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1. (15 points, 5 points each): A string vibrates to produce standing waves. Using a strobe which flashes 200 times per second, five successive pictures are taken one after the other. We see that the maximum displacement occurred for pictures 1 and 5:

The string is 30.0 cm long and has linear mass density 0.100 g/m.

(a) Find the wavelength λ (in m), frequency f (in Hz), period T (in s), and wave speed (in m/s) for the traveling waves on this string.

(b) How fast is point P moving when the string is in position 3?

(c) Draw a history graph of the particle at point P, assuming that picture 3 is where we set $t = 0$. Label both horizontal as well as vertical axes, and provide some values for scale. Include at least $t = 0$ to $t = T$ in your history graph.

a) $\boxed{\lambda = 0.3\,m}$

$\boxed{T = \frac{8}{200}\ \text{s} = 0.04\ \text{s}}$ $\boxed{f = 25\ \text{Hz}}$

$V = \lambda f = \frac{3}{10} \cdot 25\ m/s = \boxed{7.5\ \text{m/s} = V}$

b) $D(x,t) = A\cos(Kx - wt)$

$\frac{dD}{dt} = Aw\sin(Kx - wt) \Rightarrow \max\left(\frac{dD}{dt}\right) = Aw = 2\pi\,(25)\,(0.05)\,m/s$

$\boxed{\frac{dD}{dt} = 7.85\ m/s}$

c)

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2. (15 points, 5 points each): A plano-concave (diverging) lens is made with a material of index of refraction $n = 1.50$. The curved portion of the lens has radius of curvature of magnitude 100.0 cm.

   (a) What is the focal length of this lens?

   (b) An object is placed in such a location that the magnification has magnitude $|m| = 0.5$. Draw an accurate ray diagram of this situation. How far is the object from the lens?

   (c) Suppose this lens helps someone see better. Is this person far-sighted or near-sighted? What is their near point or far point (whichever is different from that of a person with "normal" vision)? Remember that the "normal" near point is 25 cm and the "normal" far point is ∞.

a) $\frac{1}{f} = (n-1)\left[\frac{1}{R_1} - \frac{1}{R_2}\right] = (1.5-1)\left[-\frac{1}{1m} - \frac{1}{\infty}\right] = -0.5m$

$\boxed{f = -2m}$

b)

$m = -\frac{S'}{S} = \frac{1}{2} \Rightarrow S' = -S/2$

$\frac{1}{f} = \frac{1}{S} + \frac{1}{S'} \quad -\frac{1}{2} = \frac{1}{S} - \frac{2}{S}$

$\boxed{\begin{array}{l} S = 2m \\ S' = -1m \end{array}}$

c) <u>Near Sighted</u>

far point $< \infty$

$\frac{1}{\infty} + \frac{1}{S'} = -\frac{1}{2m} \Rightarrow \boxed{S' = -2m}$

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3. (15 points, 5 points each): An engine operates via two isochoric and two isothermal processes. The temperature extremes are T_0 and $3T_0$, and the volume extremes are V_0 and $2V_0$. The working substance of the engine is n moles of monoatomic gas.

   (a) Draw this engine on a pV diagram (label the processes and axes, and indicate the direction of the cycle). If the lowest pressure in the cycle is p_0, then what is the highest pressure in the cycle (in terms of p_0)? Label the point with the highest pressure point **1**, and label points **2** through **4** for the next steps in the cycle (so that the cycle is **12341**).

   (b) Which steps (e.g., **12**, **23**, etc.) transfer heat from the surroundings to the gas? For this step (or, for each of these steps), find Q, the heat delivered to the gas, in terms of n, T_0, V_0, and/or any fundamental constants.

