



PLANCK'S CONSTANT

IDEA TO REMEMBER!

No idea is too small to be big!

OBJECTIVE:

Explore the significance of Planck's constant of proportionality h in the world of Physics and how it started the quantum revolution.

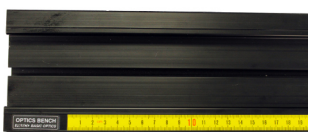
MATERIALS:



PASCO Interface



Multimeter



Optics Bench



Screen w/ Clamps



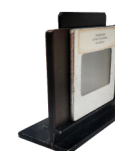
LED Box w/ Eye Tube & Cables



Ruler w/ Clamp



Light Shield w/ Clamps



Slide Holder w/ Single Slit and Diffraction Grating

CONCEPT:

In the 19th century, many fascinating experiments and discoveries were centered around the nature of light. There was one particularly “hot” debate around **black body radiation**.

Though it was practically known by blacksmiths of old, scientists wanted to understand how substances interacted with radiation (light) and how they produced their own light at certain temperatures, like in **Figure (1)**. In order to study this, in 1860, Gustav Kirchhoff conceptualized a *black body*, which he defined as a “hot, **opaque** solid, liquid, or gas [that] will produce a continuum spectrum.” Simply put, a black body is an object that perfectly absorbs and perfectly emits electromagnetic radiation. (It has nothing to do with the color!) A true black body is not found in nature—though stars are close—so, experimental approximations were devised, such as a box made of any opaque substance with a very small hole to allow light in and reflect inside. Any light that escaped would satisfy something close to perfect emission. See **Figure (2)**.

Many years later, funded by German industry's desire for better light bulbs, Wilhelm Wien was able to derive *Wien's dis-*



Figure 1: The hot steel produces its own light! Why?

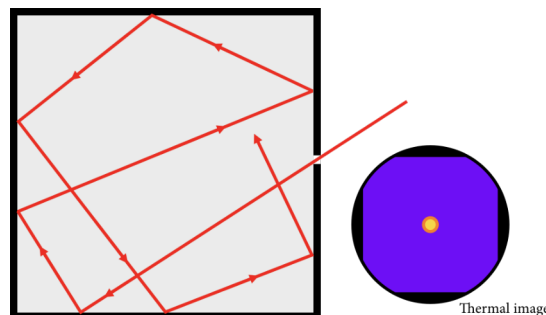


Figure 2: A black body approximation.

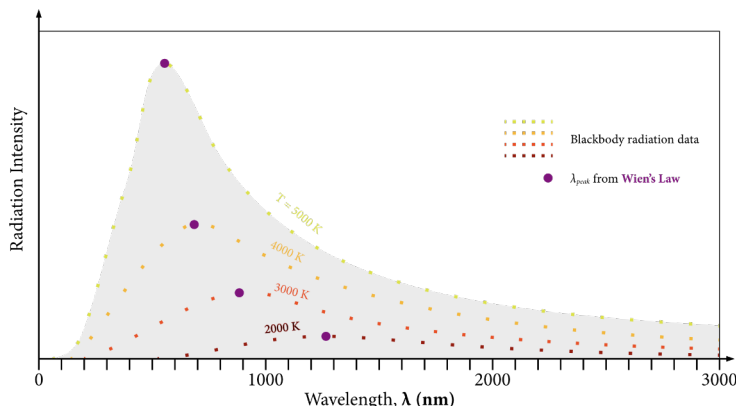


Figure 3: Black body radiation data in 1890s and Wien's displacement law, which finds the peaks of the curves.

placement law in 1893, showing that the peak frequency f_{peak} of the black body radiation is proportional to temperature T —or put another way, the peak wavelength λ_{peak} is inversely proportional to the temperature T :

$$\lambda_{peak} = \frac{0.0029}{T} \quad (1)$$

See **Figure (3)** for a plot of Wien's displacement law. In 1896, [he also developed](#) the *Wien's approximation* to model the entire curve:

$$I(\lambda, T) = Af^3 e^{-af/k_B T}$$

Where $e^{-af/k_B T}$ is the *Maxwell–Boltzmann thermodynamic probability distribution*—developed in the 1860s and 70s to **predict the speed or energy of atoms by density**—and A, a are an undetermined constants. However, this formula failed at low frequencies in the infrared region.

