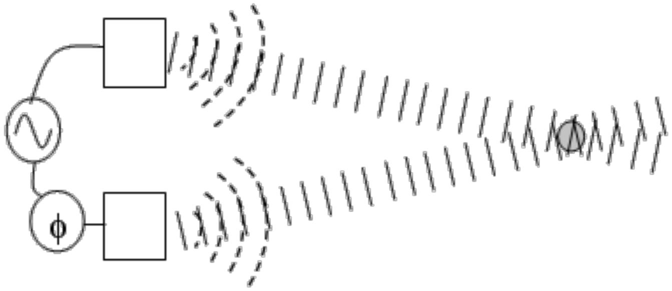
This is the Spring 2009 Midterm Exam

Single-frequency sound waves emerging from two speakers are detected at the point shown in the figure below. The relative phase Φ of the two signals driving the speakers can be adjusted. The speakers are equidistant from the observer.



1. The intensity at the observer from each wave alone is 2.0 W/m^2. The net intensity of the sound received at the point shown is 3.5 W/m^2. What is the relative phase Φ between the sources?

(a) Φ = 43°

(b) Φ = 60°

(c) Φ = 97

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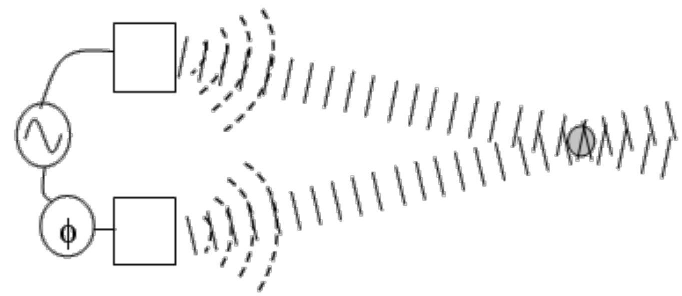

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The two speakers have equal intensities, so we can use the trig identity:

$$I = 4I \cos^2(\phi/2)$$

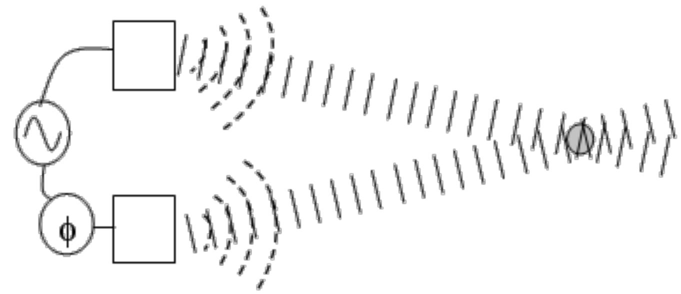
$$3.5 = 8\cos^2(\phi/2)$$

$$\cos(\phi/2) = \sqrt{3.5/8}$$

$$\phi = 97.2°$$

2. The relative phase Φ is now changed to Φ = 0. The relative amplitudes of the waves are changed such that the intensity at the observer from the top speaker alone is 2.0 W/m^2 and the intensity at the observer from the bottom speaker alone is 1.0 W/m^2. What is the net intensity I at the observer?

(a) I = 2.0 W/m^2
(b) I = 2.5 W/m^2
(c) I = 3.0 W/m^2
(d) I = 4.3 W/m^2
(e) I = 5.8 W/m^2



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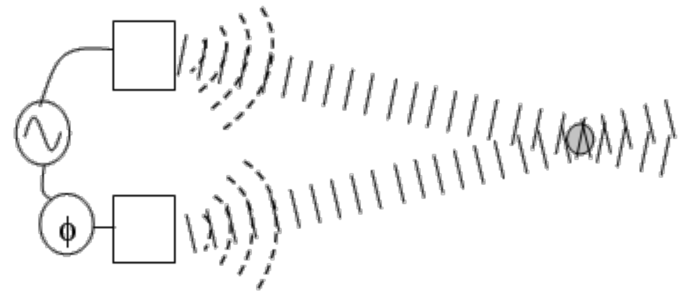
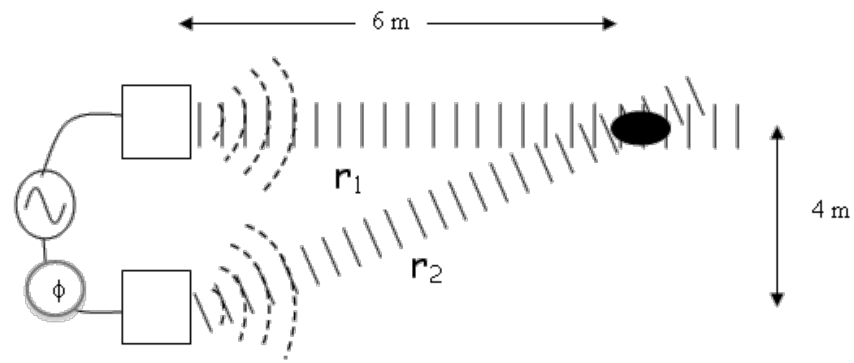


The two waves are now in phase at the observer. Therefore:

$$A = A_1 + A_2 = \sqrt{2} + \sqrt{1} = 2.414$$
$$I = A^2 = 5.83$$

A pure harmonic signal generator with adjustable frequency f is used to drive two speakers as shown in the figure below. Sound waves emerging from the speakers are detected at the point shown in the figure. The relative phase Φ of the two signals driving the speakers can be adjusted.