   (c) Find the actual efficiency of this engine and compare with the maximum (ideal) efficiency between these two temperature extremes.

a)

$P_3 = P_0 \quad P_0(2V_0) = nRT_0$

$n = \frac{2P_0V_0}{RT_0}$

$P_1V_0 = nR(3T_0)$

$P_1 = \frac{3\cancel{R}\cancel{T_0}}{\cancel{V_0}}\left(\frac{2P_0\cancel{V_0}}{\cancel{R}\cancel{T_0}}\right) \Rightarrow \boxed{P_1 = 6P_0}$

b) $\boxed{1 \to 2,\ 4 \to 1}$

$\Delta E_{12} = 0 \Rightarrow W + Q = 0$

$Q_{12} = -W_{12} = \int_{V_i = V_0}^{V_f = 2V_0} P\,dV = nR(3T_0)\ln\left(\frac{2V_0}{V_0}\right)$

$\boxed{Q_{12} = 3nRT_0\ln(2)}$

$Q_{41} = \Delta E_{41} = nC_V(3T_0 - T_0) \Rightarrow Q_{41} = n\left(\frac{3}{2}R\right)\cdot 2T_0$

$\boxed{Q_{41} = 3nRT_0}$

c) $\eta = \frac{W_{out}}{Q_H} = 0.27$ $\qquad \eta_{carnot} = 1 - \frac{T_0}{3T_0} = 0.66$

$Q_H = Q_{12} + Q_{41}$ $\qquad W_{12} = -3W_{34} \Rightarrow W_{out} = W_{12} + W_{34} = \frac{2}{3}W_{12}$

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4. (10 points, 5 points each): A linearly-polarized EM wave in vacuum traveling in the $-\hat{x}$ direction has, at $x = 0$ and $t = 0$, the electric field pointing in the $+\hat{y}$ direction with magnitude 4.00×10^4 V/m (this is the amplitude of the electric field wave).

   (a) Find an expression for the magnetic field $\vec{B}(x,t)$. Take $\lambda = 632$ nm.

   (b) Suppose we want to pass this EM wave through a polarizer that will decrease the electric field amplitude to 1.00×10^4 V/m. Find a unit vector in the yz plane that is parallel to the direction we should orient the polarizing filter.

a) $\vec{B}(x,t) = B_0 \cos(kx + \omega t)(-\hat{z})$

$\hat{y} \times \hat{B} = -\hat{x}$

$\hat{B} = -\hat{z}$

$B_0 = \frac{E_0}{c} = \frac{10^4 \text{ V/m}}{3\times10^8 \text{ m/s}} = \frac{1}{3}\times10^{-4}$ T

$k = \frac{2\pi}{\lambda} = \frac{2\pi}{632\text{nm}} = 9.94\times10^6$ 1/m

$\omega = ck = (3\times10^8 \text{ m/s})(9.94\times10^6 \text{ 1/m}) = 2.98\times10^{15}$ rad/s

b) $I \propto E^2$

$\frac{I_i}{I_f} = \frac{E_i^2}{E_f^2} = \frac{4^2}{1^2} = 16$

$I_i = 16 I_f$

$I_f = I_i \cos^2\theta$

$\frac{1}{16} = \cos^2\theta$

$\cos(\theta) = 1/4$

$$\boxed{\frac{\hat{y} + \sqrt{15}\,\hat{z}}{4}}$$

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5. (10 points, 5 points each): In the figure below, light initially in material 1 refracts into material 2, crosses that material, and is then incident at the critical angle θ_c on the interface between materials 2 and 3. The indexes of refraction are $n_1 = 1.60$, $n_2 = 1.40$, and $n_3 = 1.20$.

(a) What is angle θ?

(b) If θ is increased, is there refraction of light into material 3? Explain.

a)

$$n_2 \sin(\overbrace{90-\theta_2}^{\theta_c}) = n_3 \overbrace{\sin(90)}^{1}$$

$$\theta_2 = 90 - \sin^{-1}\left(\frac{n_3}{n_2}\right) = 31^\circ$$

$$\sin\theta_1 = \frac{n_2}{n_1}\sin(31) = 0.45$$

$$\boxed{\theta_1 = 26.74^\circ}$$

b) θ_1 inc $\rightarrow$ θ_2 inc

θ_2 inc $\rightarrow$ θ_c dec $\rightarrow$ now less than critical angle

Yes there is refraction

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6. (12 points, 4 points each) The figure below gives the interference maxima of two double-slit interference experiments.

