PAPERS | SEPTEMBER 01 2023

# A teaching-learning sequence about climate change: From theory to practice[a)]

**Special Collection:** Teaching about the environment, sustainability, and climate change

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*Am. J. Phys.* 91, 676–684 (2023)
https://doi.org/10.1119/5.0137089

# A teaching-learning sequence about climate change: From theory to practice[a)]

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(Received 30 November 2022; accepted 14 July 2023)

We describe a collection of relatively simple experiments and laboratory demonstrations devoted to the physics of Earth's energy balance. Many of the experiments also address fundamental aspects of physics at the undergraduate level. Results of classroom testing of this sequence of activities are presented and discussed. https://doi.org/10.1119/5.0137089

## I. INTRODUCTION

Climate change, a phenomenon with no political or geographical boundaries, is one of the most important issues facing our world. It is part of the role of science to relate issues concerning global warming to the physics and chemistry of the atmosphere using formal theoretical and experimental tools and protocols. At the university level, through carefully structured laboratory investigations, students can study the physics of the atmosphere, learn methods of experimental and theoretical investigation, and understand the ethical commitment of the scientific community to address issues of importance to humanity and the planet.[1,2]

We present here an experiment-based teaching-learning sequence (TLS), suitable for undergraduate and masters students, mainly devoted to the physical basis of the greenhouse effect (GHE), leading to the development of a simple but effective model for the Earth's climate[3] that is within reach of students and allows qualitative predictions of the radiative steady-state average temperature of the Earth-atmosphere system receiving radiation from the Sun and understanding of the effects of the increase in greenhouse gases in the atmosphere. Feedback effects can be included as well. The need for a TLS dedicated to this specific topic stems from the fact that the GHE is difficult to place in traditional physics and science curricula because it requires concepts from several traditionally distinct areas in physics. The TLS includes interesting phenomena in optics, thermodynamics, and radiative transfer that help students integrate knowledge and see physics as a unitary discipline.

The paper is organized as follows: In Sec. II, we outline the methodology we adopted in developing and improving the TLS. Then, in Sec. III, we describe the model we construct in the TLS. In Sec. IV, we provide a short description of the context of the experiments and the methods for data collection, and in Sec. V, we discuss the difficulties and misconceptions of students, considering both the literature and the results of our pre-tests. In Sec. VI, we provide a detailed description of the various experimental activities. In Sec. VII, we describe the results of the assessments we have conducted on the students who completed the sequence. Section VIII is devoted to our conclusions.

## II. FRAMEWORK

### A. Design principles

Designing a TLS for a complex phenomenon like the GHE requires integrating concepts from different areas of physics. The sequence must also be accessible, appealing, and useful for students with diverse backgrounds, including future teachers of many disciplines: physics, mathematics, chemistry, Earth, and life sciences. Finally, a basic goal is to provide a progressive construction of a model of the GHE with increasing complexity.

These considerations make it almost essential to build the teaching-learning sequence around a series of experimental activities. Constructing concepts through experimental activities keeps all students engaged, even those who may already have a reasonable working knowledge of the topic at hand, through laboratory activities that may still be novel to them and help consolidate their knowledge. On the other hand, for students who are novices, experiments constitute a meaningful context for laying the foundations of a progressive construction of concepts.

### B. Design of experiments

In designing the experiments, we were guided by the AAPT Recommendations for the Undergraduate Physics Laboratory Curriculum[4] which emphasizes designing experiments; modeling, analyzing, and visualizing data; and communicating physics. We tried to implement structured inquiry-based lab activities[5] in which the teacher specifies the problem and the procedure to be followed, but the outcome of the experiment is not known in advance, and some decision-making space is left for students during the investigation. We frequently (for example, in the activity on thermal equilibrium of different bodies under radiation or the one on the Beer–Lambert absorbance law) use the Predict-Observe-Explain (POE) strategy as the base of the structured inquiry approach: The inquiry research question is the one which is posed to students in the "predict" phase, and subsequently, the student is guided to perform the experimental activity, collect data and analyze the results, compare them to their initial prediction, and possibly develop a new model.

In some cases, a POE-based inquiry is not applicable or effective. For example, in the activity on the Stefan-Boltzmann law (cf. Sec. VI B), most students would not know where to start from to formulate a prediction. Hence, they are guided by the instructors to investigate the role of temperature. The use of demonstration experiments is limited to cases where it is necessary to show some aspect of a phenomenon, but there is not enough time or instrumentation to have students safely carrying it out (see Figs. 3 and 4).

## III. FROM THE MODELS TO THE CONCEPTS

The main emphasis of our activities is on building a physical model to make predictions and compare them with experimental measurements. Students also engage in data analysis and visualization.

The activity proposed to the students is centered on the step-by-step construction of two different simple models for Earth's climate, both of which crucially involve the concept of radiative equilibrium. The first, simpler, model only includes the two main "actors," namely, the Earth and the Sun.[6] This model predicts a steady-state temperature which is $-18\,^{\circ}$C and hence—although the relative error is a mere 10%—far from the expected mean value for the Earth. This failure prompts the development of a revised model that includes the Earth's atmosphere. This will give a much better estimate. The many further refinements that can be considered, which are important in order to obtain a quantitatively accurate model, will not concern us since the second model already allows a satisfactory general insight into the phenomenon.