3. If the wave at the observer goes through a positive maximum every millisecond, what is the wavelength of the sound produced by these sources? (Assume the speed of sound is 330 m/sec.)

(a) 0.0010 m
(b) 0.053 m
(c) 0.33 m

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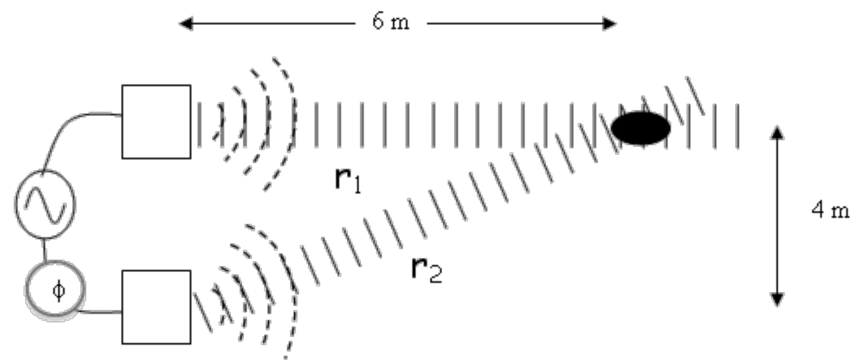

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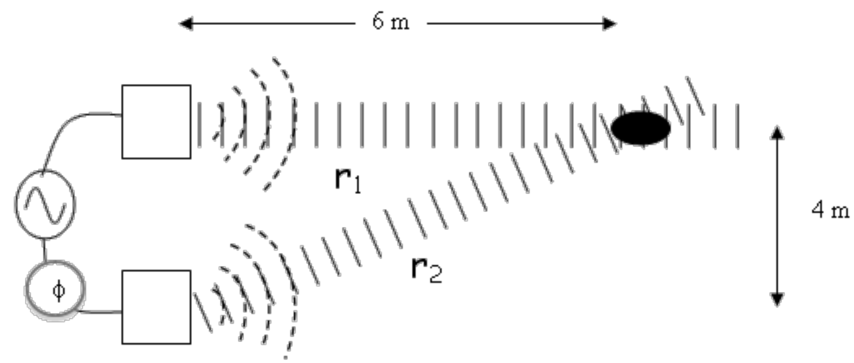
We are told that the period is $T = 1$ ms, or $f = 1000$ Hz.
Using $v = \lambda f$, we have $\lambda = (330 \text{ m/s}) / (1000 \text{ 1/s}) = 0.33$ m.

4. The frequency of the sound waves is now changed to f = 500 Hz. What is the value of Φ closest to 0° that produces an intensity at the observer of 0 W/m^2 ?

(a) -480°
(b) -120°
(c) 0°
(d) 60°
(e) 180°



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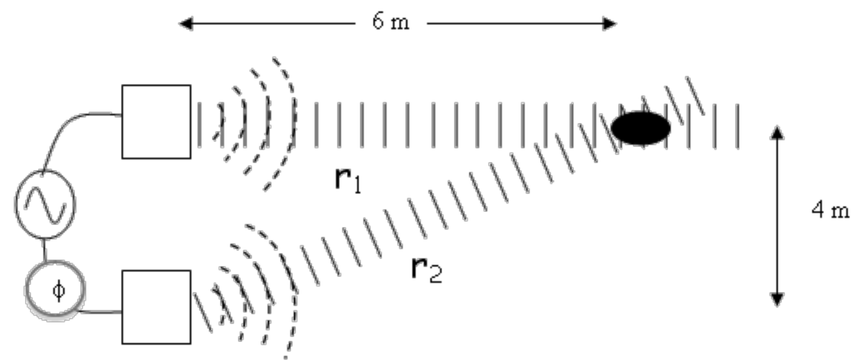


This is a hard problem.

Both Φ and δ contribute to the phase difference at the observer.

We want the smallest $|\Phi|$ such that $\Phi + 2\pi(\delta/\lambda)$ = an odd multiple of π.

Here,

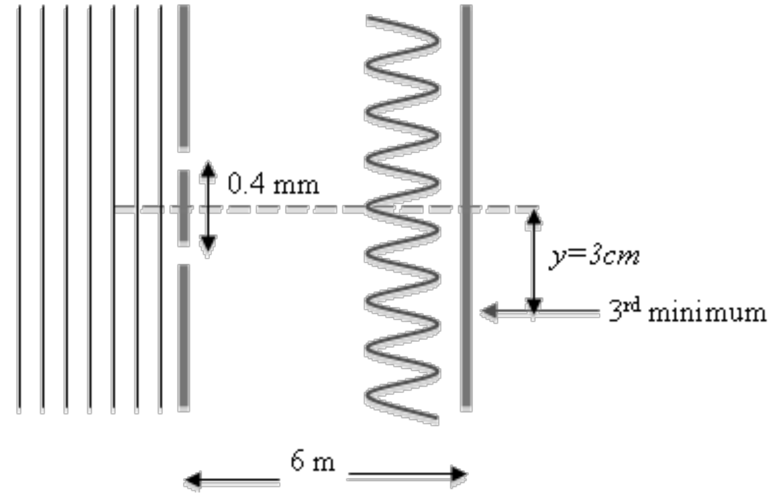
$\delta = \sqrt{(36+16)} - 6 = 1.21$ m

$\lambda = 0.66$ m (double the answer to question 3).

