Module Name: Understanding the Planck's Law of Black-Body Radiation

1. Learning Outcomes

Upon completion of this module the learner will be able to: -

- Remember the definition of Planck's law.
- Understand the phenomenon of black-body radiation.
- Apply to any curve fitting.
- Analyze radiation spectrum.
- Evaluate the Wien's displacement law.
- Create animation/visual effects for other laws associated with black-body radiation.

2. Introduction

Planck's Law: The Planck's Law of the black-body radiation in physics, the concept of radiation is a fundamental idea that is used to describe the spectral energy distribution of electromagnetic radiation that is emitted by a perfect black body when it is in thermal equilibrium. In the year 1900, as part of his efforts to explain the known radiation spectrum that is emitted by heated objects, Max Planck developed this law.

The key concepts in Planck's Law are:

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- **Radiation from a black body:** A black body is an idealized theoretical object that does not reflect or transmit any of the radiation that strikes it and instead absorbs all of it. In addition to this, it also emits radiation across a continuous range of frequencies or wavelengths.
- **Thermal equilibrium:** It is assumed that the black body is in a state of thermal equilibrium, which indicates that its temperature is unchanging over the course of time.
- **Spectral energy distribution:** The law specifies how the total amount of radiation emitted by a black body is dispersed over various wavelengths or frequencies. This concept is referred to as the spectral energy distribution. It gives information regarding the intensity or power that is radiated per unit area per unit solid angle per unit frequency or wavelength.

Planck's Law can be represented in a number of different ways, depending on whether one is looking at the wavelength domain or the frequency domain. Here, it is presented in terms of wavelength (λ), which is as follow:

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{\left(\frac{hc}{\lambda k_B T}\right)}-1} \qquad (1)$$

In this equation:

- B(λ, T) represents the spectral radiance or energy density emitted by the black body at a given wavelength (λ) and temperature (T).
- h is Planck's constant ($6.62607015 \times 10^{-34}$ J·s).
- c is the speed of light in a vacuum (2.99792458×10^{8} m/s).
- k_B is Boltzmann's constant (1.380649×10^{-23} J/K).
- T is the temperature of the black body in Kelvin (K).

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The Term "$\left(\frac{hc}{\lambda k_B T}\right)$" may be found in the equation's denominator and is referred to as the reduced Planck constant multiplied by the reciprocal of the product of temperature and wavelength. This quantity is frequently abbreviated as "x".

