Q1–Q15: Lecture multiple choice — Fill in the correct answer on your bubble sheet.

SI prefixes:	$k = 10^3$	$c = 10^{-2}$	$m = 10^{-3}$	$\mu = 10^{-6}$	$n = 10^{-9}$

1. [4 pts] A light wave moves from a relatively slow medium into a relatively fast medium. Which of the following best describes the changes that occur to the wavelength and frequency of light upon entering the faster medium?

   A. Frequency increases. Wavelength increases.

   B. Frequency increases. Wavelength decreases.

   C. Frequency decreases. Wavelength increases.

   D. Frequency decreases. Wavelength decreases.

   E. None of these are completely correct.

Frequency is determined by the source.

$\Rightarrow$ freq. is constant.

2. [4 pts] A two-slit interference experiment is conducted involving light of wavelength 555 nm and a mask containing two very narrow slits separated by 0.10 mm. (SI prefixes are given at the top of this page.) The distance between the 3rd dark spot to the left of center all the way to the 3rd dark spot to the right of center is measured to be 6.0 cm.

   What is the distance from the mask to the screen?

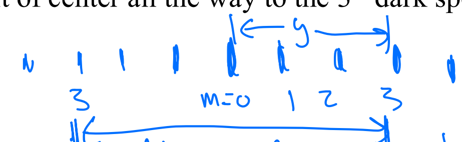
   A. 1.5 m

   B. 2.2 m

   C. 3.1 m

   D. 4.3 m

   E. None of these are correct.



Assume small angle, then check assumption at end.

$y_m = \frac{L\lambda m}{d}$ $m = 2.5$ for 3rd dark spot

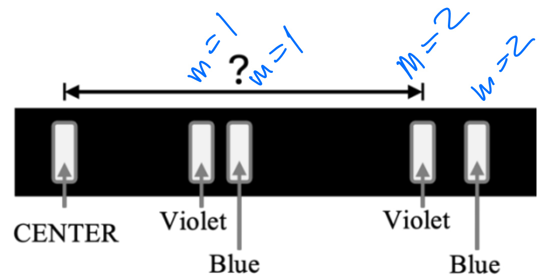
$$\Rightarrow L = \frac{y_{2.5}\, d}{\lambda \cdot 2.5} = \frac{(0.03\,\text{m})(0.1\times10^{-3}\,\cancel{\text{m}})}{2.5\times555\times10^{-9}\,\cancel{\text{m}}}$$

$$= 2.16\ \text{m}$$

$$= 2.2\ \text{m}$$

Small angle is justified... $y \ll L$

3. [4 pts] Blue light (λ_{blue} = 470 nm) and violet light (λ_{violet} = 390 nm) pass through a diffraction grating with line density 800 lines/mm. The diagram at right shows bright spots on a very wide screen that is 3.0 m away.



(Not to scale)

What is the unknown distance labeled on the diagram?

A. 0.94 m

B. 0.99 m

C. 1.9 m

D. 2.4 m

E. 8.0 m

d is so small, cannot safely assume small angle

$\Rightarrow d \cdot \sin\theta = m\lambda \Rightarrow \theta = \arcsin\left(\frac{m\lambda}{d}\right) = \arcsin\left(\frac{2 \times 390 \times 10^{-9}\,m}{1 \times 10^{-3}\,m / 800}\right)$

$= 38.6°$ (not small!)

$\Rightarrow y = L \cdot \tan\theta$

$= (3.0\,m)\tan(38.6°) = 2.4\,m$

4. [4 pts] Light of wavelength 600 nm travels from air (n = 1.00) and strikes a thin film of material (n = 1.20) that sits atop a much thicker material (n = 1.60). What is the smallest non-zero thickness of the thin material that would produce **minimum reflection** due to destructive interference?

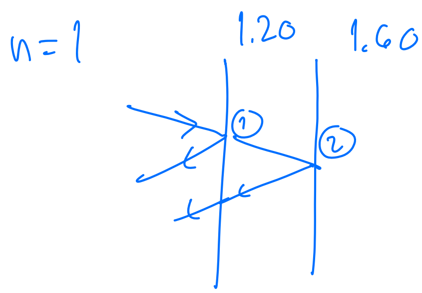
A. 125 nm

B. 150 nm

C. 250 nm

D. 300 nm

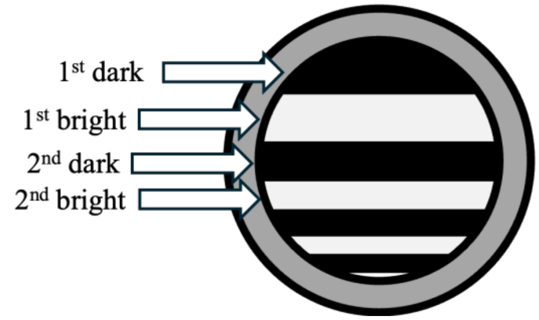
E. 500 nm



Two phase changes. C.D.I. $\Rightarrow 2t = \frac{(m+\frac{1}{2})\lambda}{n}$

$\Rightarrow t = \frac{\frac{1}{2}\lambda}{2n} = \frac{300\,nm}{2 \times 1.2} = \boxed{125\,nm}$

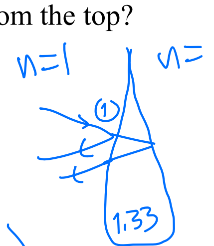
5. [4 pts] A circular, thin film of soapy water (n = 1.33) is oriented vertically. Gravity acts downward so the film is *very thin* at the top (i.e., essentially zero thickness. Air (n = 1.00) is on either side of the film.



