Oscillating charge simulation

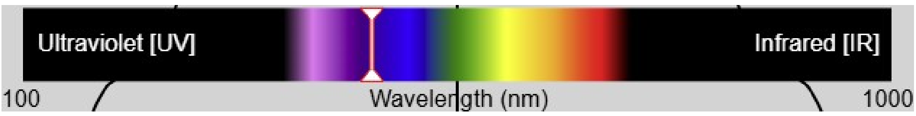
Tutorial for teachers

1. Controls and display

The simulation initializes by default, showing the electric field lines generated by a positive static source charge in a vacuum.

The simulation control buttons are located in the right-hand side menu. This menu can be hidden by clicking on › , for example if the user needs more space to measure wavelengths (see below).

- Click **Play** to oscillate the charge harmonically on the vertical axis.
  The static field lines transform into *progressive sine waves*.
- Click **Pause** to freeze the electric waves.
- **Grid** displays a 100 nm interval grid allowing the wavelength to be measured approximately on the horizontal wave.
- **Measurement arrow** allows you to measure wavelength more accurately.
  Click on the small target above the arrow 200nm to move the measurement arrow, then adjust the length of the arrow using the buttons ⊖ ⊕ .
- **Spectrum** displays a horizontal electromagnetic spectrum bar with the UV, VIS (represented in colors), and IR domains. The white indicator automatically adjusts to locate the emitted wavelength in the spectrum, without giving its value, in order to encourage students to measure it. For the same reason, the wavelengths limiting the IR, VIS, and UV ranges are not indicated.



- The **Frequency** slider allows you to vary the frequency of agitation of the charge. The buttons ⊖ ⊕ next to the slider allow you to adjust the frequency precisely.
  The frequency values have been discretized in order to produce relatively regular variations in wavelength (see Sect. 4).
  ⇒ When the simulation is in Play mode, the displayed wavelength and the white indicator in the spectrum bar adjust automatically.
- The **Amplitude** slider allows you to increase/decrease the oscillation amplitude for better visibility, e.g. to facilitate wavelength measurement.
- The button resets the simulation.

2. About the simulation

The Oscillating Charge simulation allows you to generate electrical waves (or "electromagnetic" waves, although the magnetic field is not represented) by oscillating a simple charge in order to introduce a wave description of radiation.

Prerequisites

The only prerequisites are an understanding of electrical charge, e.g., positive atomic nuclei, and an introduction to the concept of electric fields. These concepts are reintroduced through images, quizzes, and videos in the interactive activity Understanding the Greenhouse Effect.

Relationship with the other simulations

This simulation is the first in a series of four physics and chemistry simulations designed to sequentially introduce the concepts needed to build a coherent model of the causes of global warming, while dispelling misconceptions reported in the literature (see Sect. 3). Each simulation in the series targets a category of concepts necessary for understanding the subsequent simulations (see Fig. 1).

