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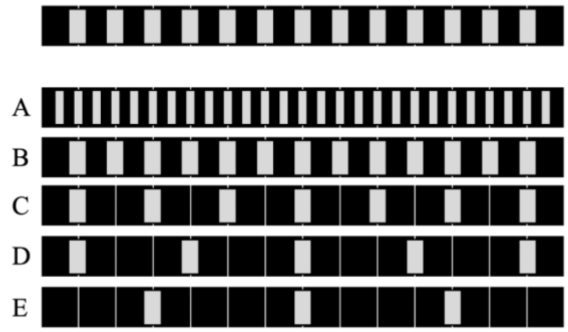
1. [5 pts] The interference pattern shown in the figure at right (topmost image) was produced using a laser of wavelength λ, a two-slit grating with slit spacing d, and a screen-to-grating distance L.

   Suppose the conditions are altered such that the laser's wavelength is $\frac{3}{2}\lambda$, the distance between the slits is $\frac{d}{5}$, and the screen-to-grating distance is $\frac{2}{5}L$. Which of the interference patterns at right (A-E) would be produced with these new conditions?



   A) Diagram A
   B) Diagram B
   C) Diagram C
   D) Diagram D
   E) Diagram E

The fringe spacing for a two-slit interference experiment is given as:

$$\Delta y = \frac{\lambda L}{d}$$

Under the new conditions listed, the new fringe spacing, $\Delta y'$, would be:

$$\Delta y' = \frac{\left(\frac{3}{2}\lambda\right)\left(\frac{2}{5}L\right)}{\frac{d}{5}} = 3\frac{\lambda L}{d}$$

So, the new fringe spacing would be three times larger than the original spacing. This is depicted in diagram D.

2. [5 pts] A red laser and a green laser ($\lambda_{red} > \lambda_{green}$) are both incident on a diffraction grating with 500 lines/mm. Which of the following is true about the diffraction patterns seen from each laser?

   A) They are identical.
   B) The bright fringes from the red laser are more spread out.
   C) The bright fringes from the green laser are more spread out.
   D) There is not enough information to answer.

For a diffraction grating $\sin\theta_m = \frac{m\lambda}{d}$, so since $\lambda_{red} > \lambda_{green}$, we expect θ_m to be larger for red than green. Angular difference translates to the fringes being spread farther apart.

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3. [5 pts] A single-slit diffraction experiment is done by shining a red laser ($\lambda = 633$ nm) onto a slit of width 0.1 mm. Suppose the slit width is doubled. Using the small angle approximation, the central maxima of the diffraction pattern then:

   A) halves in width.

   B) decreases in width but not by half.

   C) stays the same width.

   D) doubles in width.

   E) Increases in width, but not by a factor of two.

   The dark fringes of a single-slit diffraction pattern can be found at $\sin\theta_p = \frac{p\lambda}{a}$. *With the small angle approximation,* $\sin\theta_p \approx \theta_p$. *The width of the central is given as* $2\lambda L/a$. *If the slit width is doubled* ($a \to 2a$)*, then the width of the central maximum halves in width.*

4. [5 pts] A photoelectric-effect experiment finds a stopping potential of 1.56 V when a light of 200 nm is used to illuminate the cathode. From what metal is the cathode made?

Element	E_0 (eV)
Potassium	2.30
Sodium	2.36
Aluminum	4.28
Copper	4.65
Gold	5.10

   A) Potassium

   B) Sodium

   C) Aluminum

   D) Copper

   E) Gold

   We apply $KE_{max} = E_\gamma - E_0$, *where* $E_0 = hf = \frac{1240\ eV\ nm}{200\ nm}$, *and* $KE_{max} = 1.56\ eV$. *Solving for* E_0 *we find* $4.65\ eV$, *which matches copper in the table.*

5. [5pts] In a photoelectric effect experiment, a 100 W violet light source incident on a metal produces faster moving electrons than a 100 W green light source. Why?

   A) Violet light travels faster than green light.

   B) Violet light has more photons than green light.

   C) Violet light has more energy than green light.

