

# USING A PYTHON-BASED CALCULATION TOOL IN TEACHING THE CONCEPTS OF THE PHOTON AND THE ELECTROMAGNETIC SPECTRUM

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## Abstract

The article examines the main difficulty encountered when teaching the topics of the photon and the electromagnetic spectrum, namely the problem of picturing the relationships between quantities through formulas alone. To ease this problem, a photon calculator was developed using Python and Tkinter. Given a wavelength entered in nanometers, the program calculates the photon's frequency, energy (in joules and electron-volts), momentum, and the mass equivalent of energy, and also shows which region of the spectrum the given wavelength falls into and, for visible light, the name of the color. The article presents the algorithm, the main code fragments, the way the formulas are expressed in the program, and sample calculations ranging from X-rays to radio waves, and describes ways of using the tool in the classroom. No pedagogical trial with students was conducted in this work; measuring effectiveness is defined as a task for the next stage.

**Keywords:** Photon, electromagnetic spectrum, wavelength, photon energy, Python, Tkinter, physics education, simulation, visualization.

## Introduction

Concepts such as the photon, wavelength, frequency, and spectrum are usually presented in a physics lesson through formulas:  $E = h\nu$ ,  $\lambda\nu = c$ . Memorizing a formula is not difficult. The difficulty lies elsewhere: picturing how energy, frequency, and momentum change together when the wavelength changes. A photon cannot be seen, and an X-ray or a radio wave cannot be demonstrated in the classroom either, so the concept often remains at the level of an abstract symbol.

Foreign researchers have widely studied the use of computer simulations in such situations. Wieman, Adams, and Perkins write that PhET simulations encourage students to actively master scientific concepts [1]. Finkelstein and co-authors showed that, on the topic of electric circuits, conceptual outcomes were no worse even when a simulation replaced real equipment [2]. In an experiment on electromagnetism with Grade 11 students, Kotoka and Kriek found that the group that used a simulation as an interactive demonstration achieved higher results

than the control group; the authors also note that how the simulation is integrated into the lesson matters more than the simulation itself [3]. Maries and colleagues, in turn, showed that even in an abstract field such as quantum mechanics, guided interactive tutorials can support students' thinking [4]. The practical conclusion from these works is as follows: a program is useful only when it is given together with a task that prompts students to compare and draw conclusions. Feynman, too, viewed physics not as a collection of ready-made formulas but as a curiosity about understanding nature [5]. An interactive tool can serve as a bridge between a symbol in a formula and its real physical meaning. In Uzbekistan as well, the question of introducing digital tools and virtual experiments into physics lessons is being studied: in the works of Qosimjonov and Xakimova it is considered from the standpoint of developing analytical thinking and experimental competencies [6], [7].

The aim of this article is to propose a simple calculation tool based on Python and Tkinter for the topic of the photon and the electromagnetic spectrum, to explain its algorithm, and to show ways of using it in lessons. It should be emphasized that what is described here is the structure and methodological basis of the software tool; no trial with students has been conducted.

### PROBLEM STATEMENT

Three difficulties are especially noticeable in studying the topic. The first is that the relationships are inverse: as the wavelength increases, the frequency, energy, and momentum decrease. One might intuitively think of a longer wavelength as a "stronger" light, so it is useful to check this idea with numbers. The second is scale: in the electromagnetic spectrum the wavelength varies from nanometers to tens of meters, that is, by about ten billion times, and such a range is hard to grasp by looking at numbers alone. The third is units: energy is given both in joules and in electron-volts, while the relationship between the two is often simply told to students ready-made.

Thus, the task is to create a simple tool that makes it possible to change the wavelength in one environment and see all the dependent quantities at once, link the result with the spectrum region, and compare the values with each other. The tool should work on computers common in schools and higher education without any separate complex software.

### RESEARCH METHODOLOGY

The input parameter of the program is the wavelength  $\lambda$  (entered in nanometers and converted to meters for the calculation:  $\lambda[\text{m}] = \lambda[\text{nm}] \cdot 10^{-9}$ ). The remaining quantities are found using the following relations valid for a photon:

$$v = c / \lambda \quad (1)$$

$$E = hv = hc / \lambda \quad (2)$$

$$E[\text{eV}] = E[\text{J}] / e, \quad 1 \text{ eV} = 1.602 \times 10^{-19} \text{ J} \quad (3)$$

$$p = h / \lambda = E / c \quad (4)$$

$$m_{eq} = E / c^2 = h / (\lambda c) \quad (5)$$

Here  $h = 6.626 \times 10^{-34} \text{ J} \cdot \text{s}$  (Planck's constant),  $c = 3 \times 10^8 \text{ m/s}$  (the speed of light in vacuum). Since 2019, the values of  $h$  and  $c$  in the SI system have been fixed exactly ( $h = 6.62607015 \times 10^{-34} \text{ J} \cdot \text{s}$ ,  $c = 299\,792\,458 \text{ m/s}$ ) [9]. Because the program uses rounded values, its results differ



from those obtained with these exact values by less than about 0.1 %, which is sufficient for educational purposes.