The diagram at right shows dark and bright bands of light caused by reflection of light from the film using light of wavelength 511 nm.

What is the thickness of the soap film at the **2nd bright band** counting from the top?

Only 1 phase change.
Constructive



A. 192 nm
B. 288 nm
C. 384 nm
D. 576 nm
E. 1020 nm

$\Rightarrow 2t = \dfrac{(m+\frac{1}{2})\lambda}{n}$ (m=1 for 2nd bright)

$\Rightarrow t = \dfrac{\frac{3}{2}\times 511\text{ nm}}{2\times 1.33} = 288$ nm

6. [4 pts] Suppose you are looking at the central diffraction maximum on a screen that is caused by monochromatic light going through a single slit. If the frequency of light is increased and no other changes are made to the physical setup, what happens to the width of the central diffraction maximum?

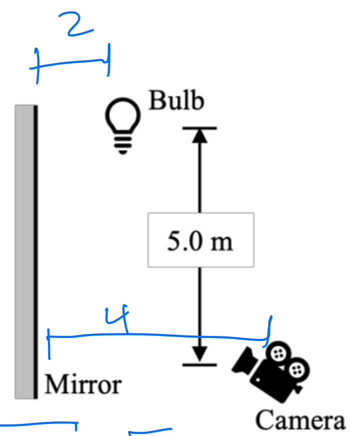
A. The width increases.
B. The width decreases.
C. The width remains the same.
D. None of these are correct.

$v = \lambda f$. $f\uparrow \Rightarrow \lambda\downarrow$

$a\cdot\sin\theta = m\lambda$. $\lambda\downarrow \Rightarrow \theta\downarrow$

$\Rightarrow$ width decreases

7. [4 pts] A light bulb is located 2.0 m from the surface of a mirror. A camera is located 4.0 m from the surface of the mirror and is viewing the image of the bulb due to the mirror. The camera can only see the image of the bulb, not the bulb itself. The distance between the bulb and camera that is parallel to the mirror is given in the diagram. The mirror is 100% efficient at reflecting light.



If the power output of the bulb is 100 W, what is the intensity of light from the image as measured by the camera?

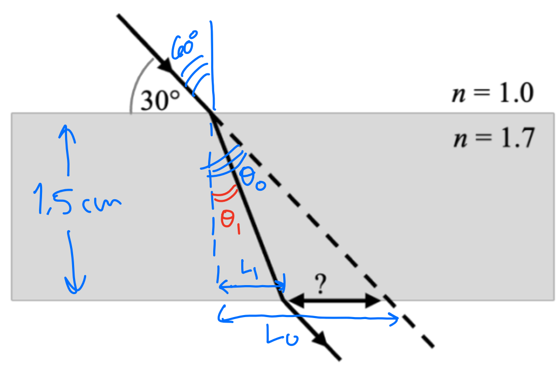
Distance $r = \sqrt{h^2 + L^2} = \sqrt{(5m)^2 + (6m)^2} = \sqrt{61}$ m

A. 0.066 W/m^2
B. 0.072 W/m^2
C. 0.13 W/m^2
D. 1.03 W/m^2
E. None of these are correct

$I = \frac{P}{A} = \frac{100W}{4\pi r^2} = \frac{100\,W}{4\pi\ 61\ m^2} = 0.13 \frac{W}{m^2}$

$n_a \sin\theta_a = n_b \sin\theta_b$

8. [4 pts] Light enters a transparent medium (n = 1.7) from air (n = 1.0), as shown. The dashed line represents the path that light would take without the medium present. If the vertical height of the medium is 1.5 cm, determine the unknown distance in the diagram labeled with a '?' mark.



A. 0.60 cm
B. 0.89 cm
C. 1.1 cm
D. 1.7 cm
E. 2.1 cm

We want $L_0 - L_1$

$L_0 = (1.5\,cm)\cdot \tan 60° = 2.598$ cm

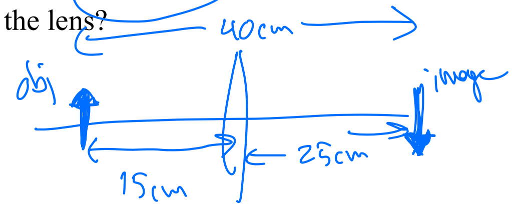
$L_1 = (1.5\,cm)\cdot \tan\theta_1 = (1.5\,cm) \tan\left[\arcsin\left(\frac{1.0 \times \sin 60°}{1.7}\right)\right]$

$= 0.888$ cm

$\Rightarrow L_0 - L_1 = 1.7$ cm

So converging, $f>0$
$s'>0$

9. [4 pts] An object is placed 15 cm from an unknown type of thin lens. A **real image** is formed 40 cm **from the object** (not from the lens!). What is the focal length of the lens?



A. +38 cm

B. –25 cm

C. –12 cm

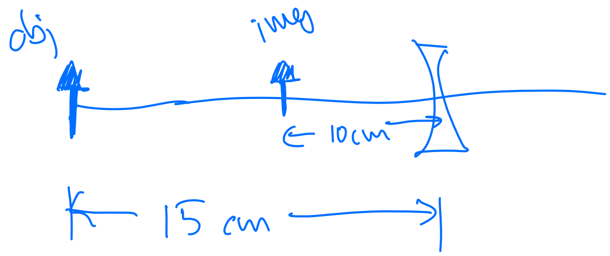
D. +11 cm

E. +9.4 cm

$$\frac{1}{f} = \frac{1}{s} + \frac{1}{s'}$$

$$\Rightarrow f = \frac{1}{\frac{1}{15\,\text{cm}} + \frac{1}{25\,\text{cm}}} = 9.375\,\text{cm} \approx 9.4\,\text{cm}$$

10. [4 pts] An object is placed 15 cm from a **diverging lens.** The distance from the lens to the image, as measured by a ruler, is 10 cm. What is the focal length of the lens?