   D) Violet light has a larger amplitude electric field than green light.

   A – the speed of light is the speed of light. B – The number of photons does not affect the speed with which an electron is ejected. ***C – This is correct*** *– the frequency of violet light is larger than that of green light, so the energy of violet light is larger than that of green light* ($E = hf$)*. D – This is the wave model of light, which is not applicable to the photoelectric effect.*

6. [5 pts] According to the wave model of light, the photoelectric effect will occur as long as the intensity of incident light is large enough, regardless of the frequency of light. Yet this is not observed – instead electrons are only ejected when the frequency of the incident light exceeds a threshold value. Einstein explained this by:

A) Postulating that the time it takes for an electron to absorb enough energy from low frequency light is longer than the lifetime of the Universe.

B) Postulating that the number of electrons that are ejected with low frequency light is too small to measure.

C) Postulating that an electron absorbs energy from light in a single quanta, and the energy of the light quanta depends on the frequency of light.

D) Postulating that electrons behave as waves and the interference between electron and light waves imposes a threshold frequency for the photoelectric effect.

A – Absorption, when it occurs, is in 10^{-24} *seconds (this isn't exact and depends on the particular interaction, but is the right order). B – We know we can see light that won't eject electrons – the demo in class, for example, with the glass filter that removed UV photons – the charge no longer leaked away from the electroscope.* ***C – Yes!*** *D – Electrons and photons don't interfere – they aren't the same kind of "wave" (e.g. medium).*

7. [5 pts] A speck of dust with a mass of 4.0×10^{-7}g is traveling with some velocity v and diffracts through a small hole and then travels to a screen 45 cm away. If the speck of dust is to form a matter wave whose diffraction pattern we can see, it must have some observable wavelength. How long will it take for the speck of dust to travel from the hole to the screen, assuming it only needs to travel 45 cm (in a straight line), if its effective wavelength is 0.50 mm?

A) 1.4×10^{-21} years

B) 4.3×10^{12} years

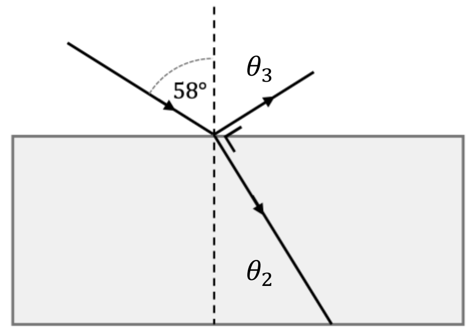
C) 4.3×10^{15} years

D) 2.7×10^{15} years

E) 3.4×10^{22} years

De Broglie's - $\lambda_{matter} = \frac{h}{p}$*, and solving for v:* $v = \frac{h}{m\lambda}$*. The time to traverse the 45 cm we can then pull from 121,* $x = v\Delta t$*, and putting that all together:* $\Delta t = \frac{\Delta x m \lambda}{h} = \frac{(0.45\text{ m})(4\times10^{-4}\text{kg})(0.0005\text{ m})}{6.626\times10^{-34}\text{Js}} =$ 4.3×10^{12} *years.*

8. [5 pts] Light in air is incident on the surface of a transparent substance at an angle of 58° with respect to the normal. The reflected and refracted rays are observed to be mutually perpendicular. What is the index of refraction of the transparent substance?



A) 1.2

B) 1.4

C) 1.6

D) 1.8

E) 1.9

This is an application of Snell's law and geometry. Start by labeling $\theta_1 = 58$*, the angle of refraction below we can label* θ_2*, and* θ_3 *as the outgoing angle. Since the incoming and outgoing angles are the same,* $\theta_3 = \theta_1$ *Then* $\theta_2 + 90 + \theta_3 = 180$ *or* $\theta_2 = 90 - \theta_1$*. Snell's law gives us* $n_1 \sin\theta_1 = n_2 \sin\theta_2$*. Since the outside block is air,* $n_1 = 1$*. We can then solve these two equations for* $n_2 = \frac{\sin\theta_1}{\sin 90 - \theta_1} = 1.60$

9. [5 pts] A converging mirror has a focal length $f = 13$ cm. How far from the mirror must an object be placed to create an upright image two times the height of the object?