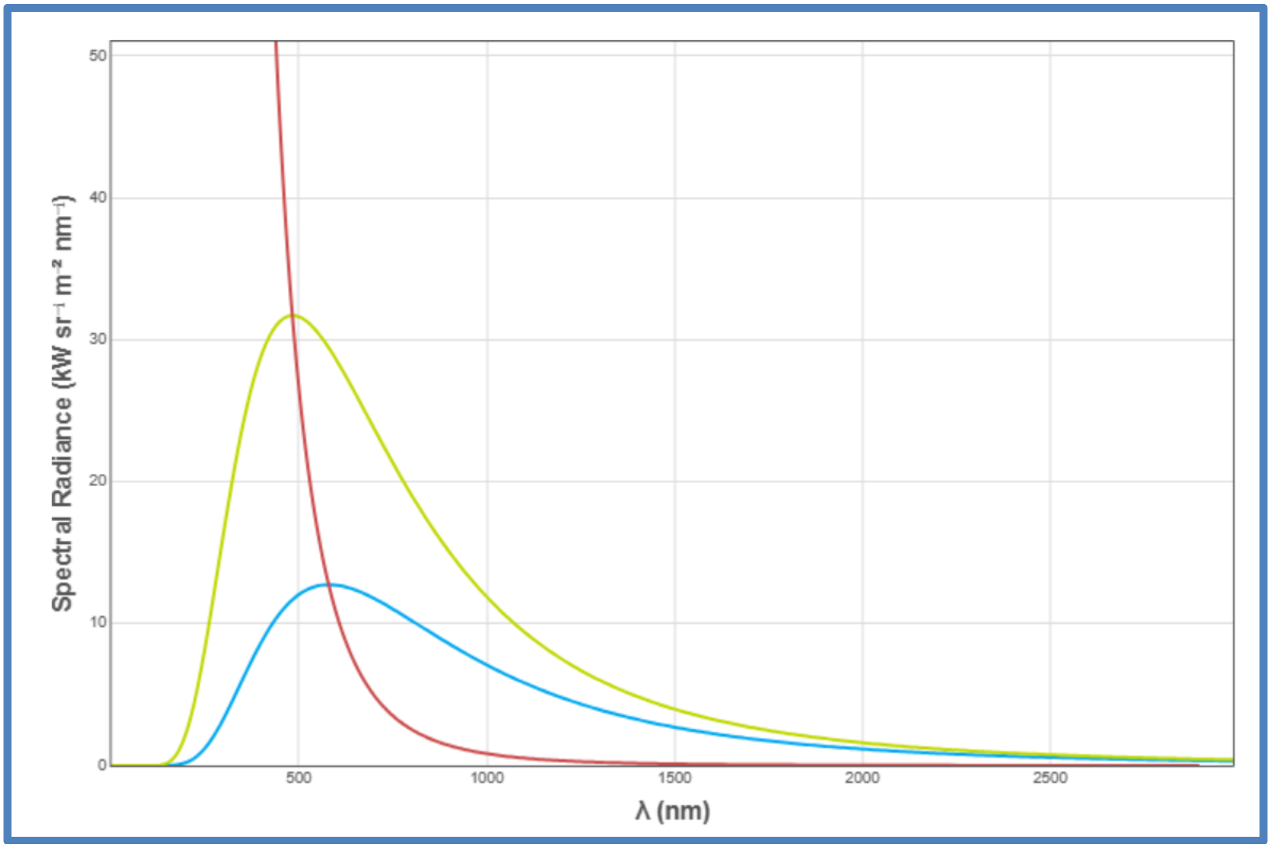


Figure 1: Black-body radiation is precisely described by Planck's law. Presented is a family of temperature-dependent curves.

It can be seen from the equation (1) and figure 1 that the spectral radiance is a function of both the temperature of the black body and the wavelength of the radiation that is being emitted. Increases in spectral radiance are seen at shorter wavelengths, whilst declines in spectral radiance are seen at longer wavelengths.

Planck's Law accurately describes the observed black-body radiation spectrum and successfully resolved the ultraviolet catastrophe, a problem encountered by classical physics. It played a crucial role in the development of quantum mechanics and laid the foundation for understanding the behavior of light and matter at the atomic and subatomic levels.

Wien's Displacement Law: Wien's displacement law is a fundamental physics principle that relates the wavelength at which a black body emits the most intense radiation to its temperature. It reveals how the temperature affects the distribution of emitted radiation.

The mathematical expression for Wien's displacement law is:

$$\lambda_{max} = \frac{b}{T} \tag{2}$$

where:

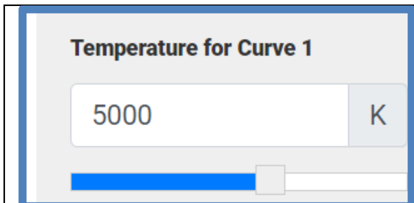
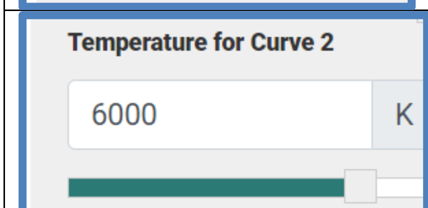
- λ_{max} is the wavelength at which the maximal intensity of radiation occurs
- b is Wien's displacement constant (approximately equal to 2.8977729 10^{-3} mK
- T is the black body's temperature in Kelvin (K).

According to Wien's displacement law, as the temperature rises, the wavelength at which the maximal intensity occurs decreases. In other terms, objects with a higher temperature emit electromagnetic radiation with shorter wavelengths and higher frequencies.

This relationship can be understood in terms of the atomic or molecular behavior of the black body's constituents. As temperature increases, so does the average kinetic energy of the particles. This causes more energetic collisions and energy level transitions, which results in the emission of radiation with shorter wavelengths.

The displacement law of Wien has many practical applications. It aids in determining, for instance, the temperature of stars based on their observed spectra. By analyzing the maximal wavelength of a star's emitted radiation, astronomers can determine the surface temperature of the star. In addition, the law is applicable in disciplines like thermal imaging, where the temperature of objects can be deduced by measuring the intensity of the infrared radiation they emit.

Step I: Different buttons available with the interface.

	**Sider:** Temperature range for curve #1, from 2000 K to 7000 K
	**Sider:** Temperature range for curve #2, from 2000 K to 7000 K
	**Checkbox:** to overlay Wiens' displacement law.

Results: The Planck's law is understood successfully by plotting spectral radiance with wavelength.

Exercise: Prepare and execute a program for Planck's law in any of following programming: Mathcad, MATLAB, Python.

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