A. –15 cm

B. +6.0 cm

C. +18 cm

D. –30 cm

E. –20 cm

$$\frac{1}{f} = \frac{1}{s} + \frac{1}{s'}$$

$$\Rightarrow f = \frac{1}{\frac{1}{s} + \frac{1}{s'}} = \frac{1}{\frac{1}{15\,\text{cm}} + \frac{1}{-10\,\text{cm}}} = -30\,\text{cm}$$

11. [4 pts] The near point of your eye is 60 cm. You want to wear glasses so that the near point of your eye becomes 40 cm. What is the refractive power of glasses that you should wear?

A. 0.83 D

B. –0.83 D

C. 1.7 D

D. –1.7 D

E. 1.9 D

with glasses: $P_{e_{max}} + P_g = \frac{1}{s_{near,g}} + \frac{1}{s'}$

$= \frac{1}{0.40\ m} + \frac{1}{s'}$

w/o glasses: $P_{e_{max}} = \frac{1}{s_{near}} + \frac{1}{s'}$

$= \frac{1}{0.60\ m} + \frac{1}{s'}$

$\Rightarrow P_g = \frac{1}{0.40\ m} - \frac{1}{0.60\ m} = 0.83$

12. [4 pts] You purchase a magnifying glass that claims its “magnification” is 2.5X. If this magnifying glass is used to form an image of an object that is infinitely far away, what is the image distance?

A. 0.025 m

B. 0.050 m

C. 0.063 m

D. 0.075 m

E. 0.10 m

$P = \frac{0.25\ m}{f} \Rightarrow f = \frac{0.25\ m}{P} = \frac{0.25\ m}{2.5} = 0.1\ m$

$\frac{1}{f} = \frac{1}{\cancel{s}_{\infty}} + \frac{1}{s'} = \frac{1}{s'} \Rightarrow s' = f = 0.1\ m$

13. [4 pts] You purchase a standard microscope. The manufacturer claims its “objective power” is 20X. What is the focal length of the objective lens?

A. 8.0 mm

B. 20 mm

C. 80 mm

D. 100 mm

E. 160 mm

$f = \frac{160\ mm}{P}$

$= \frac{160\ mm}{20} = 8\ mm$

14. [4 pts] Amazingly, it is possible for the human eye to detect infrared light! It can occur when two separate infrared photons strike a photoreceptor at the same time. Our eye and brain interpret this occurrence as a **single photon** with energy equal to the **sum of the energies** of the two separate photons.

Suppose that two such infrared photons of wavelengths 900 nm and 1300 nm strike your eye and you can see a flash of light. What is the wavelength that your brain perceives this 'single' photon?

A. 400 nm
B. 495 nm
C. 530 nm
D. 1100 nm
E. 2100 nm

$$E = \frac{hc}{\lambda} \Rightarrow E_{new} = \frac{hc}{\lambda_{new}} = \frac{hc}{\lambda_1} + \frac{hc}{\lambda_2}$$

$$\Rightarrow \lambda_{new} = \left(\frac{1}{\lambda_1} + \frac{1}{\lambda_2}\right)^{-1} = 531.8 \text{ nm} \approx 530 \text{ nm}$$

15. [4 pts] In a photoelectric effect experiment, you shine light of wavelength 200 nm on a metal. The maximum kinetic energy of the electrons that are ejected is 2.0 eV.

What wavelength of photons can you shine on the metal and still eject photons?

A. Any wavelength **smaller** than 295 nm
B. Any wavelength **~~larger~~** than 295 nm
C. Any wavelength **~~larger~~** than 310 nm
D. Any wavelength **smaller** than 620 nm
E. Any wavelength **~~larger~~** than 620 nm

$$E_{photon} = \frac{1240 \text{ eV}\cdot\cancel{\text{nm}}}{200\ \cancel{\text{nm}}} = 6.20 \text{ eV}$$

$$E_0 = E_{photon} - K_{max} = 6.20 \text{ eV} - 2.0 \text{ eV} = 4.20 \text{ eV}$$

$$E_{photon} > E_0 + \cancel{K_{max}}^{0} = 4.20 \text{ eV} < \frac{hc}{\lambda} \Rightarrow \lambda < 295 \text{ nm}$$

All students will receive $\boxed{\text{FULL CREDIT}}$ since one resource online indicated that the photoelectric effect would not be covered.

Q16–Q20: Lecture free-response — Unless otherwise noted, explain your reasoning or show your work.

16. [4 pts] You shine light of wavelength 520 nm on a diffraction grating that has a total of 4000 lines across its length of 2.0 cm. How many bright spots will be produced on a semicircular screen? Show your work.