In this section, we briefly discuss these two models and the key concepts we have extracted from them. These concepts are gradually learned by students as the sequence is carried out, achieving in the end the construction of the second model.

### A. First model—Radiative energy budget

As previously stated, the first model only involves the radiative exchange between the Sun and the Earth and the energy budget. In this model, the Sun is considered as an ideal black body which emits electromagnetic radiation in space. Based on the Earth–Sun distance and the Sun's temperature, one can compute the solar constant; that is, the average power that each unit of area of the Earth receives from the Sun.

From the solar constant and knowing Earth's albedo, we can write down the condition for radiative equilibrium between the solar radiation absorbed by the Earth and that emitted by the Earth. Also, if the Earth is assumed to emit radiation with emissivity equal to 1, we can use the Stefan–Boltzmann law to compute its average temperature.

#### *1. Definition of the relevant concepts*

The physical concepts that underlie the model we just described, which students must master to understand it, are summarized in Table I. In this table, for each stage of the TLS, we describe the relevant conceptual area and sub-area and the list of experiments to be performed. Then, we specify whether the experiments will be quantitative, involving detailed measurements and data analysis, or just qualitative,

Table I. First model concepts.

| Stage | Conceptual area | Sub-area | Experiments/activity [type] (section) | Learning goals |
|---|---|---|---|---|
| 1 | Electro-magnetic (EM) spectrum | Spectral bands and their energies | Comparison between continuous and line spectra using a Home-Made Spectroscope (HMS) [qualitative] (Sec. VI A) | Developing technical and practical laboratory skills |
| 2 | Radiation-matter interaction | Reflection, refraction, absorption, scattering | Tray experiment (with collimated beam and red-green-blue (RGB) filters) [qualitative] (Sec. VI C) | Designing experiments, Technical and practical laboratory skills, Data analysis |
| | | Snell's law | Tray experiment with collimated beam and no filter [quantitative] | |
| 3 | Radiation-matter interaction | Selective absorption | Tray experiment with RGB filters [qualitative] (Sec. VI C) | Designing experiments |
| 4 | Thermal radiation | Stefan–Boltzmann law | Stefan Boltzmann lamp[7] [Quantitative] | Modeling, Data analysis |
| 5 | Energy balance | Radiative equilibrium, stationary states | Experiment witd the black and white plates [quantitative] (Sec. VI D) | Practical skills, Data analysis |
| | Definition of the GHE | Albedo | | |
| | Heat | Heat propagation; heat and energy | | |
| 6 | Energy balance | Radiative equilibrium, stationary states | Measurement of the power of a bulb (and of the solar constant)[8] [quantitative] | Modeling, Data analysis |
| 7 | Energy balance | Radiative equilibrium, stationary states | Leaking bucket with one hole [qualitative] (Sec. VI D) | Collecting data, Data analysis |
| 8 | Thermal radiation | Wien's displacement law | Experiment of the bulb (with HMS) and PhET simulation (Blackbody Spectrum[9]) [qualitative + simulation] (Sec. VI A) | Modeling, Data analysis, Technical and practical skills |
| 9 | Thermal radiation | Emissivity, Stefan–Boltzmann law for gray bodies | Leslie's cube with thermocouple and FLIR[10] [qualitative] (Sec. VI B) | Modeling |
| 10 | Definition of the GHE | Average surface temperature | Construction of the first model for the climate [theoretical] (Sec. VI D) | Modeling |

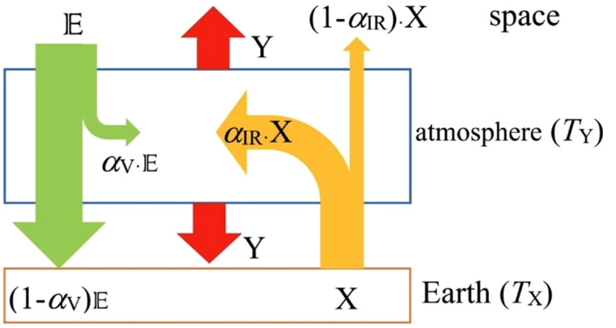

Fig. 1. A model for the radiative balance of the Earth that includes the atmosphere which absorbs a fraction of visible radiation from the Sun (𝔼) and a fraction of infrared radiation from the Earth (X). The model also includes the radiation emitted by the atmosphere (Y).

or whether the phase will involve theoretical computations and modeling. Finally, the learning goals are indicated.

### B. Second model—Inclusion of the atmosphere

The model described in the preceding subsection is very useful for introducing simple concepts. However, as mentioned earlier, it predicts a very low value for Earth's average temperature. Therefore, students are encouraged to consider the atmosphere, which plays a pivotal role due to the presence of greenhouse gases (GHGs).