A) 6.5 cm

B) 7.5 cm

C) 13 cm

D) 15 cm

E) 26 cm

We need to figure out the regime – we are given two clues – the image should be ***upright****, and* ***x2*** *magnification. That means the object must between the focal point and the mirror, and the image will be virtual. We can set-up the following equations:*

$$m = -\frac{s'}{s} \Longrightarrow from\ the\ question, m = 2$$

$$2 = -\frac{s'}{s} \Longrightarrow -2s = s'$$

We also need to consider the thin lens equation:

$$\frac{1}{f} = \frac{1}{s} + \frac{1}{s'} \Longrightarrow \frac{1}{f} = \frac{1}{s} + \frac{1}{(-2s)} = \frac{2}{2s} - \frac{1}{2s} = \frac{1}{2s}$$

$$\frac{1}{f} = \frac{1}{2s} \Longrightarrow s = \frac{f}{2} = \frac{13\text{ cm}}{2} = 6.5\text{ cm}$$

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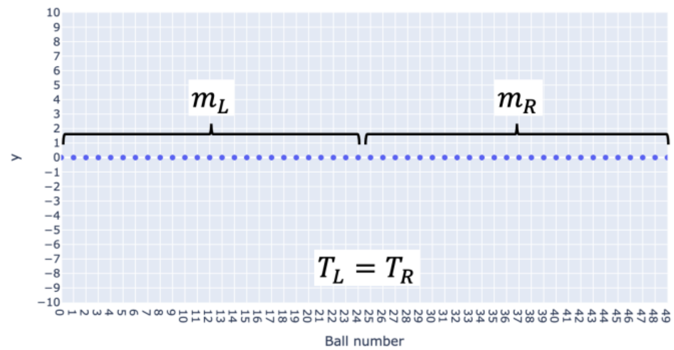
Lab Multiple Choice Questions

10. [5 pts] Students in Lab A3 setup the string in the simulation to have 50 balls. Balls 1 to 25 have a mass m_L and the balls 26 to 50 have mass m_R. They measure the speed of a pulse in the left half of the string (v_L) and in the right half of the string (v_R). They then make a graph with the ratio of the speeds (v_L/v_R) on the vertical axis and ratio of the masses of the balls (m_L/m_R) on the horizontal axis. Which of the statements below are correct?



I. Speed of the pulse is the independent variable.
II. Mass of the balls on the string is the independent variable.
III. The graph is linear with a positive *y*-intercept.
IV. The graph is linear with an intercept at the origin.
V. The graph is non-linear.

A) Statements I and III

B) Statements I and IV

C) Statements II and III

D) Statements II and IV

E) Statements II and V

Since the students can directly change the mass of the balls, this is in the independent variable. The speed of the pulse is dependent on the mass of the balls and is given as:

$$v = \sqrt{\frac{T}{\mu}} \Longrightarrow \mu = \frac{m}{L} \Longrightarrow v = \sqrt{\frac{TL}{m}}$$

We can write the ratio of the speeds as follows:

$$\frac{v_L}{v_R} = \sqrt{\frac{m_R}{m_L}}$$

We can see that the ratio of the speeds is linearly proportional to the square root of the masses. This means that a graph of (v_L/v_R) vs (m_L/m_R) will be non-linear. (A graph of (v_L/v_R) vs ($\sqrt{m_R/m_L}$) would be linear and an intercept at the origin.)