Adjacent slit sep $d = \frac{2.0\,cm}{4000} = \frac{0.02\,m}{4000} = 5\times10^{-6}\,m$

Find max order 'm' in $d\cdot\sin\theta = m\lambda$ with $\theta = 90°$:

$$m = \frac{d\cdot\cancel{\sin\theta}^{\,1}}{\lambda} = 5\times10^{-6}\,m \cdot \frac{1}{520\times10^{-9}\,m} = \frac{5}{520}10^{3} = 9.6$$

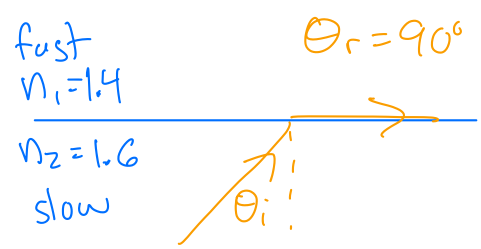
Highest integer m is $m=9$ $\Rightarrow$ $m = 0, 1, 2, \ldots 9$ $\Rightarrow$ $1+2\cdot 9 = \boxed{19}$ spots

1 spot

2 spots

17. [4 pts] Suppose you have two different transparent materials that are in contact. Material 1 has index of refraction $n_1 = 1.4$ and material 2 has index of refraction $n_2 = 1.6$. Describe carefully and completely the requirements for **total internal reflection** to occur at the boundary between these two media. In particular, you should describe (a) in what **direction** the light ray should travel (from medium 1 to 2 or from medium 2 to 1) as well as (b) any numerical requirement on the incident **angle.**

(a) Must go slow → fast for TIR (so $\theta_r > \theta_i$) so must go from $\boxed{\text{medium 2 to 1.}}$



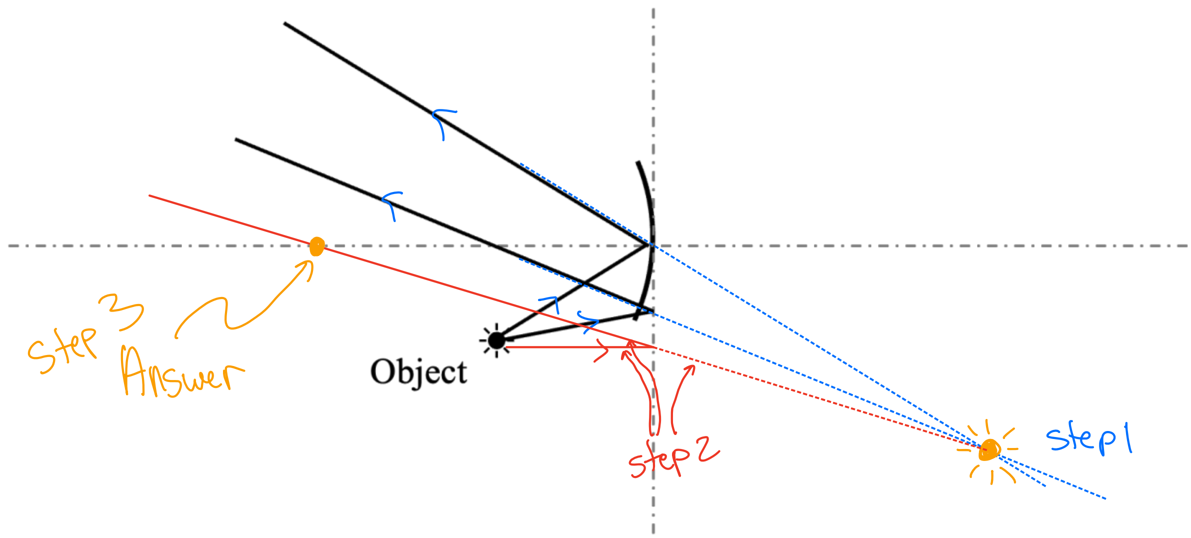
(b) Incident angle θ_i must be at or greater than the critical angle θ_c that causes $\theta_r = 90°$:

$$n_2 \sin\theta_c = n_1 \sin \underbrace{90°}_{1}$$

$$\Rightarrow \theta_c = \arcsin\left(\frac{n_1}{n_2}\right) \approx 61.0°$$

$$\Rightarrow \boxed{\theta_i \geq 61.0°}$$

18. [4 pts] The diagram below shows two rays of light that leave an object (a very small bulb) and reflect from a converging (concave) mirror. Use your knowledge of image formation and ray diagrams to **label the focal point of the mirror** somewhere along the optical axis. **Use ray diagrams,** not the thin-lens equation. Make sure your drawing is clear, including any backtracking you have done. No explanation is necessary.



19. [4 pts] In this problem, all lenses are oriented along and perpendicular to the optical axis, which we will take to be the *x*-axis.
An object is located at $x = 0$. A converging lens with focal length 5.0 cm is located at $x = 15.0$ cm. A second converging lens with focal length 2.0 cm is located at $x = 25.0$ cm. What is the location x_{final} of the final image produced by the second lens? Show your work using the thin-lens equation. Ensure your final answer uses the indicated coordinate system.

Image 1:

$$\frac{1}{f_1} = \frac{1}{s_1} + \frac{1}{s_1'}$$

$$\Rightarrow s_1' = 1 \Big/ \left(\frac{1}{5\text{cm}} - \frac{1}{15\text{cm}}\right)$$

$= 7.5$ cm which is at $x_1 = 15$ cm $+ 7.5$ cm $= 22.5$ cm

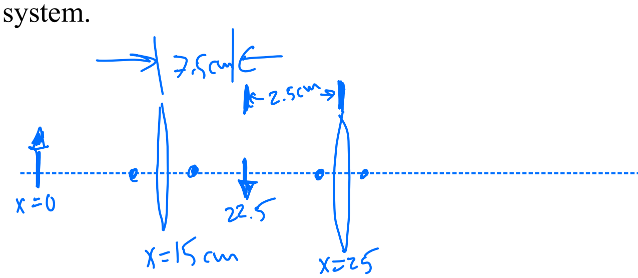


Image 2.