A simplified version of the Manabe model[11,12] is our basis in developing the model (Fig. 1), where the interaction of the atmosphere with radiation coming from the Sun and from the Earth's surface is modeled using two coefficients, called $\alpha_V$ and $\alpha_{IR}$, which, respectively, represent the fractions of incoming visible and IR radiation that are absorbed by the atmosphere. The emission properties of the atmosphere, both toward Earth and toward outer space, are assumed to be described by the Stefan–Boltzmann law with emissivity equal to one. Like the first model, this is a highly simplified zero-dimensional model in which Earth and its atmosphere are treated as uniform, but it is sufficient to understand the crucial role played by the atmosphere in the radiative balance of the Earth and to obtain a reasonable quantitative result for the equilibrium temperature.

#### *1. Definition of the concepts*

The introduction of the atmosphere in the model requires the understanding of some further concepts with respect to those already listed in Table I, mainly in connection with the ideas of selective absorption and selective transparency, especially in the unfamiliar case of IR radiation. The new concepts are listed in Table II, which is organized in the same way as Table I.

## IV. CONTEXT OF INSTRUCTION AND METHODS FOR DATA COLLECTION

The sequence presented in this paper was tested with 85 students in the first or the second year of their master's degrees in mathematics or physics at the University of Trento between 2017 and 2022. The mathematics students had all taken general (classical) physics classes, as is compulsory in Italy. Some of them had also taken an introductory course in modern physics (i.e., basics of quantum theory and special relativity).

Data on student understanding were collected by means of pre- and post-tests, with questions covering the main conceptual areas described earlier (for more details, see supplementary material online[13]) Items were either taken or adapted from some works in the literature[3] or are of our own design, and over the years, some of them have undergone minor revisions while preserving the general meaning and objectives of the original ones. A very important source of information is an item requiring students to describe and represent in a drawing, the physical mechanisms involved in the GHE.

Table II. Additional concepts needed for the second model.

| Stage | Conceptual area | Sub-area | Experiments/activity [type] (section) | Learning goals |
|---|---|---|---|---|
| 11 | EM spectrum | Distinguishing between visible and IR radiation | FLIR vision [qualitative] (Secs. VI A–VI C) | Modeling, technical and practical laboratory skills |
| 12 | Radiation-matter interaction | Absorption (Beer's law) | Experiment on the thickness of the absorber (sheets of paper) [quantitative] (Sec. VI C) | Collecting data, modeling, data analysis |
| | | Absorption (Beer's law) | Experiment on the concentration of the absorber (tray with dye) [Quantitative] (Sec. VI C) | |
| | | Selective absorption (mean free path as a function of the wavelength) | Experiment on the absorption of incident light with different wavelength (tray with dye and source with RGB filters) [quantitative] (Sec. VI C) | |
| | | Selective absorption | PhET simulation on Beer's law[9] for different substances [simulation] | |
| 13 | Radiation-matter interaction | Selective transparency in the IR | Selective transparency with FLIR (of glass, plastic, and silicon wafers) [qualitative] (Sec. VI C) | Collecting data, modeling, data analysis |
| 14 | Radiation-matter interaction | Microscopic aspects of selective transparency | PhET simulation on the interaction of various GHGs molecules with photons of different wavelengths[9] [simulation] | Modeling |
| 15 | Energy balance | Radiative equilibrium, stationary states | Leaking bucket with two holes [qualitative] (Sec. VI D) | Modeling |
| 16 | Definition of the GHE | Average surface temperature; albedo; selective absorption of GHGs | Construction of the second model for the climate [theoretical] (Sec. VI E) | Modeling |

## V. STUDENT DIFFICULTIES WITH CONCEPTS RELATED TO THE GHE

Some of the difficulties that students experience come from the lack of adequate knowledge of the electromagnetic spectrum, in particular concerning radiation that cannot be detected by the human eye such as IR radiation. Before being exposed to the relevant part of the TLS, students exhibited a widespread difficulty in associating each band to a position in the electromagnetic spectrum, and about 20% of the students had difficulty in identifying the bands themselves.

It is well known that students generally do not consider the phenomenon of IR radiation as a mechanism for energy transfer. During studies on climate change, Jarrett[14] and Jarrett *et al.*[15] pointed out that students often lack an adequate understanding of blackbody radiation, and still more often they neglect the fact that all bodies emit thermal radiation characterized by their temperature.[3] According to our preliminary tests, many students (about 39%) even at advanced undergraduate levels do not consider the transfer of energy from a hot body through the vacuum to be possible.

Before the experiments, students are asked to predict what should happen to a light beam going through a tray filled with liquid. What emerged in our case was that, while the majority of students consider the phenomena of reflection (52%) and refraction (82%), they tend to neglect light absorption (mentioned by 5%) and scattering (mentioned by 4%). No student listed all four phenomena.

A second open-ended question concerned transparency (i.e., "explain what it means for a body to be transparent"). Only 13% of students mention that this is a wavelength-dependent property. More than half of the students (58%) understand transparency as an absolute phenomenon, stating explicitly that if a body is transparent, it has this property with respect to any kind of electromagnetic radiation.