The quantity in expression (5) should not be understood as the mass of the photon. The rest mass of a photon is zero, and  $m_{eq}$  is nothing other than energy expressed in units of mass. In current teaching literature, it is recommended to abandon the concept of “relativistic mass” and to use energy and momentum instead [8]. For this reason, the program gives this value to show the relationship between energy and mass, and it occupies a secondary place among the results. The spectrum region is determined by the upper limits of the wavelength: up to 0.01 nm gamma rays, up to 10 nm X-rays, up to 380 nm ultraviolet, 380–750 nm visible light, up to  $10^6$  nm (1 mm) infrared, up to  $10^9$  nm (1 m) microwaves, and longer ones are taken as radio waves. In the visible region the color name is also output (violet, blue, green, yellow, orange, red). These boundaries differ somewhat depending on the source, so they should be regarded as a didactic convention rather than a strict physical boundary.

The program can be used in a lesson in three stages: the student chooses a wavelength; the program calculates the numerical quantities and shows the spectrum region; the student compares several values and draws their own conclusion.

## PROGRAM STRUCTURE

The program algorithm is shown in Figure 1. Its main part consists of two functions; their code is given in Figure 2.



Change the value → calculate → compare → draw a conclusion

Figure 1. Operating procedure of the photon calculator.

```

h, c, eV = 6.626e-34, 3e8, 1.602e-19

def find_band(lam_nm):
    spectrum = [(0.01, "Gamma"), (10, "X-ray"), (380, "UV"), (450, "Violet"),
                (495, "Blue"), (570, "Green"), (590, "Yellow"), (620, "Orange"),
                (750, "Red"), (1e6, "Infrared"), (1e9, "Microwave")]
    return next((r for lt, r in spectrum if lam_nm <= lt), "Radio")

def calculate():
    try:
        lam_nm = float(entry_lambda.get())
        if lam_nm <= 0: raise ValueError

        lam = lam_nm * 1e-9          # Wavelength (m)
        nu, p = c / lam, h / lam     # Frequency (Hz) and momentum (kg·m/s)
        E_J = h * nu                # Energy (J)
        E_eV, m = E_J / eV, E_J / c**2 # Energy (eV) and equiv. mass (kg)

        result_text.set(f"ν: {nu:.3e} Hz | E: {E_J:.3e} J ({E_eV:.2f} eV)\n"
                       f"p: {p:.3e} kg·m/s | m: {m:.3e} kg\n"
                       f"Region: {find_band(lam_nm)}")
    except ValueError:
        messagebox.showerror("Error", "Enter a positive number!")
  
```

Figure 2. Main functions of the program: find\_band() and calculate().

At the beginning of the code, three constants are defined: Planck's constant  $h$ , the speed of light  $c$ , and the conversion factor from electron-volts to joules  $eV$ . Defining the constants in one place makes it possible to write the formulas compactly inside the code and, if necessary, to replace them with more precise values.

The `find_band()` function goes through a list of (upper limit, name) pairs and returns the name of the first region whose upper limit the entered wavelength does not exceed. If no suitable region is found by the end of the list, the wave is taken to belong to the radio range. In this way, one function gives both the spectrum region and the color name of visible light.

The `calculate()` function converts the entered value to a number with `float()` and checks that it is greater than zero. Then the nanometers are converted to meters, and the frequency, energy, momentum, and equivalent mass are found using relations (1)–(5). The result is collected in scientific notation (`:.3e`) using an f-string into a single text block. If the user enters text, an empty field, or zero or a negative number, the `try/except` block catches the `ValueError` and the program displays the message "Enter a positive number!" without stopping. The window, input field, and button are built with Tkinter widgets (Label, Entry, Button); the button is bound to the `calculate()` function and is not shown in the figure.

## RESULTS AND DISCUSSION

Table 1 gives sample calculations obtained with the program's constants ( $h = 6.626 \times 10^{-34}$  J·s,  $c = 3 \times 10^8$  m/s,  $1 \text{ eV} = 1.602 \times 10^{-19}$  J). To cover not only the visible region but also the values from X-rays to radio waves, the wavelengths 1 nm, 10  $\mu\text{m}$ , and 10 m were added.