Use $x = 22.5$ cm as location of object 2. This location has an object distance $s_2 = |25\text{ cm} - 22.5\text{ cm}| = 2.5$ cm

$$\frac{1}{f_2} = \frac{1}{s_2} + \frac{1}{s_2'} \Rightarrow s_2' = 1 \Big/ \left(\frac{1}{2\text{cm}} - \frac{1}{2.5\text{cm}}\right) = 10\text{ cm},$$ which

is at location $x_2 = 25$ cm $+ 10$ cm $= \boxed{35\text{ cm}}$

All students will receive full credit on this problem since one resource online mentioned that photoelectric effect would not be tested.

20. [4 pts] You are conducting a photoelectric effect experiment. You shine monochromatic light on a metal and observe electrons being ejected. Suppose you were to **double the intensity** of the light that falls on the metal. Would the following quantities *increase, decrease,* or *remain the same?* Explain briefly.

(a) [2 pts] The maximum kinetic energy of each ejected photon

$K_{max} = E_{photon} - E_0$

Increasing intensity does <u>not</u> change energy E_{photon} of each photon. $E_{photon} = hf$ is same, and work function E_0 too, so K_{max} $\boxed{\text{unchanged.}}$

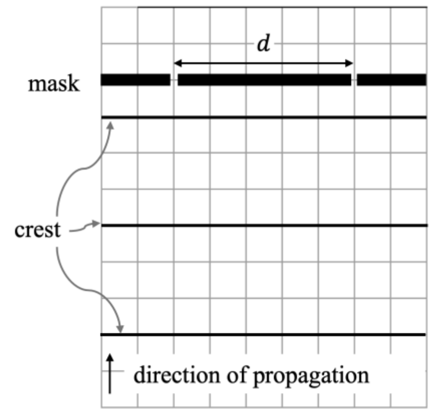
(b) [2 pts] The number of electrons ejected each second.

Stronger intensity $\Rightarrow$ more photons per sec

$\Rightarrow$ $\boxed{\text{more ejected electrons per sec}}$

Note: In the diagrams representing interference patterns below, lines of **maximum constructive** interference are represented by **solid lines** and *nodal lines* are represented by *dashed lines.*

In Experiment 1, a periodic wave is generated by a dowel in a big tank of water. The diagram at right shows the crests of the periodic wave incident on a mask with two very narrow slits.

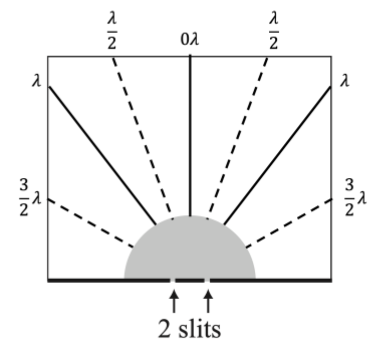


21. [4 pts] Determine the distance between the slits, d, in terms of the wavelength λ. Briefly explain.

The distance between two consecutive crests of the periodic wave is the wavelength λ. Therefore, the wavelength equals 3 units (measured in terms of the length of the side of the square).

Since the distance between the slits is 5 units, the distance in terms of λ is $d = \frac{5}{3}\lambda$.

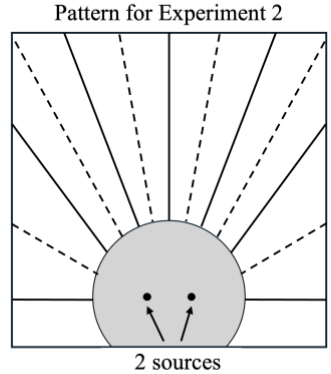
22. [4 pts] Sketch the approximate locations of all the lines of maximum constructive interference (solid) and nodal lines (dashed) in the region of the tank far away from the slits (the unshaded region in the box at right). You need not calculate angles. Explain briefly.



Since $\Delta D_{horizontal}$ is the maximum possible difference in distance, and $\Delta D_{horizontal} = d = \frac{5}{3}\lambda$ $(\sim 1.67\lambda)$, the lines corresponding to $\Delta D = 0\lambda, \Delta D = \lambda$ represent lines of maximum constructive interference and dashed lines corresponding to $\Delta D = \frac{\lambda}{2}$ and $\Delta D = \frac{3\lambda}{2}$ represent nodal lines. Since $d = \frac{5}{3}\lambda > \frac{3}{2}\lambda$, the $\frac{3\lambda}{2}$ nodal line does not appear on the line connecting the two sources.

In Experiment 2, two point sources generate periodic waves by tapping the surface of the water with the frequency f_1. The diagram at right shows an interference pattern for Experiment 2 in the region far away from the sources (unshaded). The propagation speed of the waves is v_1.

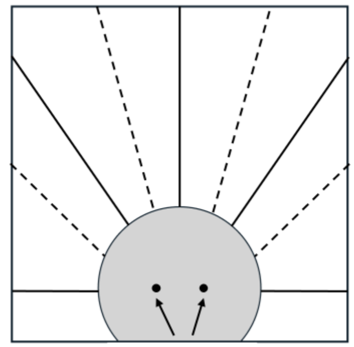
Pattern for Experiment 2



23. [4 pts] Determine the source separation, d, in terms of the wavelength λ. If an exact value cannot be determined, give the smallest range into which d must fall. Explain.