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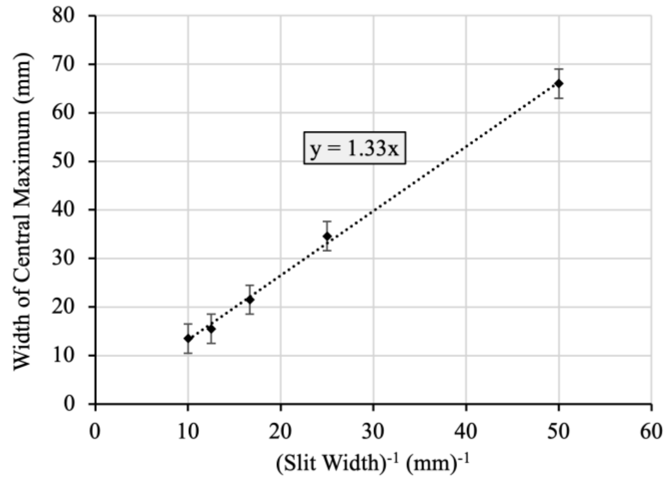
11. [5 pts] In a lab similar to Lab B1, students have access to a grating that contains single slits of 5 different widths. They shine a laser through the slit with the smallest width, and an interference pattern is formed on the screen. The students measure the width of the central maximum on the screen. They then repeat the experiment using the other 4 slits and form the plot at right. (Note the units and that the horizontal axis is the inverse of the slit width). If the distance between the grating and the screen is 1.50 m, which laser did they most likely use in their experiment?



A) Red laser, $\lambda = 635$ nm

B) Orange laser, $\lambda = 592$ nm

C) Yellow laser, $\lambda = 555$ nm

D) Green laser, $\lambda = 532$ nm

E) Blue laser, $\lambda = 450$ nm

For single-slit diffraction, the width of the central maximum is given as:

$$w = \frac{2\lambda L}{a} = 2\lambda L \frac{1}{a}$$

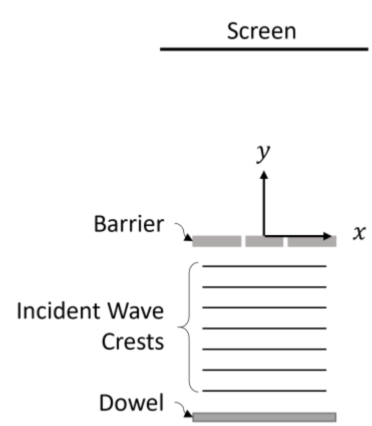
We can see from the above equation that the slope of a graph of w *versus* $1/a$ *has a slope equal to* $2\lambda L$*. The slope of the trendline is 1.33 but we must consider the units. The slope is equal to* $\Delta y/\Delta x$ *so the units must be* mm^2*. We can now solve for* λ*.*

$$2\lambda L = 1.33\ \mathrm{mm}^2 = 1.33 \times 10^{-6}\ \mathrm{m}^2$$

$$\lambda = \frac{1.33 \times 10^{-6}\ \mathrm{m}^2}{2L} = \frac{1.33 \times 10^{-6}\ \mathrm{m}^2}{2(1.50\ \mathrm{m})} = 4.43 \times 10^{-7}\ \mathrm{m} = 443\ \mathrm{nm}$$

Given some uncertainty in their measurements, this value is closest to the blue laser

12. [5 pts] A pan of water contains a dowel that moves up and down at a constant rate producing straight wavefronts that propagate towards a barrier. The barrier contains two very narrow slits through which the waves can pass. Consider a coordinate system with the origin at the center of the barrier, as shown in the diagram at the right.



Consider water waves with a wavelength of 0.60 m, and a barrier with slit L at (-0.80 m, 0.00 m) and slit R at (0.80 m, 0.00 m).

Consider a point P on the screen with (x,y) coordinate of (1.694 m, 2.400 m). Will the interference of the two waves from the left and right slit at point *P* be maximum constructive, complete destructive or something in between? For something in between, path length difference is $\approx \left(m + \frac{1}{4}\right)\lambda$)?