So $2\pi(\delta/\lambda) = 3.67\pi$.

Therefore, we want $\Phi = -0.67\pi = -120°$.

In a two-slit interference experiment, a viewing screen is placed 6 meters directly behind two slits separated by 0.4 mm. Coherent, monochromatic light emerges (in phase) from the slits.



5. If the distance y between the maximum of light intensity at the center of the screen and the third minimum away from the center is 3.0 cm, what is the wavelength of the light?

(a) 420 nm
(b) 680 nm
(c) 740 nm
(d) 800 nm
(e) 960 nm

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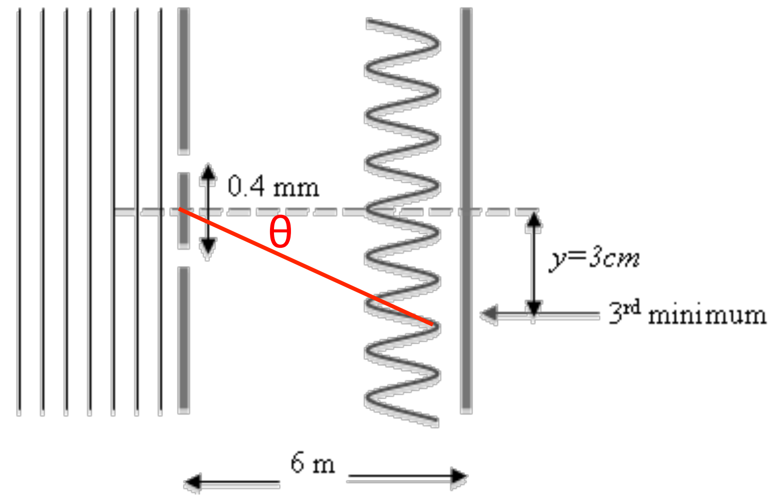

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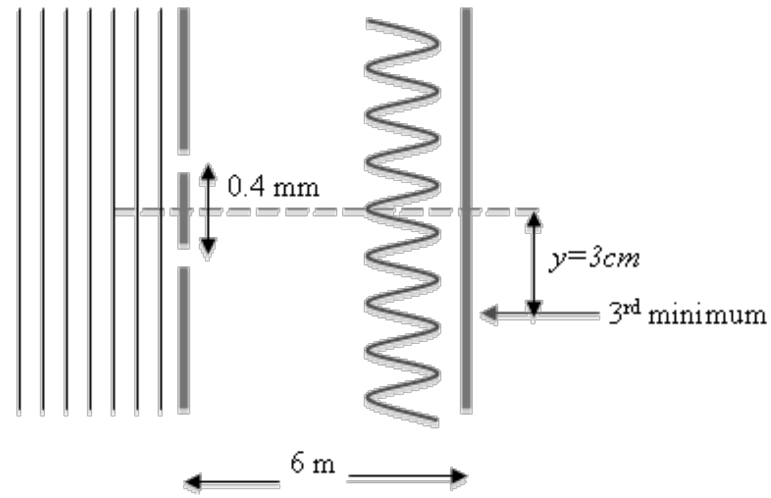
$\theta = 0.03$ m / 6 m = 0.005 (a small angle)
$= \delta/d$

$\delta = 2.5\,\lambda$ (3rd minimum)