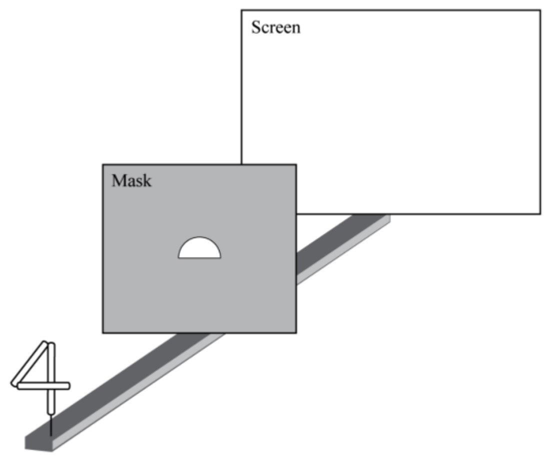
The diagram shows the 0λ, λ, 2λ and 3λ antinodal lines and the 0.5λ, 1.5λ, and the 2.5λ, nodal lines. The 3λ antinodal line is formed along the line that connects the two sources, and since $\Delta D_{horizontal} =$ d, we can conclude that the source separation is equal to 3λ.

24. [4 pts] A single change is made to Experiment 2. As a result, the interference pattern is changed, as shown at right. Could increasing the frequency of the sources result in the change in the interference pattern? Explain.

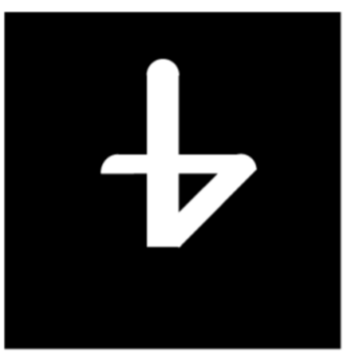


In the previous question, we concluded that $d = 3\lambda$. After the modification, the $2\lambda'$ occurs along the line connecting the two sources. We can thus conclude $d = 2\lambda'$. Therefore λ' must be greater than λ ($\lambda' = d/2$, while $\lambda = d/3$). An increase in wavelength is consistent with a decrease in frequency (we can assume the wave speed remains the same). This means that an increase in frequency could not have caused the change in the interference pattern.

25. [4 pts] A mask with a semi-circular aperture is placed between a bulb in the shape of the number 4. Draw the image that would be produced on the screen in a darkened room when the bulb is turned on. No explanation required.



Correct image is shown below.



This page intentionally left blank.

Phys 116, Equation Sheet, Final Exam

Constants

Free-fall acceleration	$g = 9.80\ m/s^2$
Newton	$1\ \mathrm{N} = 1\ \mathrm{kg\ m/s^2}$
Boltzmann's constant	$k_\mathrm{B} = 1.38 \times 10^{-23}\mathrm{J/K}$
Gas constant	$R = N_\mathrm{A} k_\mathrm{B} = 8.31\ \mathrm{J/(mol \cdot K)}$
Minimum sound intensity	$I_0 = 1 \times 10^{-12}\mathrm{W/m^2}$
Speed of light	$c = 3.00 \times 10^8 \mathrm{m/s}$
Permittivity of free space	$\epsilon_0 = 8.85 \times 10^{-12}\mathrm{C^2/N \cdot m^2}$
Permeability of free space	$\mu_0 = 1.26 \times 10^{-6}\mathrm{N/A^2}$
Planck's constant	$h = 6.626 \times 10^{-34}\mathrm{J \cdot s}$
	$h = 4.141 \times 10^{-15}\mathrm{eV \cdot s}$
Electron volt	$1\ \mathrm{eV} = 1.6 \times 10^{-19}\mathrm{J}$
Elementary charge	$e = 1.6 \times 10^{-19}\mathrm{C}$
Atomic mass unit	$1\ \mathrm{u} = 1.6605 \times 10^{-27}\mathrm{kg}$
	$= 931.49\ \mathrm{MeV}/c^2$
Mass of electron	$m_\mathrm{e} = 9.1094 \times 10^{-31}\mathrm{kg}$
Mass of proton	$m_p = 1.6726 \times 10^{-27}\mathrm{kg}$
Curie	$1\ \mathrm{Ci} = 3.7 \times 10^{10}\mathrm{Bq}$
Becquerel	$1\ \mathrm{Bq} = 1\ \mathrm{decay/s}$
Gray	$1\ \mathrm{Gy} = 1.00 \dfrac{\mathrm{J}}{\mathrm{kg}}\ \text{of absorbed energy}$
Rad and Gray	$1\ \mathrm{rad} = 0.01\ \mathrm{Gy}$
Rem and Sieverts	$1\ \mathrm{rem} = 0.01\ \mathrm{Sv}$

Mathematics

Components of a 2D vector $\vec{A}$	$A_x = A\cos\theta, \quad A_y = A\sin\theta$
Magnitude and direction of $\vec{A}$ relative to x-axis	$A = \sqrt{A_x^2 + A_y^2}, \quad \theta = \tan^{-1}(A_y/A_x)$
Volume & surface area of a sphere	$V = \frac{4}{3}\pi r^3, \quad A = 4\pi r^2$

Equations from 114 and 115

Kinematics (const. accel. a)	$(v_x)_\mathrm{f} = (v_x)_\mathrm{i} + a_x t$
	$x_\mathrm{f} = x_\mathrm{i} + (v_x)_\mathrm{i} t + \frac{1}{2} a t^2$
	$(v_x)_\mathrm{f}^2 = (v_x)_\mathrm{i}^2 + 2 a_x \Delta x$
Newton's Laws	$\sum \vec{F} = m\vec{a}, \quad \vec{F}_{12} = -\vec{F}_{21}$
Weight	$w = mg$
Work due to a constant force	$W = F_\parallel d = Fd\cos\theta$
Conservation of energy	$\Delta E = W$
Power	$P = \dfrac{\Delta E}{\Delta t} = \dfrac{W}{t} = Fv$
Kinetic energy	$K = \frac{1}{2} m v^2$
Elastic potential energy	$\Delta U_\mathrm{s} = \frac{1}{2} k (x_\mathrm{f}^2 - x_\mathrm{i}^2)$
Gravitational potential energy	$\Delta U_\mathrm{g} = mg\Delta y$
Momentum	$\vec{p} = m\vec{v}$
Torque	$\tau = rF\sin\phi$
Pressure	$p = \dfrac{F}{A}$
Hooke's Law	$(F_\mathrm{spring})_x = -kx$