(a) Assume the only difference between the two experiments is the wavelength of the monochromatic light incident on the double-slit. If experiment 1 used light of wavelength $\lambda_1 = 560$ nm, what is the wavelength of light λ_2 used in the 2nd experiment?

(b) Assume the only difference between the two experiments is the slit separation. If experiment 1 used a slit width of $d_1 = 80\ \mu$m, what is the slit separation d_2 used in the 2nd experiment?

(c) Assume the only difference between the two experiments is the distance to the screen. If experiment 1 used a distance of $L_1 = 2$ m, what is the distance to the screen L_2 used in the 2nd experiment?

a) $m\lambda = \frac{dy_m}{L}$ $\quad y_1^1 = 2y_1^2 \Rightarrow \lambda_1 = 2\lambda_2$

$\boxed{\lambda_2 = 280\text{nm}}$

b) $\lambda = \frac{dy}{L} \Rightarrow y = \frac{L\lambda}{d}$ $\quad \frac{\cancel{L\lambda}}{d_1} = \frac{2\cancel{L\lambda}}{d_2}$

$d_2 = 2d_1$

$\boxed{d_2 = 160\mu\text{m}}$

c) $\lambda = \frac{dy}{L}$ $\quad L_1 = 2L_2$

$\boxed{L_2 = 1\text{m}}$

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(30 points, 3 points each): 10 Multiple-choice questions / fill-in-the-blanks on various topics.

Directions for multiple-choice questions: COMPLETELY FILL IN THE SQUARE for the answer. Directions for fill-in-the-blank questions: Your answer should be entirely in the boxed region. Include the number of significant figures ("sig. figs.") requested in the problem.

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7. A lens produces an inverted, enlarged, real image. What can we say about the lens and/or the object location?

   - ☐ The lens is diverging and the object is farther away from the lens than the focal point.
   - ☐ The lens is diverging and the object is closer to lens than the focal point.
   - ☐ The lens is diverging, but we can't tell where the object is relative to the focal point.
   - ■ The lens is converging and the object is farther away from the lens than the focal point.
   - ☐ The lens is converging and the object is closer to lens than the focal point.

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8. An ideal monoatomic gas expands quasi-statically to twice its volume. If the process is isothermal, the work done by the gas is $W_{by,i}$. If the process is adiabatic, the work done by the gas is $W_{by,a}$. Which of the following is true?

   - ☐ $W_{by,i} = W_{by,a}$
   - ☐ $0 = W_{by,i} < W_{by,a}$
   - ☐ $0 < W_{by,i} < W_{by,a}$
   - ☐ $0 = W_{by,a} < W_{by,i}$

   None are true

$W = \text{Area}$

$W_i > W_a > 0$

---

9. Unpolarized light passes through two polarizers, the second at an angle 30.0° with respect to the first. The final intensity of the light after it passes through the two polarizers is 9.00 W/m^2. What would the final intensity be if instead you orient the 2nd polarizer at an angle 60.0° with respect to the first? (3 sig. fig. answer)

$\boxed{3.00\ W/m^2}$

$\frac{I_0}{2}\cos^2(30) = 9$

$\frac{I_0}{2}\cos^2(60) = I_7$

$\frac{I_7}{9} = \frac{\cos^2(60)}{\cos^2(30)}$ $\quad I_7 = 3$

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10. An EM wave is traveling in the $-\hat{y}$ direction. At one instant in time and space, the electric field points in the $+\hat{x}$ direction and has magnitude 300 μV/m. What is the magnetic field $\vec{B}$ at this same instant in space and time?