A) Maximum constructive interference

B) Complete destructive interference

C) Something in between

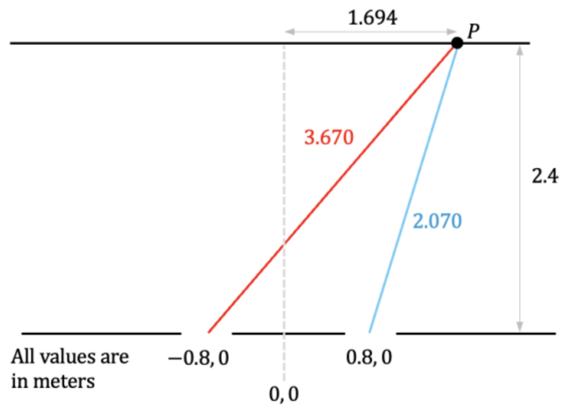
D) Not enough information

Consider the two lines that represent wavefronts shown in the diagram at right. The path length to point P for the wavefront from the left slit is 3.670 m and the path length for the wavefront from the right slit is 2.070 m.

$$\sqrt{(2.4\text{ m})^2 + (1.694 + 0.8\text{ m})^2} = 3.670\text{ m}$$

$$\sqrt{(2.4\text{ m})^2 + (1.694 - 0.8\text{ m})^2} = 2.070\text{ m}$$

The path length difference is therefore 1.6 m.



We are told that the wavelength is 0.60 m. This means that the path length difference is equal to 1.5λ*. This corresponds to the condition for complete destructive interference.*

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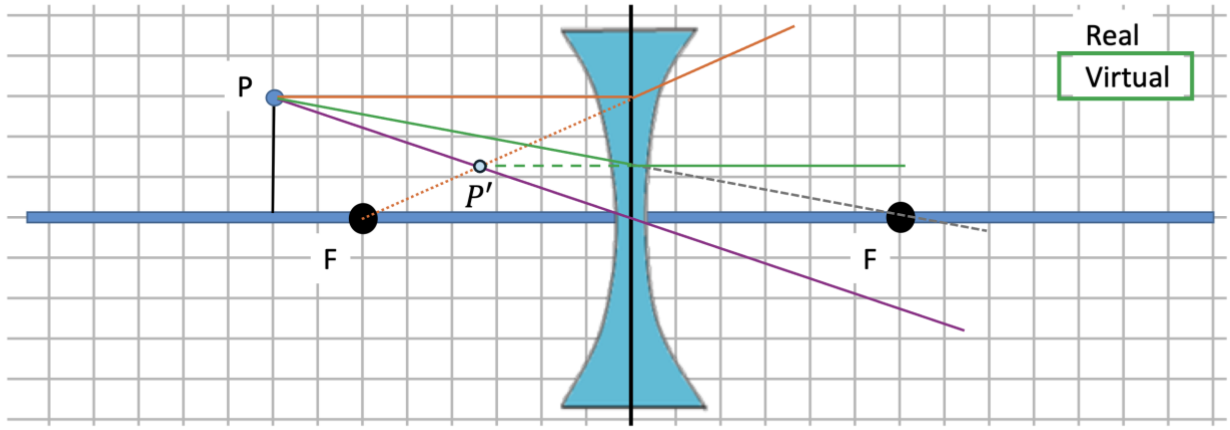
Lecture Free Response

A diverging lens along an axis with an object located at point *P* is shown below. The focal point distance from the lens is 15 cm. Point *P* is located 20 cm from the lens.



13. [6 Points] Draw on the figure above at least two rays from *P* that clearly indicate where the image is located. Label that point as P'. To indicate if the image is real or virtual, box the appropriate word on the figure.

14. [5 Points] Describe differences, if any, if the point *P* were 10 cm from the lens (instead of 20 cm). Explain your reasoning for each of the questions below.

    a. Does the real/virtual status change?

    *The **image is virtual**. Diverging lenses can only produce virtual images, and as shown above, the image is formed on the same side of the lens as the object, indicating a virtual image. Changing the object distance will not change the type of image formed.*

    b. Does the image orientation (upright/inverted) change?

    *The **image is upright**. Diverging lenses can only produce upright (and reduced) images. The ray diagram above depicts the reduced size of the image as compared to the object. As above, changing the object distance will not change the orientation of the image.*

    c. Does P' change location? Explain.