When we asked students to predict what happens to objects that are identical except for their colors (white or black) are exposed to solar radiation, more than 80% of them correctly concluded that the equilibrium temperature is higher for the black object. Most students correctly selected the reason that they absorb and reflect radiation differently. Despite this, the idea of balance between absorbed and emitted energy is very often not behind the students' answers, as they mention the different capability to absorb radiation but not equilibrium between rates of absorbing and losing energy. Combining these results with those of the question on energy transfer through the vacuum, it appears that many students have a mental model for which luminous objects such as the Sun can emit radiant energy, but ordinary objects cannot, and can only absorb radiation from a luminous object with higher or lower efficiency. This problem becomes evident when students are questioned about the energy balance of the Earth and is seen in the majority of the GHE diagrams made by students before they began the TLS. The drawings produced before the TLS clearly show the pre-instructional ideas that are identified in the literature as underlying the most common explanations of the GHE:[16]

- Trapping due to single or multiple reflections, both at the Earth and at the upper "surface" of the atmosphere;
- presence of a delimited layer of greenhouse gas (or sometimes dust) acting as a physical barrier;
- inadequate analogy with an actual farming greenhouse.

Only 11% of the students link the energy of the radiation to the color (drawing solar radiation as yellow and Earth's radiation as red) or to the wavelength (drawing short waves for the Sun's radiation and long waves for the Earth's radiation).

## VI. THE EXPERIMENTS

In this section, we describe in detail all the experimental activities listed in Tables I and II, which form the core of the TLS. For each conceptual area, we include the experimental setup, the results of measurements, and the data analysis.

### A. Electromagnetic spectrum and infrared radiation

The initial experimental activities aim at visualizing the different parts of the electromagnetic spectrum and at comparing different sources of radiation to enable students to realize that all objects emit thermal radiation. These activities are followed by a short lecture in which the main features of the electromagnetic spectrum and of all its components are summarized. For these experiments, students use simple spectrometers[17,18] based on diffraction gratings (which they build on their own, after the necessary materials and a minimum of explanations are provided) to study visible light, and they use the FLIR One Thermal Imaging Camera[19] to study IR light. Both can be attached to smart phones to display and record the images.

#### *1. Measurement results and data analysis*

In the first experiment, students make qualitative observations of different light sources that all appear white (incandescent bulb, fluorescent lamp, and LED lamp), using both the spectrometer[17,18] and the IR camera.[19] Quantitative data analysis is not expected. Students are then asked to explain what they have observed. This activity helps students understand that there are different physical mechanisms that govern the production of light and develops their skills in constructing and using the instruments.

### B. The Stefan–Boltzmann law and emission from hot bodies

After showing that different bodies emit electromagnetic radiation in different ways and pointing out that thermal radiation is not always visible, we focus on the Stefan–Boltzmann law. In Fig. 2, we show spectra of an incandescent light bulb at different voltages, taken with the smartphone camera spectroscope.

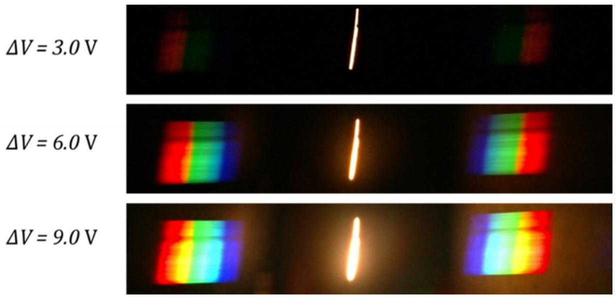

Fig. 2. A sequence of spectra for different temperatures produced by the light bulb and captured by the HMS. The camera is set to manual mode in order for its sensitivity to be constant. The voltage applied to the lamp is increased from 3 to 12 V.

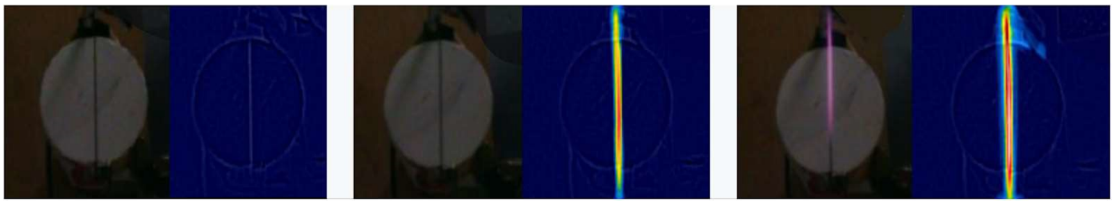

Fig. 3. Pictures of a current-carrying graphite lead, taken by the students using a FLIR ONE camera, both in the visible region (left sides of each frame) and the IR region (right sides of each frame). At low temperatures, no thermal radiation is observed (left frame), while for higher currents, the graphite lead becomes warmer and a stronger IR emitter (center frame) up to getting incandescent, emitting a red light (right frame).

From Fig. 2, one can observe that as the voltage applied to the light bulb increases, the bulb gradually becomes brighter, while the color of the filament changes from red to white. (The change in color is not evident in the photo due to unavoidable overexposure, but it is clearly visible to the naked eye.) A qualitative observation with the diffraction-grating-based spectrometer shows how the increase in temperature corresponds not only to an increase in the intensity of the radiation emitted across the whole spectrum but also to a shift of the intensity toward shorter wavelength bands (green and blue), which are almost absent at lower temperatures.