An important digression...

Before moving forward in the story, we must understand what *Maxwell's electromagnetic theory* predicted: that "oscillating electric charges produce electromagnetic waves, and the radiation emitted by a hot object could be due to the oscillations of electric charges in the molecules of the material" (pg. 1097, *Physics for Scientists and Engineers*, Douglas Giancoli, 5th Edition). Using this theory, some scientists began to postulate that an infinite number of **standing waves** developed within the black body cavity at equilibrium temperature, as shown in **Figure (4)**. So they applied Maxwell's theory and [the 3-dimensional version of the wave equation](#) to calculate the number of nodes N :

$$N = \frac{8\pi f^2}{c^3} \quad (2)$$

THINK: Why did scientists assume the number of standing waves inside the black body cavity was infinite? (See below.)

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FUN FACT: Wien's law followed the *Stefan-Boltzmann law*, named after Josef Stefan and Ludwig Boltzmann, where the intensity of the energy radiated M° was found to be proportional to the fourth power of the black body temperature T :

$$M^\circ = \sigma T^4$$

Where σ is the *Stefan-Boltzmann constant*. Stefan subsequently used his law to be the first to accurately determine the temperature of the Sun!

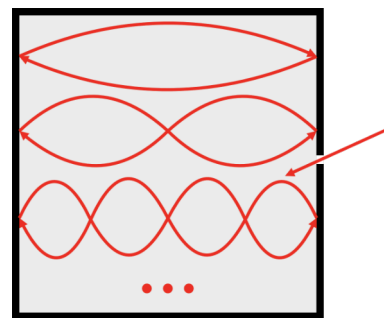


Figure 4: Rayleigh, Jeans, and Planck assumed there were standing light waves within the black body at equilibrium temperature!



We should also learn about the *Boltzmann constant* k_B , named after Ludwig Boltzmann. Though he lived in a time before the discovery of atoms, Boltzmann thought that temperature was really the kinetic energy of small particles. He was right on the macro scale, and **the Boltzmann constant shows up everywhere in black body calculations**, representing the relation of the average thermal/kinetic energy of particles in a gas with the temperature of that gas: $k_B = 1.380 \times 10^{-23}$ J/K. On the micro scale the idea fails because the Boltzmann constant is based on the law of equipartition, which assumes that energy is shared equally among the atoms. Applied to black body radiation, this suggests an infinite distribution of energy states, creating an infinite number of standing waves within the black body cavity.

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These two ideas of electromagnetic standing waves and the equipartition of energy states were the foundations and common threads found in the works of Lord Rayleigh, Sir James Jeans, and Max Planck.

Another failed attempt

Rayleigh-Jeans law, named after Lord Rayleigh and Sir James Jeans, sought to model the black body radiation intensity $I(\lambda, T)$ data in two parts. The first, and obvious step—so they thought—was to apply the accepted laws of thermodynamics, which related energy E to the temperature T , such that $E = k_B T$, where k_B is the Boltzmann proportionality constant. The second and more ingenious move was to adapt *Maxwell's electromagnetic theory* and the *wave equation* to model standing waves within the black body cavity. Putting both parts together in June 1900—mere months before Planck published his law—they published the following:

$$I(\lambda, T) = \frac{8\pi f^2}{c^3} k_B T \quad (3)$$

However, this formula diverges when integrating over every frequency! Thus, it could not accurately fit the empirical data at high frequencies. This was later called the **ultraviolet catastrophe**, shown in Figure (5).

THINK: Which component of the formula causes it to diverge?

Planck's law

Enter Max Planck.