Oscillations

Frequency	$f = \dfrac{1}{T}$
Angular frequency	$\omega = \dfrac{2\pi}{T} = 2\pi f = \sqrt{k/m}$
Position in SHM	$x(t) = A\cos(2\pi f t)$
Velocity in SHM	$v_x(t) = -2\pi f A \sin(2\pi f t)$
Acceleration in SHM	$a_x(t) = -(2\pi f)^2 A\cos(2\pi f t)$
SHM max velocity	$\lvert v_\mathrm{max} \rvert = A\omega$
SHM max acceleration	$\lvert a_\mathrm{max} \rvert = A\omega^2$
Mechanical energy in SHM	$E = K + U$
	$E = \dfrac{1}{2} k A^2 = \dfrac{1}{2} m v_\mathrm{max}^2$

Phys 116, Equation Sheet, Final Exam

Frequency and Period

Freq. of Mass on a spring	$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$
Period of Mass on a spring	$T = 2\pi\sqrt{\frac{m}{k}}$
Freq. of Simple pendulum	$f = \frac{1}{2\pi}\sqrt{\frac{g}{L}}$
Period of Simple pendulum	$T = 2\pi\sqrt{\frac{L}{g}}$
Freq. of Physical pendulum	$f = \frac{1}{2\pi}\sqrt{\frac{mgd}{I}}$
Period of Physical pendulum	$T = 2\pi\sqrt{\frac{I}{mgd}}$

Damped Oscillation

Amplitude envelope	$x_{\mathrm{max}}(t) = Ae^{-t/\tau}$

Waves and Sound

Sinusoidal wave function	$y(x,t) = A\cos\left(2\pi\frac{x}{\lambda} \pm 2\pi\frac{t}{T}\right)$
Speed of sinusoidal waves	$v = \lambda f$
Speed of a wave on a string	$v_{\mathrm{string}} = \sqrt{\frac{T_s}{\mu}}$
Linear mass density	$\mu = m/L$
Speed of sound in gas	$v_{\mathrm{sound}} = \sqrt{\frac{\gamma k_{\mathrm{B}} T}{m}}$
	$v_{\mathrm{sound}} = \sqrt{\frac{\gamma RT}{M}}$

Conversion from Celsius to Kelvin	$T = T_{\mathrm{C}} + 273$
Sound intensity	$I = \frac{P}{a}$
Sound Intensity level	$\beta = (10\ \mathrm{dB})\log_{10}\left(\frac{I}{I_0}\right)$
Moving source	$f_{\pm} = \frac{f_{\mathrm{s}}}{1 \mp v_{\mathrm{s}}/v}$
Moving observer	$f_{\pm} = \left(1 \pm \frac{v_0}{v}\right) f_{\mathrm{s}}$
Moving object reflection	$\Delta f = \pm 2 f_{\mathrm{s}}\frac{v_0}{v} \quad \text{for } v_0 \ll v$

Standing waves and Interference

On a string	$f_m = m\left(\frac{v}{2L}\right) = mf_1$
	$\lambda_m = \frac{\lambda_1}{m} = \frac{2L}{m}, \quad m = 1,2,3,\ldots$
Open-open or closed-closed pipe	$f_m = m\left(\frac{v}{2L}\right) = mf_1$
	$\lambda_m = \frac{\lambda_1}{m} = \frac{2L}{m}, \quad m = 1,2,3,..$
Open-closed pipe	$f_m = m\left(\frac{v}{4L}\right) = mf_1$
	$\lambda_m = \frac{\lambda_1}{m} = \frac{4L}{m}, \quad m = 1,3,5,\ldots$
Path length difference (constructive)	$\Delta d = m\lambda$
Path length difference (destructive)	$\Delta d = \left(m + \frac{1}{2}\right)\lambda$
Beat frequency	$f_{\mathrm{beat}} = \lvert f_1 - f_2 \rvert$
Oscillation frequency	$f_{\mathrm{osc}} = \frac{1}{2}(f_1 + f_2)$

Phys 116, Equation Sheet, Final Exam

Wave optics

Index of refraction	$v = \frac{c}{n}$
Wavelength in material	$\lambda_{\text{mat}} = \frac{\lambda_{\text{vac}}}{n}$
Double-slit interference:	
Small angle approximation	$\sin(\theta) \approx \theta$
Double-slit/diffraction grating:	
Bright fringe	$d \sin\theta_m = m\lambda \quad m = 0,1,2,\ldots$
Dark fringe	$d \sin\theta_m = \left(m + \frac{1}{2}\right)\lambda \quad m = 0,1,2,\ldots$
Position of bright fringe (2-slit)	$y_m = \frac{m\lambda L}{d}$
Position of dark fringe (2-slit)	$y_m = \left(m + \frac{1}{2}\right)\frac{\lambda L}{d}$
Spacing between adjacent bright fringes (2-slit)	$\Delta y = \frac{\lambda L}{d}$
Position of bright fringes (grating)	$y_m = L \tan\theta_m$
Index of refraction	$n = \frac{c}{v}$
Wavelength in material with refractive index n	$\lambda_{\text{mat}} = \frac{\lambda_{\text{vac}}}{n}$
Thin film phase shift due to reflection:	