The next experiment is instrumental for countering the idea that only visibly luminous bodies can emit radiation. The source is a graphite pencil lead attached to a voltage generator (which can also be replaced by a series of batteries). The current is increased until the graphite glows. Due to the intrinsic risk associated with an exposed incandescent body, we offered this activity as a demonstration, rather than as a student experiment, and we suggest that educators undertaking this TLS do the same. From Fig. 3, where pictures of the graphite lead in the visible light and in the IR are compared, it is evident that at lower temperatures, only IR radiation is emitted, while at sufficiently high temperatures, visible light also appears. (At first, this light is reddish, and then it tends to white.)

The next experiment involves the Leslie cube (Fig. 4), which is a metal cube with faces that are bare (shiny) or painted white or black. It is studied using a thermocouple, an IR thermometer, and an IR camera. Students can observe how, while the thermocouple measures the same temperature on all faces (which, of course, are in thermal contact with each other, hence at the same equilibrium temperature), the IR thermometer and the IR camera measure a lower apparent temperature for the shiny face compared to the painted faces. Hence, they can understand how the behavior of the white and black faces is closer to that of an ideal black body, with respect to the shiny face, for which quite a small emissivity coefficient ε must be introduced.

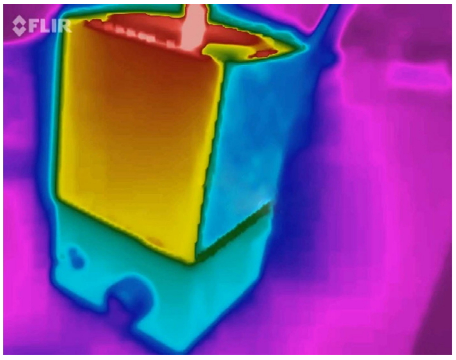

Fig. 4. The FLIR image of the Leslie cube shows emission of thermal radiation from different surfaces. Different surfaces of identical temperature can be seen to have very different emission properties. The left surface (which appears as yellow/red, indicative of high IR emission) is painted with black paint, while the right one (which appears blue, indicative of low IR emission) is made of polished aluminum. The camera software assumes that a higher IR emission corresponds to a higher temperature, and therefore, as noted earlier, it reports a higher temperature for the black surface.

This experiment contains several interesting insights related to the behavior of radiating black and nonblack bodies. In particular, it allows students to appreciate the importance of emissivity, for which a shiny body is usually very small, while it is much larger for opaque materials (regardless of their color). This leads to a distorted measurement of the glossy face temperature when using the thermal imaging camera. Therefore, calibration of the instrument is necessary: The camera's internal software uses the Stefan-Boltzmann law to calculate the temperature based on the measured radiation intensity and the given emissivity. There is an extensive literature on the operation of IR cameras, including in an educational framework, see, in particular, Ref. 19.

## C. Radiation–matter interaction

A study of the behavior of different materials under different kinds of incident radiation is used as an introduction to selective transparency, essential for discussing the role of the Earth's atmosphere.

### *1. Demonstrations*

The first demonstration involves light beams passing through a transparent plastic tray filled with water.

(a) Using white light, students observe the four relevant phenomena of light–matter interaction: Reflection, refraction, absorption, and scattering.
(b) Using a light source capable of generating beams of different colors (blue, green, and red) and coloring the water with different food dyes (Fig. 5), students observe how the attenuation of radiation depends on the wavelength and on the color of the solution.
(c) The use of the IR camera shows the different behavior of materials when visible light or IR radiation passes through them (Fig. 6).

### *2. Experimental setup*

Three experiments are included in this section. Unlike the previous experiments, these involve quantitative data analysis.

(a) The first one employs a light source whose brightness does not saturate the sensor (desk lamp with a 40 W bulb), a smartphone, and some paper sheets. We used

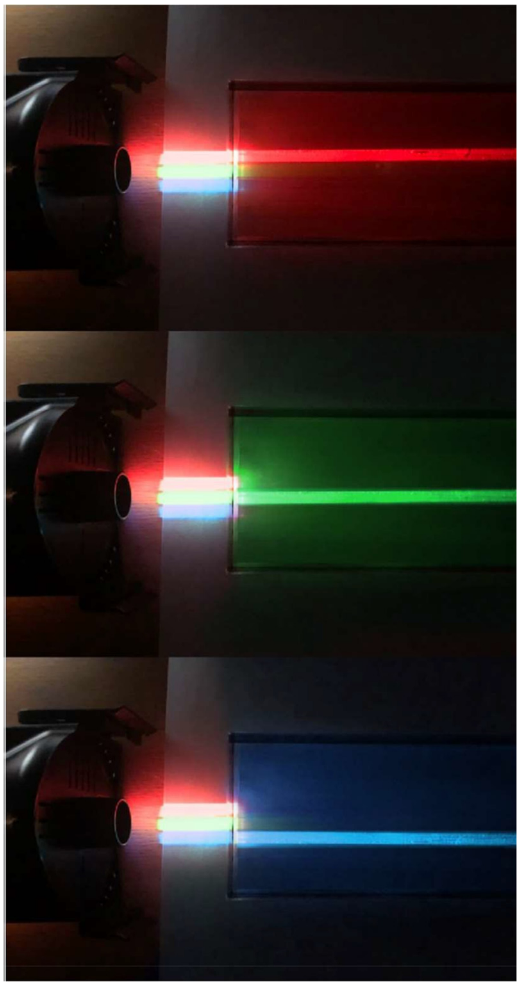

Fig. 5. The red, green, and blue filters of the Basic Optic Light Source from PASCO (Ref. 20) provide three rays of light. The color-dependent transmittance of the three beams is shown for water containing red (top), green (middle), and blue (bottom) food dye.

the Physics Toolbox suite[21] to record data from the smartphone's ambient light sensor; Phyphox is another alternative.[22]

(b) The second experiment employs an IR source (the black face of a Leslie cube can be conveniently used for this purpose), a smartphone equipped with a FLIR camera, and some plastic sheets. Figure 7 shows the IR images obtained by adding the plastic sheets one by one between the source and the FLIR camera.