Table 1. Sample results calculated using the photon calculator

| $\lambda$ , nm | $\nu$ , Hz             | E, J                    | E, eV                  | $p$ , kg·m/s            | $m$ , kg                | Region / color |
|----------------|------------------------|-------------------------|------------------------|-------------------------|-------------------------|----------------|
| 1              | $3.000 \times 10^{17}$ | $1.988 \times 10^{-16}$ | $1.241 \times 10^3$    | $6.626 \times 10^{-25}$ | $2.209 \times 10^{-33}$ | X-ray          |
| 400            | $7.500 \times 10^{14}$ | $4.970 \times 10^{-19}$ | 3.102                  | $1.657 \times 10^{-27}$ | $5.522 \times 10^{-36}$ | Violet         |
| 550            | $5.455 \times 10^{14}$ | $3.614 \times 10^{-19}$ | 2.256                  | $1.205 \times 10^{-27}$ | $4.016 \times 10^{-36}$ | Green          |
| 700            | $4.286 \times 10^{14}$ | $2.840 \times 10^{-19}$ | 1.773                  | $9.466 \times 10^{-28}$ | $3.155 \times 10^{-36}$ | Red            |
| $10^4$         | $3.000 \times 10^{13}$ | $1.988 \times 10^{-20}$ | 0.124                  | $6.626 \times 10^{-29}$ | $2.209 \times 10^{-37}$ | Infrared       |
| $10^{10}$      | $3.000 \times 10^7$    | $1.988 \times 10^{-26}$ | $1.241 \times 10^{-7}$ | $6.626 \times 10^{-35}$ | $2.209 \times 10^{-43}$ | Radio          |

As can be seen from the table, as the wavelength increases from 400 nm to 700 nm, the frequency, energy, and momentum decrease. The ratio of energies  $3.102 / 1.773 \approx 1.75$  is equal to the ratio of wavelengths  $700 / 400 = 1.75$ , that is, the inverse proportionality in formula (2) is visible in the numbers. The energy of a visible-light photon is on the order of a few electron-volts, that of an X-ray photon is more than a thousand, and that of a radio wave is smaller than even one millionth of an electron-volt. Such a difference can be felt not by looking at the formula but precisely when several values are entered one after another. Figure 3 shows the order of the regions and the direction in which the quantities change.

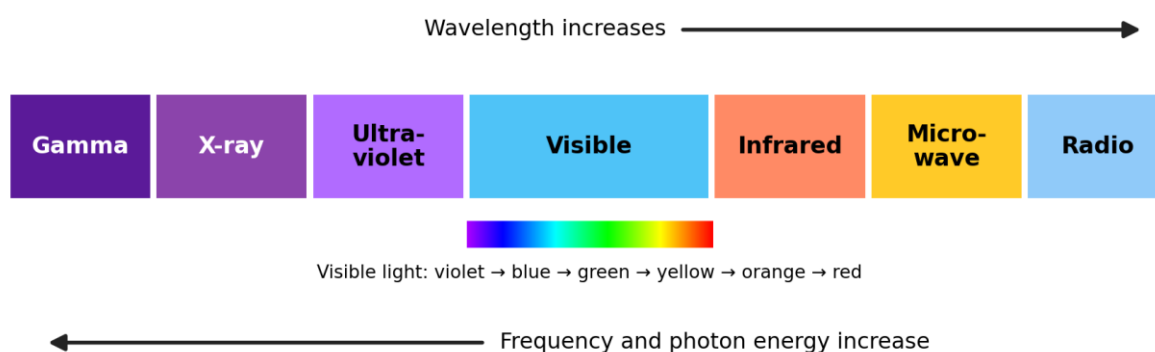


Figure 3. Simplified diagram of the electromagnetic spectrum regions (boundaries are conventional).

There are several ways to use it in a lesson. The first is predict and check: the student is given 400 nm and 700 nm and asked which photon has the greater energy, and then the answer is checked with the program and compared with the formula. The second is to enter the values 400, 450, 500, 550, 600, 650, and 700 nm one after another and record the results in a table; here the decrease in frequency and energy is observed, while the color shifts from violet toward red. The third is an inquiry task: calculating the product of  $E$  and  $\lambda$  for each value and finding that it is constant. This product is approximately 1240 eV·nm, from which the rule  $E[\text{eV}] \approx 1240 / \lambda[\text{nm}]$  follows, and the student can derive it independently. The fourth is comparing the 1 nm, 10  $\mu\text{m}$ , and 10 m rows of the table to estimate the energy difference between regions of the spectrum.

## CONCLUSION

The article described a photon calculator developed in Python and Tkinter for teaching the topic of the photon and the electromagnetic spectrum. From the wavelength, the program calculates the photon's frequency, energy, momentum, and the mass equivalent of energy, determines the spectrum region, and gives the color name for visible light. Because the formulas are written openly in the program, the student can follow each step. The sample calculations showed that frequency, energy, and momentum decrease as the wavelength increases, across the range from X-rays to radio waves. When used together with tasks such as predicting and checking, filling in a table, and finding that the product  $E \cdot \lambda$  is constant, the tool helps students analyze the relationships between quantities instead of memorizing formulas.

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