Having studied under Kirchhoff and eventually succeeding Kirchhoff's position at the University of Berlin, Planck started working in 1900 to address the error in his colleague's (Wien's) approximation to fit the infrared side of the black body radiation curve, but he ran into problems using classical thermodynamic models, just as Rayleigh and Jeans were having in England. He therefore determined to create whatever mathematical expression fit the black body data, regardless of its meaning and implications. He derived the following—now

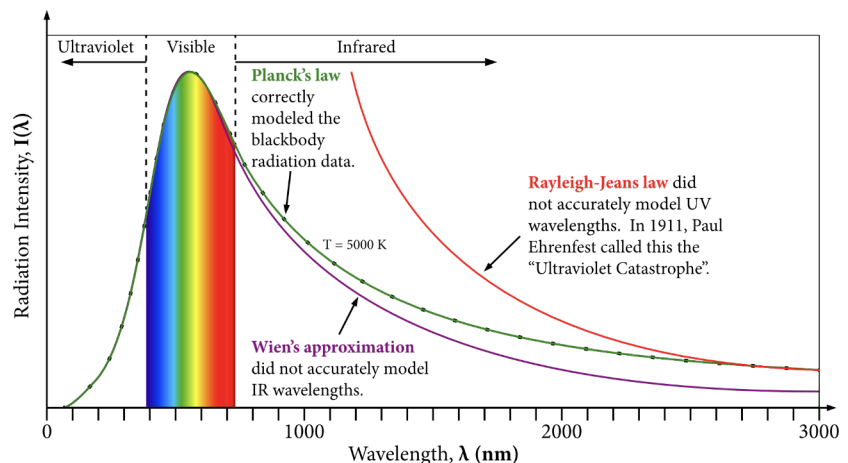


Figure 5: Various mathematical attempts to model the black body radiation data.



known as *Planck's law*—in a single night and presented it a few weeks later in October 1900 (A and a are undetermined):

$$I(\lambda, T) = \frac{Af^3}{(e^{af/k_B T} - 1)} \quad (4)$$

THINK: What is the difference between Wien's approximation and Planck's law?

It took Planck six weeks after presenting the formula to understand what it meant: that the energy behaved as “a discrete quantity composed of an integral number of finite equal parts...” (Planck, *On the Law of Distribution of Energy in the Normal Spectrum*). Where the classical laws assumed that energy could be infinitely divided (like continuous points along a rope), there were actually discrete energy quantities—or **quantized energy packets** (like the rungs of a ladder)! He imagined, like Rayleigh and Jeans, that electrons acted like **simple harmonic oscillators**, creating standing waves within the black body. From this he concluded that the number of oscillators at a particular frequency would dictate the energy emitted. He applied Boltzmann's energy distribution to the number of oscillators at each frequency and [solved for the average energy of the system](#):

$$\langle E \rangle = \frac{hf}{(e^{hf/k_B T} - 1)}$$

Replacing A in Planck's law with the number of standing wave nodes, **Equation (2)**, and replacing $(e^{af/k_B T} - 1)^{-1}$ with the average energy equation above gives:

$$I(\lambda, T) = \frac{8\pi hf^3}{c^3} \frac{1}{(e^{hf/k_B T} - 1)} \quad (5)$$

The mystery was solved! Furthermore, the discovery of electrons and determinations by Heinrich Hertz, Philipp Lenard, and J. J. Thompson created a new relation to energy at the atomic scale: see **Equation (6)**, where e is the electron charge constant of $1.602 \times 10^{-19} \text{ J}$ and V is the threshold voltage. In 1905, Albert Einstein finally supplied a cohesive interpretation to finally explain the nature of light—that light releases energy in packets, called **photons**. **Equation (7)**, known as the *Planck-Einstein relation*, shows that the amount of the energy in the packet is proportional to the product of its frequency and **Planck's constant h** :

$$E = eV \quad (6) \qquad E = hf = \frac{hc}{\lambda} \quad (7)$$

Thus, the old “heated” debate created “light” for something new, what is now known as ***quantum mechanics!***

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Real World Applications

- Planck's constant h is present in every formula that describes quantum phenomena: the **Bohr–Rutherford model of the atom** (1913), **de Broglie's wavelength of all matter** (1924), the **Schrödinger equation** (1925–1926), and the **Heisenberg uncertainty principle** (1927)!
- **Every modern electronic device** could not have been created without an understanding of quantum physics and the original work done by Planck!