(c) The third experiment employs an LED flashlight as a light source, three inexpensive colored gel filters, a smartphone, and a plastic tray filled with water where food dye is added drop by drop. Using the luxmeter of the cellphone, the light intensity is measured first without filters and then putting the three colored filters one by one between the flashlight and the glass. Then, a drop of food dye is added, the solution is mixed, and the procedure is repeated step by step. The procedure is iterated ten times.

### 3. *Experimental results and data analysis*

Typical results obtained by students are given in Fig. 8. In panel (a), we show the measurements by a group of students of the light transmitted by paper sheets. The figure shows a very clear exponential behavior. These data were obtained after the subtraction of the offset, corresponding to the background light, and are normalized with respect to the maximum intensity. The data were analyzed by students using spreadsheet software or the freeware app SciDAVis (which is particularly suitable since it automatically takes the offset into account in the fit, allowing it to be subtracted). In panel (b), we show the measurements of the transmitted IR radiation by plastic sheets. The figure shows that the exponential law gives a very good agreement also in this case. Panel (c) shows the light transmitted by the red colored water as a function of the concentration (number of droplets of food dye), while panel (d) shows the light transmitted by the blue colored water. Figure 8 shows again that the exponential law is in very good agreement with the data (the plots were obtained without subtracting the offset), and for each color of the filter, the value of the absorption coefficient was obtained. Results clearly show that the

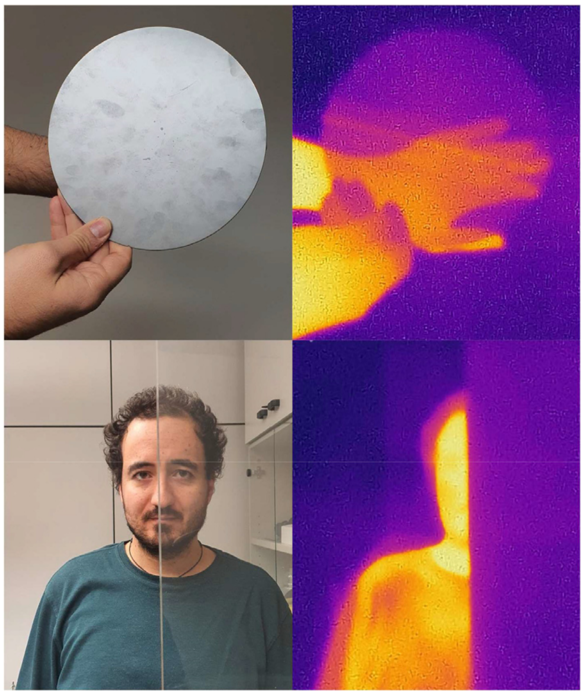

Fig. 6. A hand seen through a silicon plate with a normal camera and with an infrared camera. The image of a person, partially behind a glass, seen with a normal camera and with an IR camera.

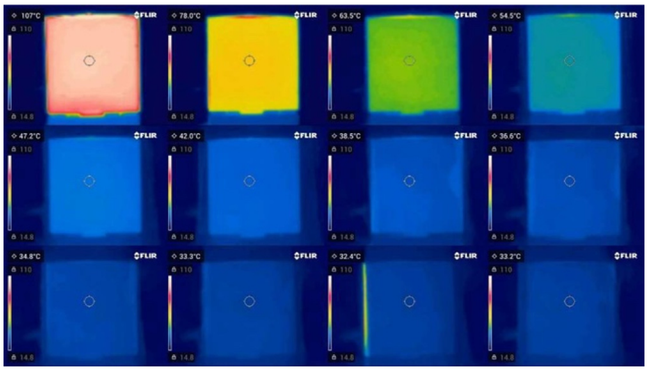

Fig. 7. Images acquired by the FLIR during the experiment; the number of plastic sheets grows from upper left (zero sheets) to lower right (11 sheets).