- [x] $+\hat{z}$ direction, magnitude 1.0×10^{-12} T.
- [ ] $-\hat{z}$ direction, magnitude 1.0×10^{-12} T.
- [ ] $+\hat{z}$ direction, magnitude 9.0×10^{4} T.
- [ ] $-\hat{z}$ direction, magnitude 9.0×10^{4} T.

$-\hat{y} \times \hat{x} = +\hat{z}$

$B_0 = E_0/c = \frac{3\times10^{-4}\ V/m}{3\times10^{8}\ m/s}$

$= 10^{-12}\ T$

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11. A camera takes a properly exposed photo with a 3.0-mm-diameter aperture and a shutter time of (1/60) s. What is the appropriate shutter time for a 6.0-mm-diameter aperture?

- [ ] (1/15) s
- [ ] (1/30) s
- [ ] (1/120) s
- [x] (1/240) s

$D = 3mm$ $\quad Exp = D^2 \Delta t$

$\Delta t = \frac{1}{60}\ s$ $\quad \frac{9}{60} = 36\Delta t$

$\Delta t = 1/240\ s$

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12. A block of wood is floating in water. It has density $k\rho_w$, where ρ_w is the density of water, and $k < 1$ is a unitless, positive constant. What fraction of the total volume of wood is submerged?

- [x] k
- [ ] $1 - k$
- [ ] $\frac{k}{k-1}$
- [ ] $\frac{k}{k+1}$

$F_g = mg = k\rho_w V_0 g$

$F_B = \rho_w V_w g$

$F_g = F_B$

$kV_0 = V_w$

$\frac{V_w}{V_0} = k$

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13. This problem is a continuation of the previous one. When you apply a downward force of magnitude F, the block becomes fully submerged (and is in equilibrium). What is the mass of the block, in terms of F, k, and g?

- [ ] $\frac{F}{kg}$
- [ ] $\frac{kF}{g}$
- [ ] $\frac{(1+k)F}{g}$
- [x] $\frac{kF}{(1-k)g}$
- [ ] None of the above

$(1-k)V_0\rho_w g = F$

$V_0 = \frac{F}{(1-k)\rho_w g}$

$m = k\rho_w \cdot \frac{F}{(1-k)\rho_w g} = \frac{kF}{(1-k)g}$

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14. On a linear X temperature scale, water freezes at $-325.0°$X and boils at $+275.0°$X. On a linear Y temperature scale, water freezes at $0.00°$Y and boils at $30.00°$Y. A temperature of $50.00°$Y corresponds to what temperature on the X scale?

- [ ] 400.0°X
- [x] 675.0°X
- [ ] 430.0°X
- [ ] 230.0°X
- [ ] 505.0°X

$T_x = 6 \cdot C - 325$

$T_y = \frac{3}{10} C \Rightarrow 50 = \frac{3}{10} C$

$C = \frac{500}{3}°C$

$T_x = 6 \cdot \frac{500}{3} - 325 = 1000 - 325$

$= 675°X$

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15. Monochromatic light of wavelength 542 nm is incident on a single, narrow slit. On a screen 0.75 m away, the distance between the 2nd diffraction minimum and the central maximum is 1.50 cm. What is the width of the slit?

- ☐ Less than 20 μm
- ☐ Between 20 μm and 40 μm
- ■ Between 40 μm and 60 μm
- ☐ Greater than 60 μm

$p\lambda = \frac{a\Delta y}{L}$

$a = \frac{\lambda L}{\Delta y} = \frac{542\text{nm} \cdot 0.75\text{m}}{0.75\text{cm}} = 54\mu\text{m}$

16. The figure below shows the displacement $y(x = 0, t)$ for a transverse wave on a string. To one significant figure, what is the wave speed given the wavelength is $\lambda = 4$ cm?

- ■ 1 cm/s
- ☐ 2 cm/s
- ☐ 3 cm/s
- ☐ 4 cm/s
- ☐ 5 cm/s

$$v = \lambda f = \frac{4\text{ cm}}{4\text{ s}} = 1\text{ cm/s}$$