1) Understanding black body radiation, and deriving Rayleigh-Jeans law
2) Deriving Planck's law



PRECAUTIONS:

Not much for worry! Have fun and learn!

PROCEDURE:

- Fill out the top information on the worksheet and complete the memory exercise—Questions M1–M3.
- REQUIRED: Read the *Concept* section.

Part 1

- Assemble the setup as described below.
 - Bridge the LED Box circuit at “A” with a Banana Cable, and connect the LED Box power to the PASCO Interface, as shown in **Figure (6a)**.
 - In PASCO Capstone *Signal Generator*, set the output voltage to 8V DC (the Interface will not reach 9V), as in **Figure (6b)**.
 - Turn on the LED Box to make sure the lights turn on, as in **Figure (6c)**; if not, ask your TA for help.

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CONCEPT & PROCEDURE VIDEOS:

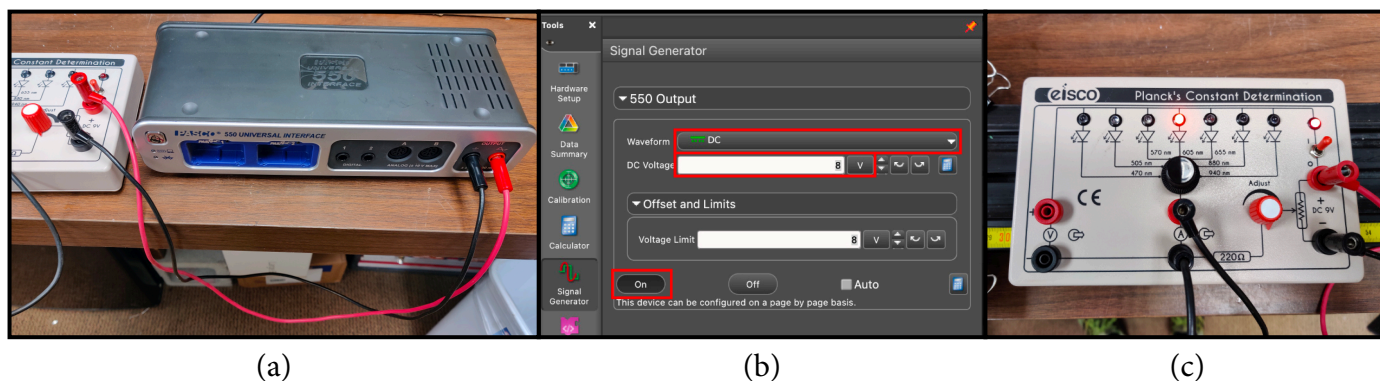


Figure 6

- Place the Screen against one end of the Optics Bench, see **Figure (7)**.
- While holding the Screen against the Optics Bench, place the Ruler on top of the Optics Bench and against the Screen and hold it in place with a Clamp, as in **Figure (8)**. *Note: place the Clamp around the 15 or 16cm mark on the Ruler.*
- Carefully place the Slide Holder on the Optics Bench so that it bridges both sides and its edge aligns with the long etched line