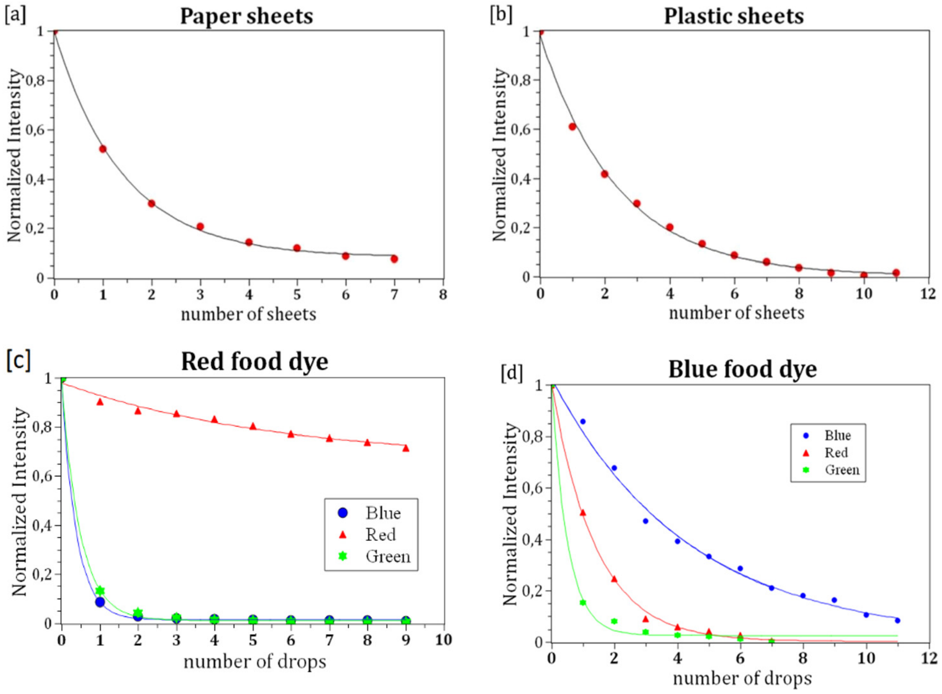

Fig. 8. Student data and analysis: (a) normalized transmitted light intensity as a function of the number of sheets. The line shows a fit to an exponential decay. (b) Normalized transmitted IR radiation as a function of the number of plastic sheets. The FLIR camera actually measures IR radiation intensity, and temperature is calculated from this measurement based on the body emissivity. Students can acquire temperature values by opening the so-called "thermal GIF" images generated by FLIR cameras and containing, in a proprietary, open format (which depends on the specific thermal camera used, in the present case, for example, see Ref. 10) radiation intensity data (converted to temperature values through emissivity calibration and the blackbody Planck curve). (c Normalized transmitted light intensity as a function of the number of droplets of red dye for each of the three light filters. (d) Blue food dye for the three light filters.

transmittance of the material strongly depends on the wavelength of the incident light.

## D. Radiative equilibrium

The last step involves investigating the concepts of energy balance and radiative equilibrium for objects that are exposed to radiation. Stationary states are characterized as states of dynamical equilibrium, in which the incoming energy flux is equal to the outgoing energy flux.

The idea of radiative equilibrium is first introduced by means of the leaking bucket analogy: water is poured into a container that has a hole in it. After an initial transient, the water level reaches a steady-state value at which the incoming flux is equal to the outgoing flux. By comparing different containers, students observe that the steady-state level depends on both the rate at which water is added to the container and the height or size of the hole. The analogy is then drawn to the dependence of an object's equilibrium temperature on the mechanism for how heat enters and leaves the object. This analogy leads into the next experiment.

### *1. Experimental setup*

The experimental apparatus consists of an incandescent 90 W light bulb positioned on a support about 30 cm from two aluminum plates (one painted black and the other white), on a polystyrene base that provides thermal isolation from the table (Fig. 9). To perform the measurements, a thermometer is put in contact with the lower side of the plate, and the temperature is recorded at 15 s intervals with the lamp turned on, until the temperature becomes stable. Then, the light is turned down, and the measurements continue as the plates cool. If weather conditions are suitable, this experiment can be repeated outside, with the Sun in place of the bulb.

### *2. Experimental results and data analysis*

In Fig. 10, we report the data that were obtained and analyzed by the students. The experiment helps students to better understand the concept of thermal equilibrium in a

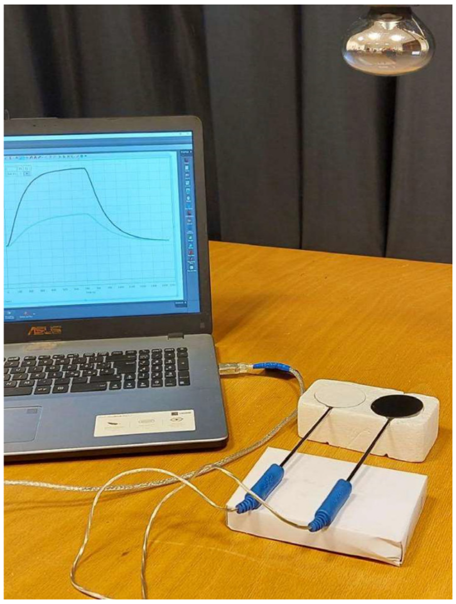

Fig. 9. The experimental apparatus. The thermometers are in contact with the black and white plates; the system is thermally isolated by a polystyrene base.