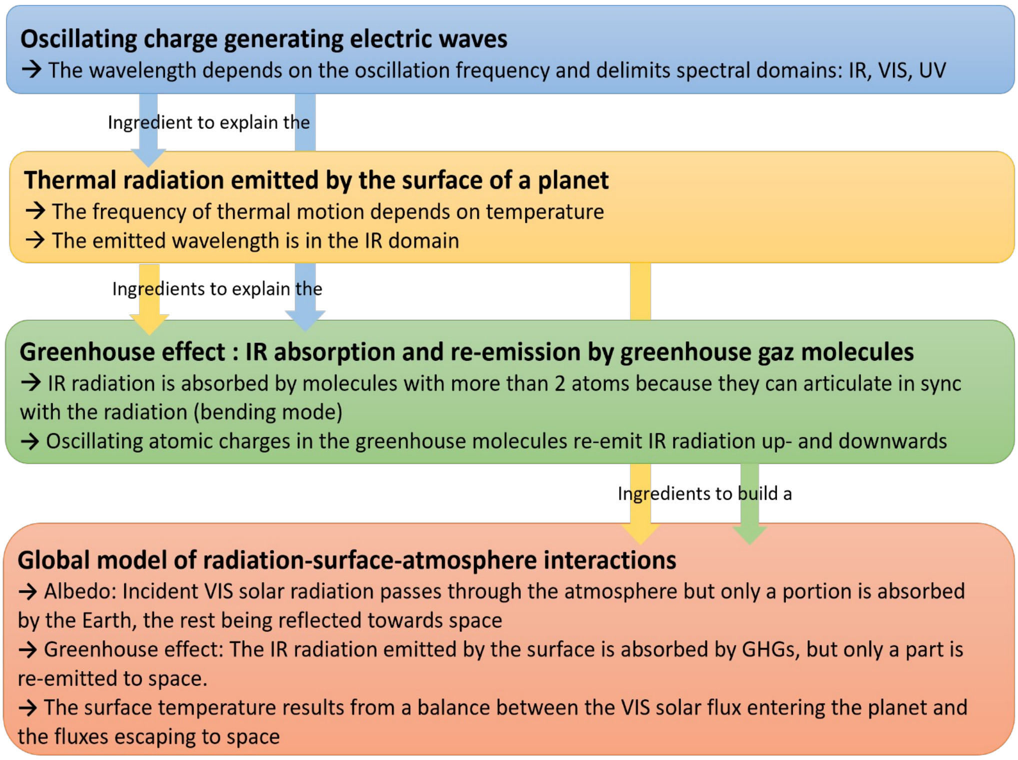


Fig. 1 : Concept map of the four simulations on the causes of global warming. Each simulation targets a category of concepts (highlighted in color), where the main concepts to be discovered are listed by small arrows. The colored arrows between categories illustrate how the concepts discovered in one simulation are necessary for the following simulations.

The *Oscillating charge* simulation allows you to discover the relationship between wavelength and agitation frequency, as well as the ultraviolet (UV), visible (VIS), and infrared (IR) wavelength ranges. These concepts can then be generalized to a ensemble of charges in thermal agitation on the surface of a planet, in order to explain the emission of *Thermal radiation* (blue arrow pointing to the second simulation in Fig. 1). They also explain why the wavelength of thermal radiation depends on temperature while remaining in the IR range.

Differentiating between VIS radiation (short-wavelength solar radiation) and IR radiation (long-wavelength radiation from the Earth's surface) is also fundamental to understanding the *Greenhouse effect* (third simulation), namely the absorption of IR radiation, but not VIS radiation, by greenhouse gas (GHG) molecules. Without this causal explanation of the spectral selectivity of the atmosphere, students are prone to develop erroneous explanations of the greenhouse effect (see Sect. 3). Finally, the concept of oscillating charge also helps explain the re-emission of IR radiation by the oscillating partial charges of GHG molecules.

The interactive activity Understanding the Greenhouse Effect includes these four simulations, scaffolded by instructions, images, and quizzes with feedback, to guide students toward constructing a coherent model of global warming.

3. Underlying misconceptions

The wave description of radiation and the concept of wavelength are generally lacking among students in middle school and high school, who are therefore unable to distinguish between different types of radiation [1].

According to the review by Varela et al. [1], most of the students surveyed before instruction referred only to “sun rays,” without mentioning wavelength. However, students are familiar with “UV rays” thanks to advertising for sunscreen, which leads them to overestimate the proportion of “UV rays” emitted by the Sun or to confuse solar radiation with UV radiation [2]. The absence of a wave description of radiation may also lead some students to equate radiation with “heat,” based on their everyday experience of the heat provided by sunlight [2].

It is therefore impossible to explain the greenhouse effect, namely that GHG molecules absorb IR radiation by vibrating asymmetrically and synchronously with the low frequencies of the radiation, while being transparent to VIS radiation, whose wavelengths are too short and frequency too high. Without this concept of spectral selectivity in the atmosphere, students are led to develop erroneous images of the greenhouse effect (see Greenhouse Effect simulation tutorial).