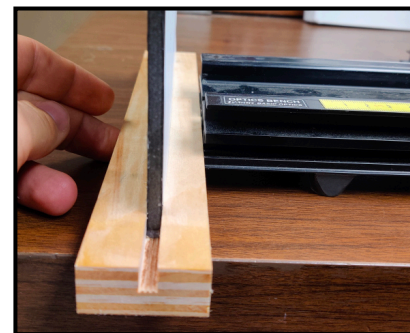
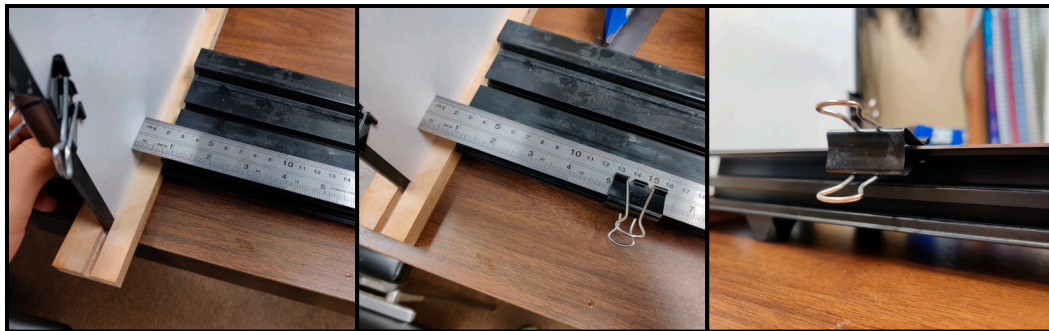


Figure 7



(a) (b) (c)

Figure 8

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on the Ruler. **The outer face of the Diffraction Grating should be at the 10cm (100mm) mark.** See Figure (9). Note: the Single Slit Slide on the opposite side of the Slide Holder will help narrow the spectral bands for marking.

- Place the Light shield on the Optics Bench against the Clamp for the Ruler and so that the slot in the middle is aligned with the Single Slit on the Slide Holder. Then pin it down with Clamps in the back, as in Figure (10).

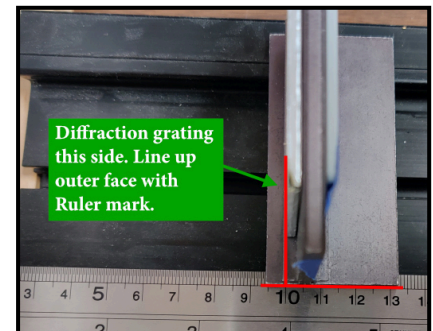
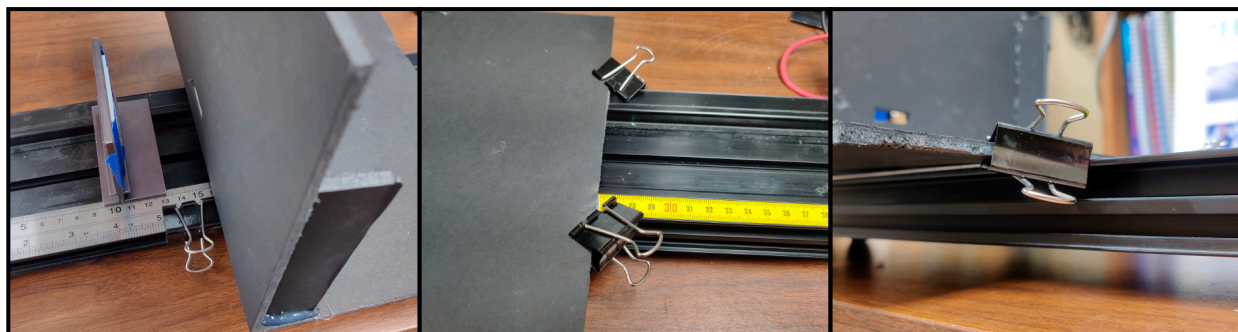


Figure 9



(a) (b) (c)

Figure 10

- Select the “470nm” (far left) LED, and turn the “Adjust” knob all the way right (full power).
- Position the LED Box upside down so that the light goes through the opening in the Light Shield. See Figure (11).
- Use two Clamps to attach someone’s worksheet to the Screen, realign the Screen against the Optical Bench and Ruler edges, and adjust the worksheet vertically and horizontally so that the cen-

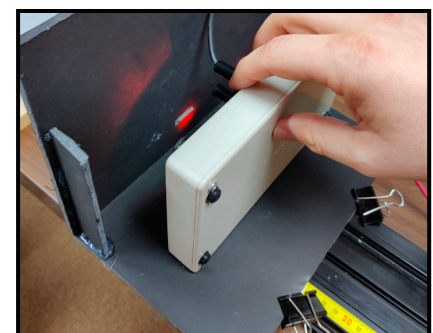


Figure 11



tral band aligns with the “0” on the worksheet measuring line, as shown in **Figure (12)**. *Note: the room must be dark for the next three steps.*