So, $\lambda = 0.005\,d / 2.5 = 8\times10^{-7}$ m

6. What happens to the separation between the intensity maxima on the screen as we *decrease* the slit spacing?

(a) decreases
(b) increases
(c) no change



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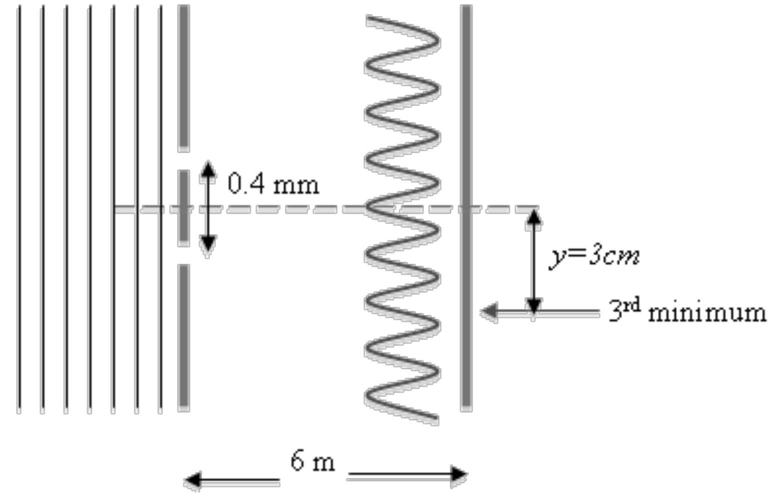
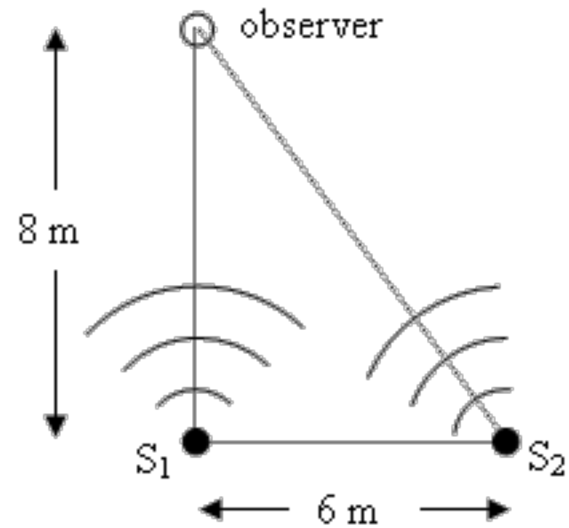


(a) decreases
(b) increases
(c) no change

For a given δ, θ is inversely proportional to d.

7. Two speakers, S_1 and S_2, are adjusted so that the observer (at the location shown in the figure) hears an intensity of 10 W/m^2 when either S_1 or S_2 is sounded alone. The speakers are coherent and in phase. The speed of sound is 330 m/s.



What is the lowest non-zero frequency for which the observer will hear the maximum intensity?

(a) 165 Hz
(b) 330 Hz
(c) 780 Hz
(d) 920 Hz
(e) 1000 Hz

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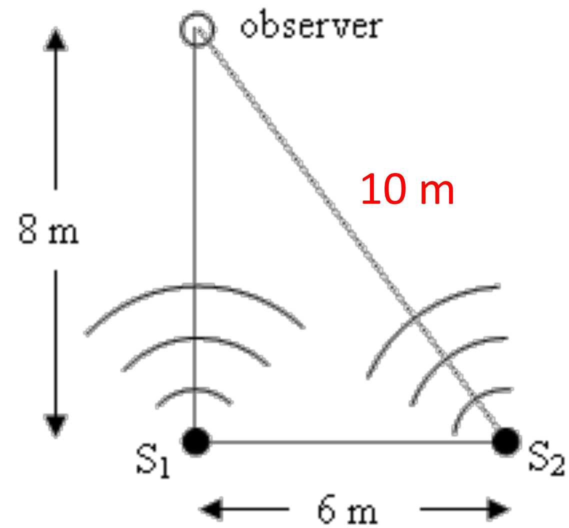

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We want 2 m = $n\lambda$, to put the waves in phase.

Lowest frequency means longest wavelength, so n = 1, and λ = 2 m.

$f = v/\lambda$ = 165 Hz.

8. We define the visible spectrum to span the wavelength range from 400 nm (violet) to 700 nm (red). Consider white light (that contains all visible wavelengths in this range) falling normally onto a plane grating with 600 slits per millimeter.

Find the angular width of the first-order visible spectrum produced by the grating. The angular width is the difference
$\Delta\theta = |\theta(700nm) - \theta(400nm)|$ between the angles of the first interference maxima of the longest and the shortest wavelengths in the visible spectrum.

(a) $\Delta\theta = 0°$
(b) $\Delta\theta = 2.3°$
(c) $\Delta\theta = 5.7°$
(d) $\Delta\theta = 10.9°$
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$d = 1\text{ mm} / 600 = 1.67\ \mu\text{m}$

First maximum:

$\sin\theta_V = \lambda_V/d = 400\text{ nm}/1667\text{ nm} = 0.24$ (not very small)

$\sin\theta_R = \lambda_R/d = 700\text{ nm}/1667\text{ nm} = 0.42$ (not very small)

$\Delta\theta = \sin^{-1}\theta_R - \sin^{-1}\theta_V = 10.9°$

9. Do the first- and second-order spectra of this wavelength range overlap?

(a) Yes.
(b) No.
(c) The answer depends on the grating's spacing between the grating's slits.

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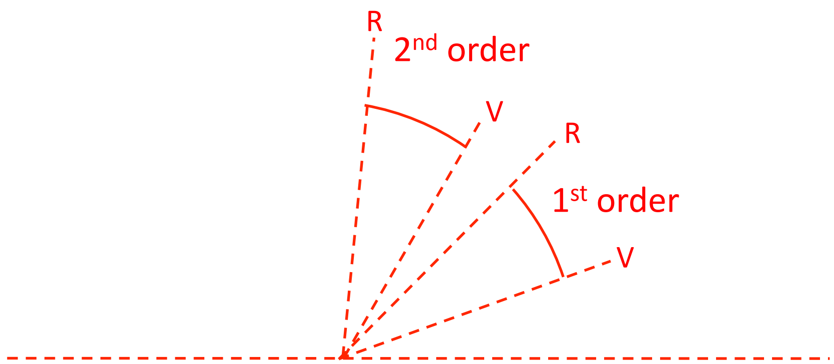
The question: Is the angle to the second order violet peak larger than the angle to the first order red peak?