    Yes, P' changes location. The image location is given by the thin lens equation ($s' = \left(\frac{1}{f} - \frac{1}{s}\right)^{-1}$). We can see that the image distance is dependent on the object distance. So, a change in the object distance will result in a change in the image distance.

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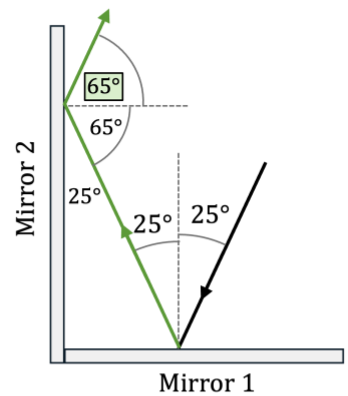
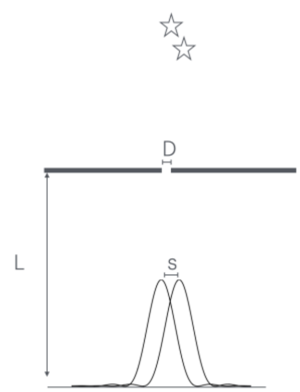
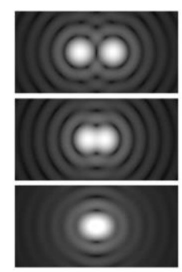
15. [4 pts] The reflecting surfaces of two mirrors meet at a vertex with an angle of 90°. A ray of light strikes mirror 1 with an angle of 25° with respect to the normal. At what angle does the ray reflect off mirror 2? Show your work.



By the law of reflection, the ray reflects off mirror 1 at 25°. *Since mirror 1 and 2 form a* 90° *vertex, the ray is incident on mirror 2 at* 65° *to the normal of mirror 2. Applying the law of reflection again, the ray reflects at* 65°*to the normal of mirror 2.*

16. [5 pts] The leftmost image at right illustrates starlight from two stars, each emitting light of wavelength 500 nm, incident on a small circular aperture of diameter $D = 0.15$ mm creating diffraction patterns on a screen a distance L = 1.0 m from the aperture. The rightmost image shows example diffraction patterns from the stars, with each panel differing by how far apart the stars are. If the stars are too close together, we cannot distinguish between them (as in the lower panel).





In order to resolve the two stars, the peaks must be separated by the width of the central maxima. What does the separation, *s,* between the two peaks of the diffraction patterns need to be for us to resolve the stars, in terms of the given quantities? Explain.

The width of the central maxima for each is calculated by:

$$w = \frac{2.44\lambda}{D} = \frac{2.44(500 \times 10^{-9}\ \text{m})}{0.15 \times 10^{-3}\ \text{m}} = 0.0081\ \text{m} = 8.1\ \text{mm}$$

So, if the peaks are separated by 8.1 mm, they will be clearly resolvable.

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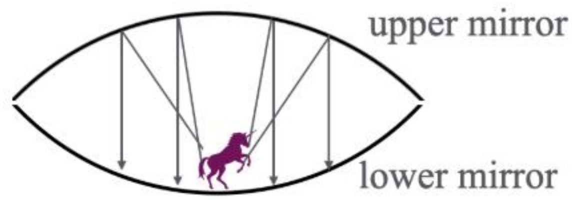
17. [5 pts] A mirascope consists of two identical spherical mirrors joined together. A small toy is placed at the focal point of the upper mirror so that the light rays from the toy that reflect off the upper mirror emerge parallel. These parallel rays are incident on the lower mirror. What kind of image does the lower mirror form from these rays? (Real or virtual). Where is the image formed and is it inverted? Explain (using a diagram if necessary).



Since the toy is placed at the focal point of the upper mirror, any ray from the toy that is incident on the upper mirror will be reflected parallel to the optical axis (or moved downward vertically in this context).

Those rays that move vertically downward are moving parallel to the optical axis of the lower mirror and will reflect through the focal point of the lower mirror.