Number of phase changes:	None or 2	One
Constructive:	$2t = m\frac{\lambda}{n}$	$2t = \left(m + \frac{1}{2}\right)\frac{\lambda}{n}$
Destructive:	$2t = \left(m + \frac{1}{2}\right)\frac{\lambda}{n}$	$2t = m\frac{\lambda}{n}$

Single-slit diffraction	
Dark fringes	$a \sin\theta_p = p\lambda \qquad p = 1,2,3,\ldots$
Small angle approx.	$\theta_p \approx p\lambda/a$
Position of dark fringe	$y_p = \frac{p\lambda L}{a}$
Central maximum width	$w = \frac{2\lambda L}{a} \quad \text{for } \frac{\lambda}{a} \ll 1$
Circular aperture	
Central maximum diameter	$w = \frac{2.44\lambda L}{D}$
First dark fringe	$\theta_1 = \frac{1.22\lambda}{D}$
	$y_1 = \frac{1.22\lambda L}{D}$

Geometrical (Ray) optics

Law of reflection	$\theta_{\text{r}} = \theta_{\text{i}}$
Image by plane mirror	
Image distance	$s = s'$
Image height	$h = h'$
Snell's law	$n_1 \sin\theta_1 = n_2 \sin\theta_2$
Critical angle	$\theta_{\text{c}} = \sin^{-1}\left(\frac{n_2}{n_1}\right), \quad n_1 > n_2$
Image by refraction	$s' = \frac{n_2}{n_1}s$
Magnification of lens or mirror	$m = -\frac{s'}{s} = \frac{h'}{h}$
Thin lenses & curved mirrors:	
Thin-lens equation	$\frac{1}{s} + \frac{1}{s'} = \frac{1}{f}$
Sign conventions:	
Object	$s > 0$ always
Image	$s' > 0$, for real image
	$s' < 0$, for virtual image
Focal length	$f > 0$, convex lens or concave mirror
	$f < 0$, concave lens or convex mirror
Magnification	$m > 0$ for upright image

Phys 116, Equation Sheet, Final Exam

Focal Length of mirrors	
Convex mirror	$f = -\frac{1}{2}R$
Concave mirror	$f = \frac{1}{2}R$
Refractive Power	$P = \frac{1}{f}$
Combined Power	$P_{\text{total}} = P_1 + P_2$
Combined magnification	$m_{\text{total}} = m_1 m_2$

EM Waves

E and B field of EM wave	$\frac{E_0}{B_0} = c$
Intensity	$I = \frac{P}{a} = \frac{1}{2}c\epsilon_0 E_0^2 = \frac{1}{2}\frac{c}{\mu_0}B_0^2$
Malus' law	$I_{\text{transmitted}} = I_{\text{incident}}(\cos\theta)^2$

Quantum Physics

Thermal radiation	$\lambda_{\text{peak}} = \frac{2.9 \times 10^6 \text{nm} \cdot \text{K}}{T}$
Photon energy	$E = hf = \frac{hc}{\lambda} = \frac{1242 \text{ eV} \cdot \text{nm}}{\lambda}$
Photoelectric effect:	
Cut-off frequency	$f_0 = E_0/h$
Stopping potential	$V_{\text{stop}} = \frac{K_{\max}}{e} = \frac{hf - E_0}{e}$
Kinetic energy of ejected electron	$K_{\max} = E_{elec} - E\_0$
de Broglie wavelength	$\lambda = \frac{h}{p} = \frac{h}{mv}$

Atomic Physics

Spectral line wavelength (Balmer formula)	$\lambda = \frac{91.127 \text{ nm}}{\frac{1}{m^2} - \frac{1}{n^2}}$
	$m\&n$ integers, $n > m > 0$
Atomic radius	$r_n = \frac{a_B}{Z} = 0.0529 \text{ nm} \frac{n^2}{Z}$
Orbital energy	$E_n = (-13.6)\frac{Z^2}{n^2}$

Nuclear physics

Atomic and mass number	$A = Z + N$
Designation	${}^{A}_{Z}\text{X}$
Binding energy	$B = (Zm_{\text{H}} + Nm_{\text{n}} - m_{\text{atom}}) \times \left(931.49 \frac{\text{MeV}}{\text{u}}\right)$
Kinetic energy of alpha particle	$K_\alpha \approx \Delta E = (m_{\text{X}} - m_{\text{Y}} - m_{\text{He}})c^2$
Alpha decay	${}^{A}_{Z}\text{X} \to {}^{A-4}_{Z-2}\text{Y} + \alpha + \text{energy}$
Beta-minus decay	${}^{A}_{Z}\text{X} \to {}_{Z+1}^{A}\text{Y} + \text{e}^- + \text{energy}$
Beta-plus decay	${}^{A}_{Z}\text{X} \to {}_{Z-1}^{A}\text{Y} + \text{e}^+ + \text{energy}$
Time (decay) constant	$\tau = \frac{t_{1/2}}{\ln 2} = (1.44)t_{1/2}$
Half-life	$t_{1/2} = \tau \ln 2 = 0.693\tau$
Number of nuclei in decay	$N = N_0 \left(\frac{1}{2}\right)^{\frac{t}{t_{1/2}}} = N_0 e^{-t/\tau}$
Activity	$R = \frac{N}{\tau} = R_0 \left(\frac{1}{2}\right)^{\frac{t}{t_{1/2}}} = R_0 e^{-t/\tau}$
Dose equivalent	Dose equivalent in Sv = dose in Gy × RBE