Second maximum:
$\sin\theta_V = 2\lambda_V/d = 800\ \text{nm}/1667\ \text{nm} = 0.48$

That's bigger than $\sin\theta_R$,
so they don't overlap.



This is a consequence of $2\lambda_V > \lambda_R$; it does not depend on d.

10. Monochromatic light of one wavelength and one frequency passes through a single slit of finite width. The diffraction pattern is observed on a screen at a certain distance from the slit. Which of the following changes would ***decrease*** the width of the ***central*** maximum?

(a) decreasing the slit width
(b) decreasing the frequency of the light
(c) increasing the wavelength of the light
(d) increasing the distance of the screen from the slit
(e) none of the above

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(b) decreasing the frequency of the light
(c) increasing the wavelength of the light
(d) increasing the distance of the screen from the slit
(e) none of the above

$\sin\theta = \lambda/a$, and $y = L\tan\theta$

Decreasing a, decreasing f, and increasing λ all increase θ (and thus y). Increasing L also increases y.

11. While conducting a photoelectric effect experiment with light of a certain frequency, you find that a reverse potential difference of 1.25 V is required to reduce the current to zero. Find the maximum speed of the emitted photoelectrons.

(a) 0 m/s
(b) 1.2 m/s
(c) 3.7×10^3 m/s
(d) 6.6×10^5 m/s
(e) Not enough information given.

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$V_{stop} = 1.25$ V means KE = 1.25 eV = $\frac{1}{2}mv^2$.

$v = (2KE/m)^{1/2} = [2\times(1.25\times1.6\times10^{-19}\text{ J})/(9.1\times10^{-31}\text{ kg})]^{1/2} = 6.6\times10^5$ m/s

12. The largest optical telescopes have apertures of about 10 m. Radio telescopes can be made that have apertures as large as the Earth (about 12.8×10^6 m). If the optical wavelengths are about 500 nm and radio wavelengths are about 1 cm, which kind of telescope can achieve better (*i.e.*, smaller) angular resolution?

(a) radio telescopes.
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(c) Both techniques achieve similar resolutions (within a factor of two).

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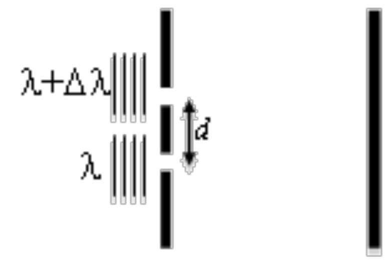
Rayleigh's criterion: $\alpha_c = 1.21\ \lambda/a$
Optical: $1.21 \times 5\times10^{-7}$ m / 10 m $= 6\times10^{-8}$
Radio: 1.21×0.01 m / 12.8×10^{6} m $= 9\times10^{-10}$

13. Suppose the two-slit experiment is performed with single photons of slightly different wavelengths: λ = 600 nm and $\lambda + \Delta\lambda$ = 602 nm (*i.e.*, $\Delta\lambda$ = 2 nm). How does the interference pattern on the screen (created by a large number of photons) differ from the usual one with equal wavelengths?



(a) The pattern is the same as the pattern that would be produced by monochromatic light with the average wavelength $\lambda + \Delta\lambda/2$ = 601 nm.

(b) For $\Delta\lambda$ = 2 nm there is an interference pattern. However, the pattern will disappear as $\Delta\lambda \rightarrow d$, where d is the spacing between the two slits.

(c) There is no interference pattern for $\Delta\lambda$ = 2 nm.

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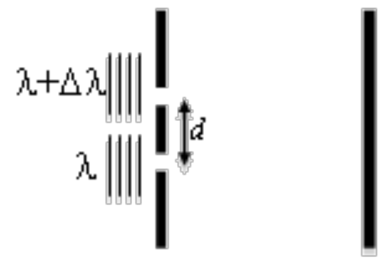

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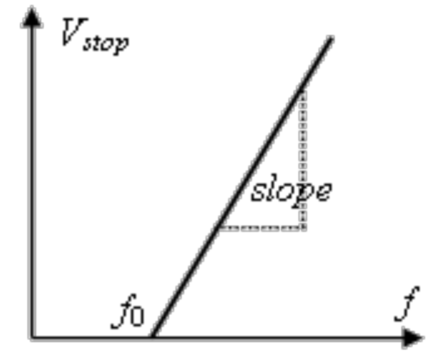
The frequencies are different, so the phase difference varies with time (i.e., "beats"). This washes out the interference pattern, because sometimes they are in phase and sometimes they are out of phase.

14. If you shine light of frequency, f, on a metal, electrons may emerge and be collected. The maximum bias on the collector for which this occurs is the stopping voltage, V_{stop}. Here is a graph (without numbers) of V_{stop} versus f:



Suppose someone else makes the same measurement and obtains a larger slope (steeper line). How might he interpret the difference in the two results?