*This means that the image of the toy **will appear at the focal point of the lower mirror**. Since actual light rays intersect at this point, the **image is real**. And due to the geometry of the mirror and the rays, the **image will be inverted**.*

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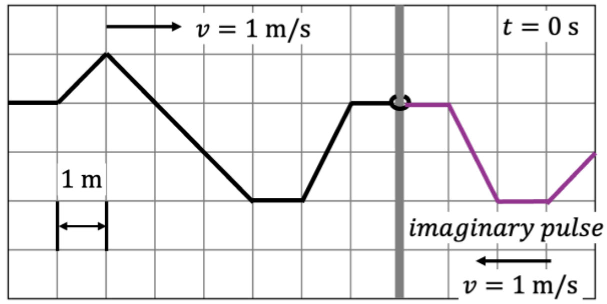
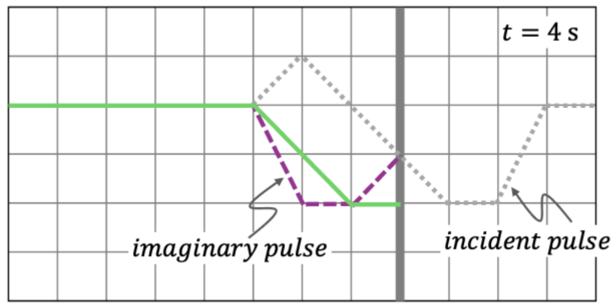
Tutorial Free Response Questions

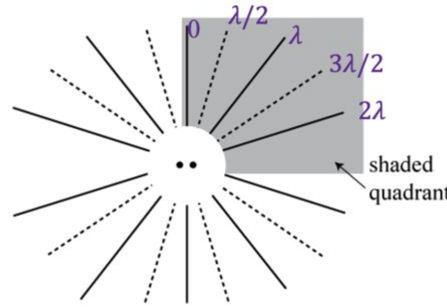
18. [5 pts] A pulse traveling at 1 m/s approaches the **free end** of a spring, as shown in the top figure at right. Sketch the shape of the spring at $t = 4$ s in the bottom figure. Briefly explain.





For a free-end reflection, we model an imaginary pulse traveling to the left that is a mirror image of the incident pulse. We then consider the superposition of the incident pulse and the imaginary pulse

19. [5 pts] A tank of water contains two point-sources that generate periodic waves of wavelength λ. The diagram shows all the nodal lines (dashed) and all antinodal lines of (solid). The sources are separated by a distance *d*. Determine the source distance *d* in terms of λ. Explain.



In the shaded quadrant, there are three antinodal lines (solid) and two nodal lines (dashed). The line that bisects the two sources corresponds to a path length difference of 0. The next line to the right is a nodal line and corresponds to a path length difference of $\lambda/2$. *Continuing outward, the path length differences increase in steps of* $\lambda/2$, *as shown in the diagram.*

The line that directly connects the two sources corresponds to a path length difference equal to the source separation, d. No nodal or antinodal line lies exactly along this line. Since the 2λ *antinodal line is present and lies above the line connecting the two sources, the maximum path length difference must be greater than* 2λ. *However, the next possible line would correspond to* $5\lambda/2$, *and no such line appears before reaching the line that connects the two sources. Therefore,* $2\lambda < d < 2.5\lambda$

20. [5 pts] Suppose the set-up in previous question is changed so that the frequency of the waves generated by the two point sources is *increased by a factor of 2*. How many antinodal lines will appear in the shaded quadrant? Explain.

The relationship between frequency, wave speed and wavelength is given as: $v = f\lambda$*. We can assume the wave speed has not changed since the medium does not change, so, if the frequency increases by a factor of 2, the wavelength decreases by a factor of 2 (*$\lambda' = \frac{\lambda}{2}$ *or* $\lambda = 2\lambda'$*). We can now write the source separation in terms of d.*

$$2\lambda < d < 2.5\lambda$$

$$2(2\lambda') < d < 2.5(2\lambda')$$

$$4\lambda' < d < 5\lambda'$$

We would therefore expect to see 5 antinodal lines in the shaded quadrant, corresponding to path length differences of $0, \lambda, 2\lambda, 3\lambda$ *and* 4λ*.*