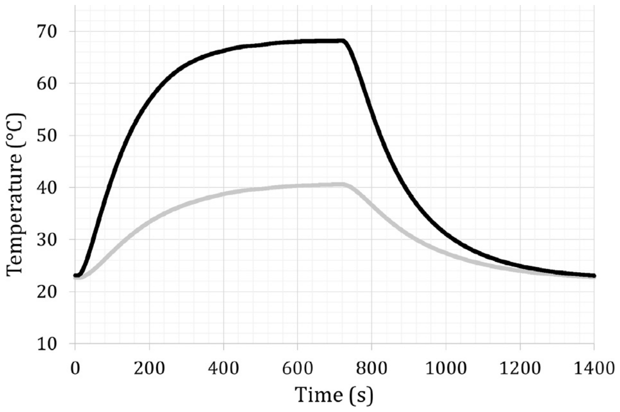

Fig. 10. Data obtained by the PASCO temperature sensors (Ref. 20) and plotted using Capstone (dark gray—black plate; light gray—white plate).

situation involving heat exchanges and the role played by the different albedos due to the colors. Pictures taken with the FLIR during the heating process show how the plate emits more and more IR radiation until constant temperature is reached.

### E. End of the sequence: Construction of models of the GHE

Once the basic physical tools which are essential to describe the energy balance of the Earth-atmosphere system have been carefully studied, as described in the previous section, students are exposed to the models described in Sec. III. Starting from the plate experiment, students are guided to build the first model and to compute the equilibrium temperature of an Earth without an atmosphere. Then, the observed phenomenon of selective transparency provides the basis for the introduction of the atmosphere in the model and for the redefinition of radiative balances, exploiting the analogy with liquids and gases, namely, selective absorption and dependence on the concentration.[23] In this step, students are guided to construct the model themselves working in groups. The teacher then collected and discussed the new hypotheses advanced by students, and where appropriate, the teacher summarizes and incorporates them in the presentation of the new model.

In this way, one can construct a schematic representation of the energy fluxes between Earth, the Sun, the atmosphere, and outer space in equilibrium[24,25] that is characterized by the measurements performed by climatologists.

## VII. RESULTS

We now discuss the educational results of our TLS, roughly following the order of presentation of topics and conceptual areas.

Concerning the electromagnetic spectrum, we observed that, after the teaching action, the percentage of students able to order the relevant spectral bands by increasing frequency grew from 44% to 85%. The remaining 15% is split between those who inverted the order (10% as before) and those who omitted parts of the spectrum (5%, compared to 37% in the pre-test). Thus, the answers indicate a significant improvement in the students' ability to associate to each spectral band its position in the electromagnetic spectrum.

Concerning radiative energy transfers, we noticed that the percentage of students who did not consider radiation emission as a mechanism for energy transmission from a hot (non-luminous) body to the vacuum decreased from 39% to 7%. Students showed improvement in considering the different types of interaction that light can have with matter, with a dramatic increase (from 5% to 90%) of students mentioning absorption and a significant increase in those mentioning reflection and scattering (from 52% to 97% and from 4% to 68%, respectively). In the post-test, 61% of students mention all four phenomena.

Concerning the concept of transparency, the percentage of students who mentioned selectivity increased from 13% to 85%, while the percentage of students viewing it explicitly as an absolute phenomenon decreased from 58% to 15%.

Before the sequence, few students used the idea of radiative balance to explain the GHE. Instead, at the end of the TLS, 70% of them recognized this concept in the case of a radiative object (plates placed under a light bulb), and 90% of them recognized it as a mechanism for the Earth's GHE to work; moreover, 81% were able to schematize the system in a similar way as proposed in Fig. 1.

At the end of the TLS, in the post-test, students were asked to briefly describe the greenhouse effect with their own words.

Most of them correctly identified the role played by the atmosphere in absorbing and re-emitting IR radiation, which increases the temperature of the Earth-atmosphere system. Students appeared confident in qualitative explanations, and many of them also included quantitative models and formulas, especially the Stefan-Boltzmann law, and about one quarter of them referred to some of the experiments performed. A positive result is that, at the end of the TLS, the pre-instructional ideas related to trapping and to the analogy with an actual greenhouse were completely discarded. However, we observed that some problems related to the idea of the presence of a thin layer of greenhouse gases in the atmosphere persisted. Subsequent discussion revealed that this idea was in most cases used for illustration and was not, in fact, related to a lack of understanding.

## VIII. CONCLUSIONS

This paper describes an experiment-based TLS designed to make undergraduate students familiar with a simple model for the Earth's climate, which contains the main physical actors and principles of the GHE, in such a way that students are guided to become thoroughly familiar with its working. A second aim of the sequence is to make students confident with laboratory experimentation, by means of quantitative and qualitative experiments and through data analysis. The results we collected up until now show a significant improvement in the students' understanding of the main conceptual issues involved and of the overall working of the GHE.

## AUTHOR DECLARATIONS

### Conflict of Interest

The authors declare no conflict of interest.

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## Half Meter Bridge

Almost all of the apparatus shown in this series was made or sold by companies in the eastern part of the United States or in Germany, France, England or Ireland. Mills College, in Oakland, California, bought locally; this half-meter Wheatstone bridge was made by the Pantechnical Mfg. Co. of nearby Berkley. The half-meter bridge can be stored more easily than the full-meter model, and was quite popular in the first half of the 20th century. (Picture by David Keeports and text by Thomas B. Greenslade, Jr., Kenyon College)