4. For students to discover

By measuring the wavelength while varying the frequency of agitation of the charge, students will discover that *as the frequency of agitation increases, the wavelength decreases*. This explanatory relationship will subsequently enable students (using the Thermal Radiation simulation) to explain why the solar radiation spectrum is centered in the VIS, while that of the Earth is essentially in the IR.

Using wavelength measurements and the spectrum bar, students will be able to identify the three wavelength domains and *determine the approximate boundaries between UV, VIS, and IR*. Knowing the VIS-IR boundary, they will then be able to conclude that the thermal radiation emitted by the planet's surface is purely in the IR range (see “Thermal Radiation” simulation).

5. Modeling and didactic choices

According to classical electrodynamics, any accelerated charge produces electromagnetic radiation [3]. The oscillation of a charge therefore classically produces continuous wave radiation, which we prefer to the quantum representation of “photons” for several educational reasons: (1) it allows students to visualize wavelengths in order to identify areas of the spectrum (see Sect. 4), which is necessary for understanding *continuous* thermal radiation emission, (2) it explains the bending vibrations of GHG molecules synchronized with IR radiation, and (3) it is aligned with the school curriculum about waves (see Box 1 for details).

Box 1. Wave vs. particle description of light

In classical electrodynamics, an accelerated charge generates continuous wave radiation [3]. However, quantum mechanics explains that in an isolated system, discrete transitions between quantized energy levels are accompanied by the absorption or emission of “photons,” i.e., packets of electromagnetic waves whose wavelength is inversely proportional to energy ($E = \frac{h}{\lambda}$, where h is the Planck constant) [4]. The concept of photons therefore explains the *discrete* absorption or emission spectra of a gas, as often studied in chemistry, e.g., during the excitation of a gas by absorption, or spontaneous emission during de-excitation.

However, the photonic description of radiation is not practical for explaining the *continuous* emission of thermal radiation by a set of atoms in thermal motion, as it requires concepts that go well beyond the scope of secondary school education. Max Planck (1901) provided a quantum explanation of thermal radiation in the ideal case of a perfectly opaque body (known as a “black body”), by modeling atoms as quantum harmonic oscillators and integrating their photon emissions [5].

To students, it is possible to explain in simplified terms that there are two mechanisms for generating radiation: *discrete* photon emission (seen in chemistry), and *continuous* radiation emission through thermal agitation. An example of the solar spectrum illustrates this point, as we can see the absorption lines (Fraunhofer lines) of the “cold” atoms of the photosphere superimposed on the continuous thermal spectrum, as in Fig. 2 or on a more complete high-resolution spectrum.

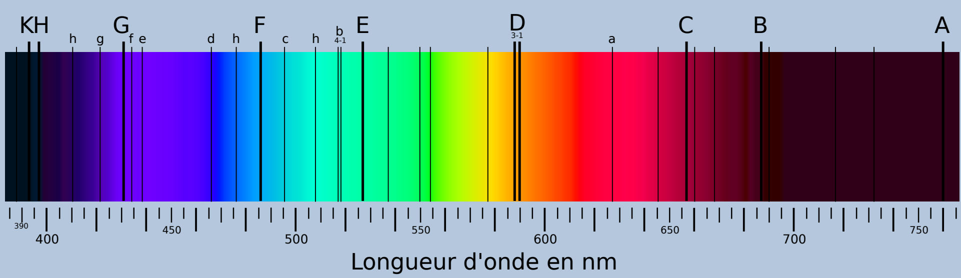


Fig. 2 : Discrete Fraunhofer absorption lines superimposed on the Sun's continuous thermal emission spectrum [Source: image by Bajart and Sapéraud, taken from Wikipedia].

We have chosen a single oscillating charge as the source of radiation (rather than a dipole, as is conventionally presented in university courses [3]), because this allows us to visualize the generation of electric waves with a minimum of prerequisites (see Sect. 2), and can easily be generalized to a ensemble of charges to explain the emission of thermal radiation (see Sect. 2) .