(a) His measured value of Planck's constant is larger than yours.
(b) His measured value of Planck's constant is smaller than yours.
(c) His measured value of the metal's work function is smaller than yours.

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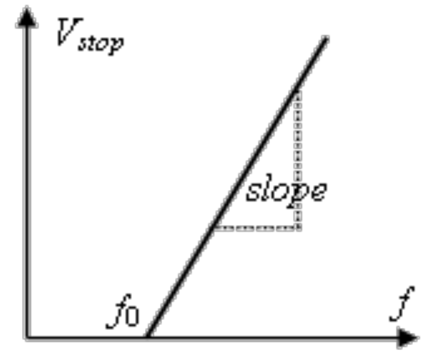

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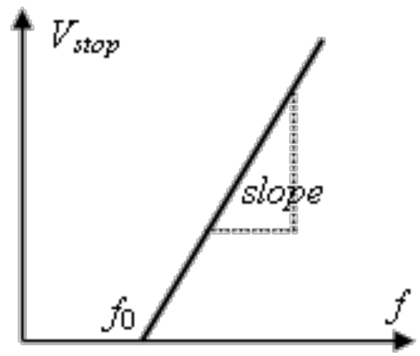
The slope measures Planck's constant.

There is a small ambiguity in the wording.
We should have specified that f_0 remains unchanged.

15. Suppose someone else makes the same measurement and obtains a smaller f_0 (x-intercept). How might she interpret the difference in the two results?



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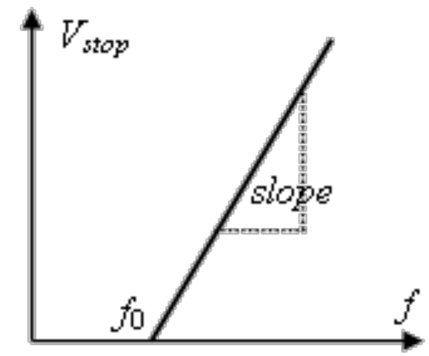

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Decreasing f_0 decreases the magnitude of the y intercept, which measures the work function.

Again, there is a small ambiguity.
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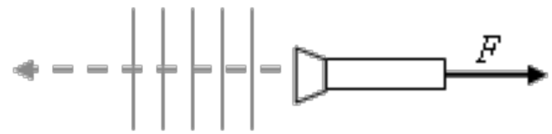
16. Suppose a lamp is emitting 100 W of orange light (λ = 600 nm). All the photons are emitted to move to the left. How large is the reaction force, F, on the lamp?



(a) $F = 4.135 \times 10^{-13}$ N
(b) $F = 3.33 \times 10^{-7}$ N
(c) $F = 0.0165$ N
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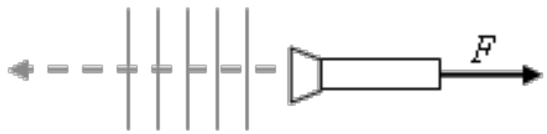

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Use $F = dp/dt$.
The photons carry off momentum, so the lamp recoils.
Each photon has $p = h/\lambda$ and $E = hc/\lambda$
The number of photons per second is: N = Power/E, so
$dp/dt = Np = \text{Power} * (\lambda/hc) * (h/\lambda) = \text{Power}/c$ (independent of λ!)
$= 100 \text{ W} / 3\times10^{8} \text{ m/s} = 3.33\times10^{-7}$ Newtons

17. When passed through a thin crystal, what energy electrons will produce a diffraction pattern that is similar to (the same spot positions) the one produced by 10 keV x-rays?

(a) E_e = 0.098 keV
(b) E_e = 6.65 keV
(c) E_e = 10 keV (*i.e.*, the same energy)
(d) E_e = 101 keV
(e) E_e = 511 keV

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We want the electrons to have the same wavelength as the photons.

For these photons, $\lambda = hc/E = 0.124$ nm.

For electrons, $E = 1.505\ \text{eV}\cdot\text{nm}^2 / \lambda^2 = 97.8$ eV

18. Light of various wavelengths is shined on a collection of "quantum wires" all of the same length. Each 'wire' consists of an electron trapped in a carbon nanotube, which we approximate as a 1-D infinite potential well of a width equal to the length of the wire.

It is observed that the longest wavelength that is absorbed by the collection of wires (corresponding to an electronic excitation in each wire), is 0.44 mm. What is the length of each wire?

(a) 4 nanometers
(b) 20 nanometers
(c) 0.22 millimeters
(d) 0.44 millimeters
(e) 0.88 millimeters

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Longest wavelength means lowest energy.

$E_{photon} = hc/\lambda = 1240 \text{ eV}\cdot\text{nm}/0.44\times10^6 \text{ nm} = 2.82\times10^{-3} \text{ eV}$.

In a square well, the smallest energy difference is between the n=1 and n=2 states: $\Delta E = 3E_1$.

So: $E_1 = 9.39\times10^{-4}$ eV

$= h^2/(8mL^2) = 1.505 \text{ eV}\cdot\text{nm}^2/(4L^2)$.