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7. Mark the center of the central band and the nearest maxima band with a Colored Pencil similar in color to the current LED color. See **Figure (13)**. *Note: it is helpful to use your other hand to brace the Screen while you mark.*



Figure 12

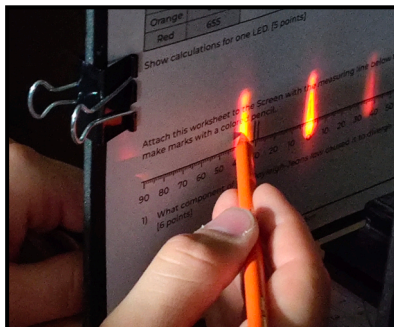


Figure 13

8. Turn the “Adjust” knob to the next LED and realign the LED Box so the light shines directly through the opening in the Light Shield.
9. Repeat steps 7–8 to the “605nm” (red) LED. *Note: use your phone’s camera to see “605nm” better.*
10. Each person in the group should go through steps 4–9 so that everyone has their own data set. *Note: those that have already completed steps 4–9 may continue.*
11. Answer Questions 1–3 on the worksheet.
12. Measure the distances between similar colored marks using the measuring line on the worksheet or another Ruler. The record the distances in Table 1 on the worksheet.
13. Create an Excel sheet with a table and formulas like in **Figure (14)**. Otherwise, calculate the values with your phone/calculator for Table 1 on the worksheet. Show your work for at least one LED.

	A	B	C	D	E	F	G	H	I
1	Table 1								
2	Color	Nominal λ (nm)	x (mm)	L (mm)	phase offset angle (tan)	sin	D (mm)	λ (m)	% error
3	Blue	470	31	100	=DEGREES(ATAN([@x (mm)]/[@L (mm)]))	=SIN([@phase offset angle (tan)]*PI/180)	=1/600	=[@D (mm)]*[@sin]/1000	=ABS([@Nominal λ (nm)]-[@ λ (m)]*1000000000)/[@Nominal λ (nm)]
10			(m = 1)		tan $\theta = x / L$	sin θ		D sin θ / m	nom - calc / nom

(a)

J	K	L	M	N
Table 2				
c (m/s)	f (Hz)	Voltage (V)	charge e (J)	Planck h (J s)
299792458	=[@c (m/s)]/[@ λ (m)]	2.2	=1.602*10^-19	=[@charge e (J)]*[@Voltage (V)]/[@ λ (m)]/[@c (m/s)]
			E = eV	

(b)

Figure 14



Part 2

14. Select the first LED (blue, “470nm”), and turn the “Adjust” knob all the way down (to the left; no light). Place the Eye Tube over the LED, and turn the Multimeter dial to DC V and insert the leads into the “V” terminals, similar to **Figure (15)**.
15. While slowly turning the “Adjust” knob to the right, look for the faintest light. Then record the Multimeter voltage reading in Table 2 on the worksheet.
16. Repeat steps 14–15 for **every** LED, and find their Planck’s constant for Table 2 on the worksheet. *Note: use your phone camera or the TA photometer for the IR LEDs (“880nm” and “940nm”).*
17. Calculate Planck’s constant from the slope of Voltage V vs Frequency f , and complete Table 2 on the worksheet. Show your work. *Note: the Procedure video shows how to create the plot of V vs f in Excel. See QR code above.*
18. Answer Questions 4 on the worksheet.
19. Follow the **Let’s THINK!** instructions below.

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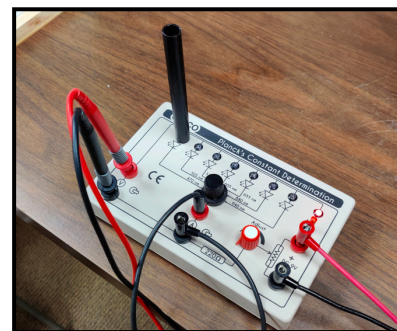


Figure 15

Let’s THINK!