In each radial direction, the electric wave is represented in simplified form as a progressive sinusoidal wave (see Box 2) in order to be consistent with the representation of waves studied in secondary school. The amplitude is maximum in the direction orthogonal to the oscillation of the charge and zero along the axis of oscillation.

Box 2. Representation of the electric waves

In each radial direction r, the transverse component of the field, E, is given by the following time-dependent equation:

$$E(r, \theta, t) = E_0 \sin\theta \sin(\frac{2\pi}{\lambda} r - 2\pi f t)$$

where E_0 is the amplitude of the wave at the source, λ is the wavelength, f is the frequency of agitation, and θ is the polar angle between the vertical axis and the direction of the wave. This equation describes a progressive plane wave, which would be strictly correct far from the oscillating source. The factor $\sin\theta$ makes the amplitude maximum in the horizontal direction and zero in the vertical direction parallel to the oscillation, which is expected for radiation generated by an oscillating dipole [3]. However, we did not include a factor $1/r$ to represent attenuation with distance, as this is already represented by wave divergence.

Rather than allowing a pseudo-continuous variation of the frequency f cursor, we have chosen discrete steps to produce relatively regular variations in wavelength λ according to the hyperbolic relationship $\lambda = c/f$, where c denotes the speed of light. This discretization allows the wavelength cursor to be scanned regularly accross the spectrum bar. It facilitates the measurement of the wavelength-frequency relationship by creating a graph such as the one in Fig. 3.

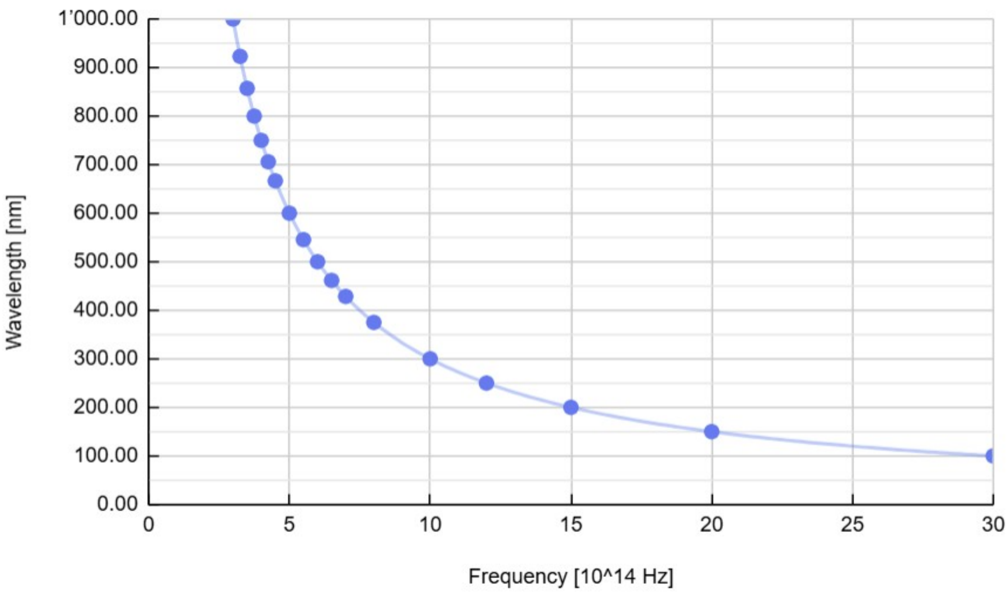


Fig. 3 : Discrete values of the oscillation frequency, chosen to generate wavelengths at relatively regular intervals of 50 nm.

References

[1] Varela, B., Sesto, V., García-Rodeja, I. (2020), *An investigation of secondary students ? Mental models of climate change and the greenhouse effect*, Research in Science Education, 50, 599–624

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[4] Cohen-Tannoudji, C., Diu, B., & Laloe, F. (1986), *Quantum mechanics*, volume 1, 651-653

[5] Planck, M. (1901), *On the law of distribution of energy in the normal spectrum*. Annalen der physik, 4(553), 1.