Thus, $L = [1.505/4/9.39\times10^{-4}]^{1/2} =$ 20.0 nm .

19. An electron in an infinite 1-D square potential well of width 8 nm, decays from the state with quantum number n (*i.e.*, the n-1 excited state) to state m.

Compare the wavelengths of the emitted photon for the two transitions: $11 \rightarrow 10$, and $5 \rightarrow 2$.

(a) $\lambda_{11\rightarrow 10} < \lambda_{5\rightarrow 2}$
(b) $\lambda_{11\rightarrow 10} > \lambda_{5\rightarrow 2}$
(c) $\lambda_{11\rightarrow 10} = \lambda_{5\rightarrow 2}$

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In a square well, $E_n = n^2 E_1$.
So, $E_{11} - E_{10} = 21E_1$, and $E_5 - E_2 = 21E_1$.

20. Now assume the electron is in the first excited state of the well, and that we shine on it photons that have an energy of 0.06 eV. Which of the following will happen and why?

(a) Nothing - each photon doesn't have enough energy to excite the electron to the next excited state.
(b) Nothing - each photon has too much energy to excite the electron to the next excited state.
(c) The electron can be excited to the second excited state.

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L = 8 nm, so

$E_1 = 1.505\ \text{eV}\cdot\text{nm}^2/4L^2 = 5.88\times10^{-3}$ eV.

$E_2 = 0.0235$ eV

$E_3 = 0.0529$ eV

$E_4 = 0.0941$ eV

Next excited state: $E_3 - E_2 = 0.0294$ eV, $< E_{photon}$.

Second excited state: $E_4 - E_2 = 0.0706$ eV, $> E_{photon}$.

The photon energy must match the energy difference.

You can't absorb a fraction of a photon.

21. Now consider the following quantities, both for an electron in an ***infinite*** well of width 8 nm (the well extends from x = 0 to x = 8 nm), and for an electron in a ***finite*** well of the same width:

P(middle) ≡ probability to find electron in the middle 10% of the well, i.e., in the interval from x = 3.6 nm to x = 4.4 nm

E_{ground} ≡ kinetic energy of the electron in the ground state

$\lambda_{2\to3}$ ≡ wavelength of photons needed to excite the electron from the n = 2 to the n = 3 state.

Which one of the following statements is correct?

(a) $P(\text{middle})_{\text{infinite}} < P(\text{middle})_{\text{finite}}$
(b) $E_{\text{ground,infinite}} < E_{\text{ground,finite}}$
(c) $\lambda_{2\to3,\text{infinite}} = \lambda_{2\to3,\text{finite}}$
(d) all of the above
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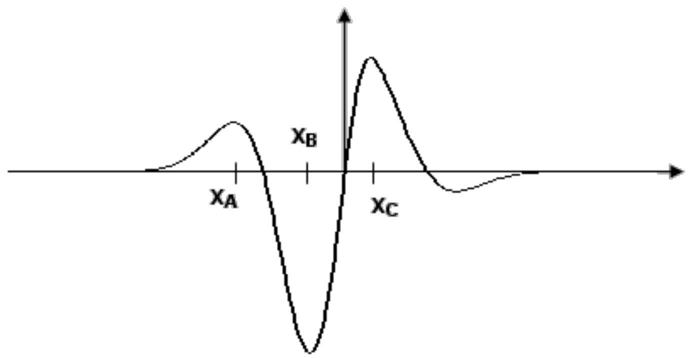
Which one of the following statements is correct?

(a) $P(middle)_{infinite} < P(middle)_{finite}$
(b) $E_{ground,infinite} < E_{ground,finite}$
(c) $\lambda_{2\to3,infinite} = \lambda_{2\to3,finite}$
(d) all of the above
(e) none of the above

Due to leakage into the walls,
the wave function in the finite well
is more spread out. Thus, it has
lower probability density, longer wavelength
and lower energy
than in an infinite well of the same depth.

22. The wavefunction shown below corresponds to an eigenstate (with quantum number n) of a particle in a potential well.

If we measure the location of the particle, where is it most likely to be found?



(a) at position x_A
(b) at position x_B
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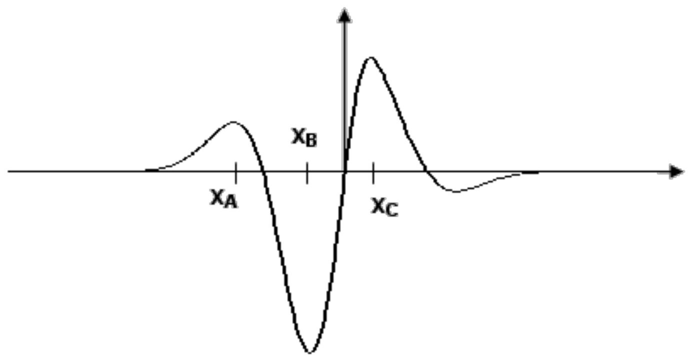

