higher by a few degrees Celsius than the cup that had its water sealed in a small plastic bag. At first this seemed like a good model for global warming via the greenhouse effect. Then we realized that by scaling our experiment to the thickness of the atmosphere, our experimental results would lead us to predict that the greenhouse effect would cause a dramatic increase in surface temperatures. That is, if we assume that the increase of 2 °C in a cup is due solely to trapping of infrared radiation by water vapour, then we would expect a temperature increase of hundreds of degrees Celsius due to water vapour in the Earth's atmosphere since it is approximately 10 000 times thicker.

We remained confused about the reason for our observed temperature difference until Craig Bohren, a Penn State University meteorologist, informed us that the specific heat of water vapour was significantly lower than that of liquid water. This difference in specific heat easily accounts for the difference in temperature that we observed. With a bit of thought, it became clear that no simple table-top experiment using greenhouse gases will yield easily measurable greenhouse effects.

The other problems we encountered were typically more pedagogical in nature. We felt that our storyline was weak. Students seemed confused about why certain activities were introduced and didn't always see how these activities would contribute to their understanding of the unit.

The weakness of the storyline is especially apparent in the section on the greenhouse effect. This section started with a rather didactic description of the electromagnetic spectrum and was followed by only one observation we described that uses a digital camera to detect invisible infrared radiation. We need to do a better job in familiarizing the students with the electromagnetic spectrum, especially with regard to the differences and similarities between visible and infrared light.

Although the other experiments on the greenhouse effect we described show each of the elements of the effect rather nicely, the chain of reasoning is long enough that most of our students need a culminating experience to show how the elements fit together. We had developed the cup experiment for this reason. Since we cannot use this experiment, we need to find another way for students to synthesize their understanding of the greenhouse effect.

We also concluded that we should introduce students to the concept of dynamic equilibrium—another aspect of the greenhouse effect that was not addressed. That is, the Earth maintains a fairly constant average temperature even though radiant energy from the Sun is constantly entering its atmosphere. The Earth can maintain this temperature because the rate at which radiant energy from the Sun is absorbed by the Earth and its atmosphere is the same as the rate at which radiant energy is lost to outer space. We feel that students need to explore the concept of dynamic equilibrium as part of developing a better understanding of global warming issues.

Another systemic problem was that many of the activities in the unit require a mastery of basic concepts founded on proportional reasoning, particularly the concepts of rate and density. Many of these concepts have been identified as impediments to learning in quantitative sciences [6]. We administered an assessment quiz at the beginning of the unit and discovered that about 40% of our students had significant difficulties with these concepts. These students tended to have more difficulty with the unit than those who did well on the quiz.

Last, but not least, we found that the computer-based measurements of carbon dioxide were often difficult. Gas CO_2 sensors are expensive, hard to calibrate and tend to be noisy. There are two types of gas CO_2 sensors available. One records in the 0–5000 ppm range [7], which works well for measuring CO_2 levels in the atmosphere and for recording CO_2 uptake in observations of photosynthesis. The other works well for higher concentrations like those found in exhaled breath (in the 0–40 000 ppm range) [8]. However, this sensor is sensitive to light and cannot be used for observations of photosynthesis. We would like a single inexpensive sensor that can be used for all our CO_2 measurements. We have been encouraging vendors to improve the performance of their sensors, and we hope to see better sensors on the market in the near future. Until better sensors are available we plan to reduce the number of activities that require CO_2 measurements.

Future improvements

We are currently rewriting this unit to address some of the problems identified in the last section. We plan to strengthen the storyline and shift the focus of the unit to emphasize population dynamics and the greenhouse effect while reducing the amount of chemistry covered in the unit. Reflecting this change in focus, we will rename this unit *Population, Climate and Environment*.

We have chosen to spend a significant part of the unit investigating population dynamics for two reasons. First, it makes sense to address population growth, since it has such a strong influence on many of the factors that affect global climate change. Second, we anticipate that a prior exposure to population dynamics will help students more easily understand the fundamental dynamics underlying global warming. We feel that this new storyline will allow students to develop a solid understanding of difficult concepts like dynamic equilibrium, transfer rates and feedback in the simple context of population dynamics. Our goal is to then apply these concepts to the more abstract problem of energy balance in the atmosphere. We also anticipate that the investigation of population dynamics will offer concrete opportunities to practise proportional reasoning, e.g. population density, food consumption per person etc. Finally, the modelling activities in the population dynamics section should provide students with valuable tools for exploring more complex systems in the project phase of the course.

We plan to begin the unit as before with a discussion of the issues surrounding global warming with particular emphasis on human-driven changes in the global climate. Next, we plan to engage students in a series of activities designed to build their understanding of population dynamics, focusing on the ideas of linear growth, exponential growth, feedback mechanisms and dynamic equilibrium. We plan to develop these ideas using simple physical models as well as straightforward population simulations using spreadsheets. Students will then investigate global warming by working through many of the activities we have already tested (and described above). The global warming section of the unit will culminate with new activities designed to help students build a model of energy balance in the atmosphere that incorporate the ideas of dynamic equilibrium developed in the section on population dynamics. These activities will help students synthesize their understanding of the greenhouse effect by giving them the opportunity to use their model of the greenhouse effect to explain the dynamics of global warming.

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