- **Ask questions:** What are you learning here?... Why is this Physics concept important and how can it be used?... What do you not understand?... (For more information on this Physics topic, scan the QR codes in the *Real World Applications* and at the start of the *Procedure* section.)
- **Discuss** the concept and demonstration with your partner to help each other understand better. Discussion makes learning active instead of passive!
- For **FULL PARTICIPATION [15 points]** you must call on the TA when you have finished your group discussion to answer some comprehensive questions. If you do not fully understand and the TA asks you to discuss more, you must call on them one more time to be dismissed with full marks.
- **CONCLUSION [10 points]:** In the Conclusion section at the end of the worksheet, write 3 or more sentences summarizing this concept, how this lab helped you understand the concept better, and the real world implications you see. Do you still have questions? If so, write those as well.

Updated Date	Personnel	Notes
2023.10	Chase Boone, Bob Swanson	Reformatted for new lab manual standard. Improved the concept, procedure, and worksheet.

Name: _____

PH2233 Section #: _____

Name: _____

TA Name: _____

PLANCK'S CONSTANT WORKSHEET [70 points]

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Memory exercise [each 2 extra credit points]:

M1) _____ can determine the pattern of interference!

Hint: non-object span from peak to peak.

M2) Waves interfere based on their _____!

Hint: extra distance traveled by a wave (non-object).

M3) _____ can bend!

Hint: photonic non-objects.

Table 1: LED Wavelength [8 points; 0.5 point per cell]

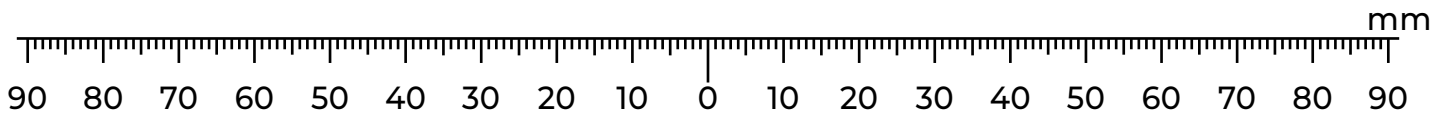
Color	Nominal wavelength (label) λ (nm)	Distance from center to maxima x_m (mm)	Distance to Screen L (mm)	* Angle of phase offset θ (°)	** Calculated Wavelength λ (nm)	% error
Blue	470					
Teal	505					
Green	570					
Orange	605					
Red	655					

Show calculations for one LED. [5 points]

* $\tan \theta = ?$

** $D = 1 \text{ mm} / 600; m\lambda = ?$

Attach this worksheet to the Screen with the measuring line below the pattern, then make marks with a colored pencil.



1) What component of the *Rayleigh-Jeans law* caused it to diverge when integrated? [8 points]

2) What is the difference between *Wien's approximation* and *Planck's law*? [5 points]

3) What did Planck decide to do when classical laws did not work? And what did he discover? [5 points]

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Table 2: Planck's constant [11 points; 0.5 point per cell]

Color	* Frequency f (Hz)	Voltage reading V (V)	Electron constant e (J)	** Planck's constant per LED h (J·Hz ⁻¹)	*** Planck's constant from slope of V vs f h (eV·Hz ⁻¹)
Blue			1.602 x 10 ⁻¹⁹		
Teal					
Green					
Orange					
Red					
IR 880					
IR 940					

* $c = 299792458$ m/s

** Eq (6) = Eq (7)

*** $V = h/e \cdot f$ ($y = mx...$)

Show a calculation for Planck's constant h for an LED, and the calculation using the slope of the linear fit for Voltage V vs Frequency f . [5 points]

4) What is the percent error of the calculated Planck's constants (average h per LED and linear fit h) against the known value (6.626×10^{-34} J·Hz⁻¹)? What components or conditions do you think are causing the error? [13 points]