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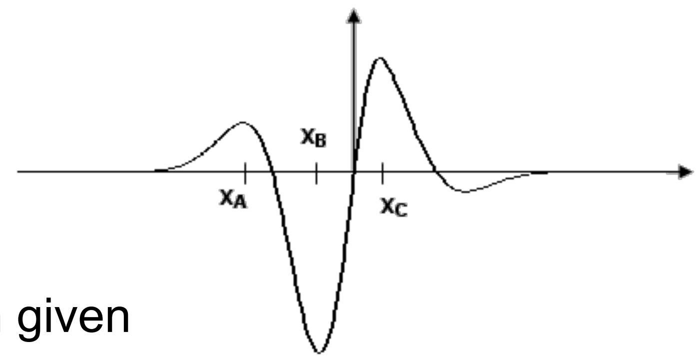
(b) at position x_B
(c) at position x_C

The probability density is $|\psi|^2$, so the magnitude, not the sign, matters here.

23. Where is the total energy of the particle the highest?

(a) at position x_A
(b) at position x_B
(c) at position x_C
(d) same at all positions
(e) cannot be determined from the information given



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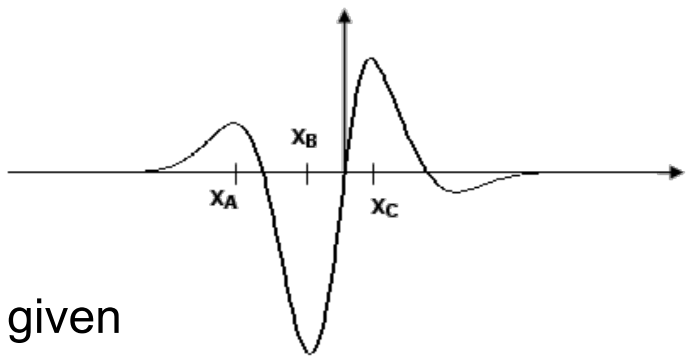
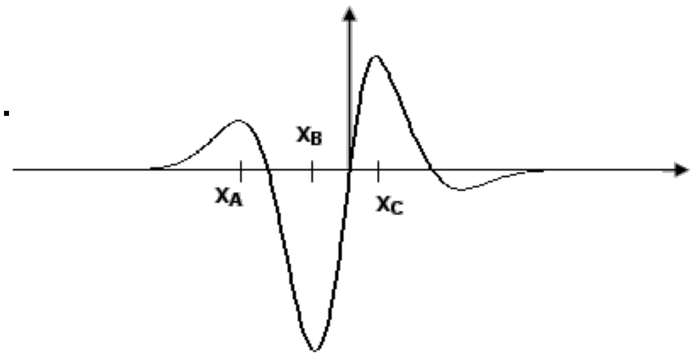


Total energy is conserved.

24. Which one of the following can we conclude about the potential?

(a) It has infinite walls.
(b) It is a symmetric potential, i.e., V(-x) = V(x).
(c) It has ***at most*** three bound states, i.e., no more than three energy eigenstates.
(d) all of the above
(e) none of the above



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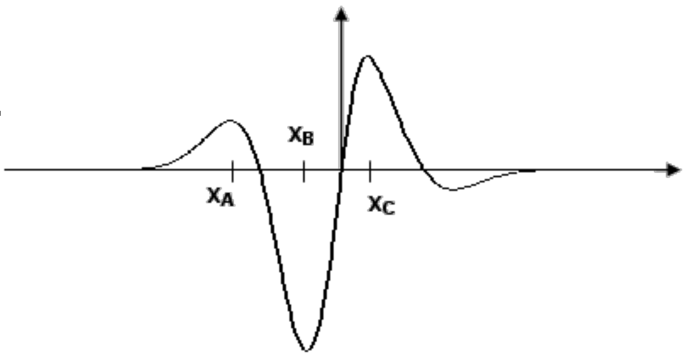
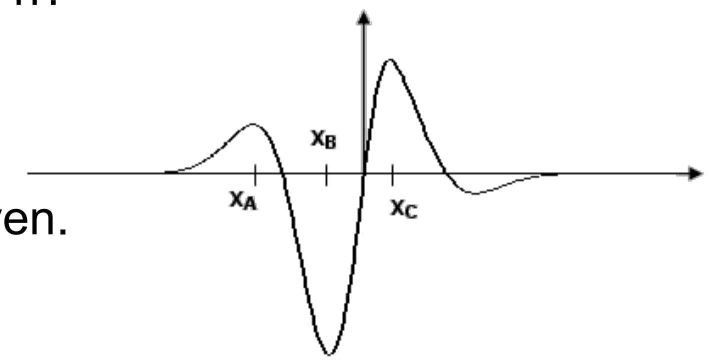


Penetration into the walls means they are finite.
Energy eigenstates of symmetric potentials must be symmetric or antisymmetric (even or odd functions).
Three nodes means it's in the 4th energy state.

25. If we reduce the width of the potential well, what will happen to the energy of the eigenstate with quantum number n?

(a) decrease
(b) increase
(c) Cannot determine from the information given.



For a given n, as we reduce the well width, we reduce the wavelength. So, the energy increases.