CAP High School/CEGEP Prize Exam

April 5, 2023

9:00 - 12:00

Student Information Sheet

The following information will be used to inform students and schools of the exam results, to determine eligibility for some subsequent competitions and for statistical purposes. Only the marking code, to be assigned by the local examination committee, will be used to identify papers for marking.

Marking Code:

This box must be left empty.

PLEASE PRINT CLEARLY IN BLOCK LETTERS

Student First Name																									
Student Last Name																									
Teacher Name																									

Address: (Street number and Apt) ____________________

(City and Province) ____________________ (Postal Code)__________

Telephone: (   ) ________________ Email: ________________

School: ____________________ Grade: __________

Date of Birth: ____________________

Gender: ________________ Citizenship: ________________

If you are not a Canadian citizen, what is your Immigration Status? ________________

For how many years have you studied in a Canadian school? ________________

Would you prefer further correspondence in French or English? ________________

By signing this page I agree that, if my score on this Exam is in the top 20 nationally or in the top 6 in my province, my name, my school's name, and my ranking can be published.

Student's signature: ____________________

Sponsored by:

Canadian Association of Physicists;
Canadian Physics Olympiad;
Department of Physics and Astronomy,
University of British Columbia.

2023 Canadian Association of Physicists Highschool/Cegep Prize Exam

This is a three-hour exam. National ranking and prizes will be based on students' performance on sections A and B of the exam. Performance on questions in section A will be used to determine whose written work in section B will be marked for prize consideration by the CAP Exam National Committee. Section A consists of 25 multiple-choice questions. The questions in section B span a range of difficulty, and may require graphing and/or measurement on the graph. Be careful to gather as many of the easier marks as possible before venturing into more difficult territory. When you are unable to solve any part of a question, you may assume a likely answer to that part and attempt the rest of the question anyway.
Non-programmable calculators may be used. Answer the multiple-choice questions ***on the answer sheet*** provided. Most importantly: write your solutions to the three long problems on ***three separate sheets*** as they will be marked by people in different parts of Canada. Good luck.
Notice: Full marks will be given to students who provide full correct solutions to problems in Section B. Partial marks will be given for partial solutions. There are no penalties for incorrect answers. The questions are not of equal difficulty. Remember that we are challenging the best physics students in Canada; it is possible that even the best papers may not achieve an overall score of 80%. This Exam is meant to be challenging!

Data

Speed of light $c = 3.00 \times 10^8$ m/s
Speed of sound in air = 343 m/s
Gravitational constant $G = 6.67 \times 10^{-11}$ N·m^2/kg^2
Acceleration due to gravity $g = 9.81$ m/s^2
Standard atmospheric pressure $P_0 = 1.01 \times 10^5$Pa
Density of fresh water $\rho = 1.00 \times 10^3$ kg/m^3
Density of ice $\rho_i = 916$ kg/m^3
Specific heat of water $C_w = 4186$ J/(kg·K)
Specific heat of ice $C_i = 2050$ J/(kg·K)
Latent heat of water $L_w = 2260$ kJ/kg
Latent heat of ice $L_i = 334$ kJ/kg
Fundamental charge $e = 1.60 \times 10^{-19}$ C
Mass of an electron $m_e = 9.11 \times 10^{-31}$ kg
Mass of a proton $m_p = 1.67 \times 10^{-27}$ kg
Planck's constant $h = 6.63 \times 10^{-34}$ J·s
1 eV $\approx 1.602 \times 10^{-19}$ J
Electrostatic constant $k = 1/4\pi\epsilon_0 = 8.99 \times 10^9 N \cdot m^2/C^2$
Permittivity of free space $\epsilon_0 = 8.854 \times 10^{-12}$ C^2/N·m^2
Boltzmann's constant $k_B = 1.38 \times 10^{-23}$ J/K
Stefan–Boltzmann constant $\sigma = 5.67 \times 10^{-8}$ W/m^2· K^4
Astronomical Unit (approximate distance from the Sun to the Earth) 1 AU = 1.49598×10^{11} m
Radius of the Earth $R_E = 6.371 \times 10^6$ m
Radius of the Sun $R_S = 6.96 \times 10^8$ m
Mass of the Earth 5.97×10^{24} kg
Mass of the Sun 1.99×10^{30} kg
H_2 Molar mass 2.016 g/mol
O_2 Molar mass 31.998 g/mol
N_2 Molar mass 28.013 g/mol

Section A

1) An aluminum wire of varying thickness is pulled at each end with a force of 30 N. Which of the following statements is true? Note: tension is a force that tends to stretch something, and stress is the force per unit area.

a) The tension is 60 N all along the wire, and stress is constant along the wire

b) The tension is 60 N all along the wire, and stress varies along the wire

c) The tension is 30 N all along the wire, and stress is constant along the wire

d) The tension is 30 N all along the wire, and stress varies along the wire

2) A 1kg object slides 3.6 m down a ramp with a 35° slope. It has an initial speed of 2 m/s and a final speed of 1.06 m/s when it reaches the bottom. What was the work done by kinetic friction ($\mu_k = 0.3$) when the object has slid to the bottom of the ramp?

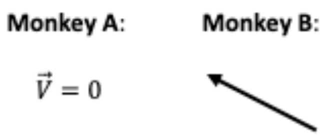
a) 10.6 Nm

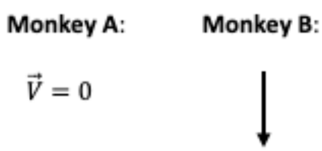
b) 21.7 Nm

c) 0 Nm

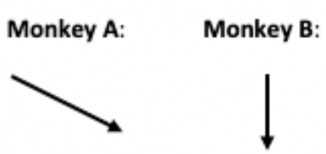
d) 19.6 Nm

3) After swinging on a vine in the jungle, monkey A releases the vine and simultaneously drops his banana. Monkey B is stationary on the ground below, watching intently. Immediately after the banana is dropped, what is the direction of the velocity of the banana from each monkey's frame of reference?

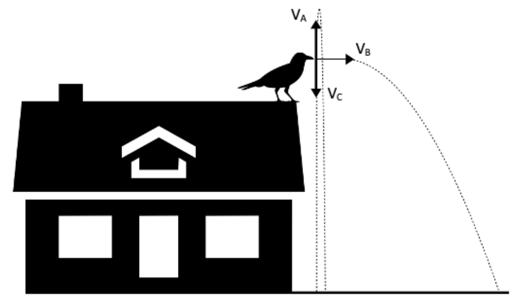
a) 

b) 

c) 

d) 

4) A very smart bird is sitting on a roof holding a shell in its beak. It wants to throw the shell so that it hits the ground with the highest speed possible. Assuming air resistance is negligible, and initial speed is constant in all scenarios ($v_A = v_B = v_c$), how should the bird throw the shell so that its final speed before hitting the ground is greatest?



a) Throw it upwards (v_A)

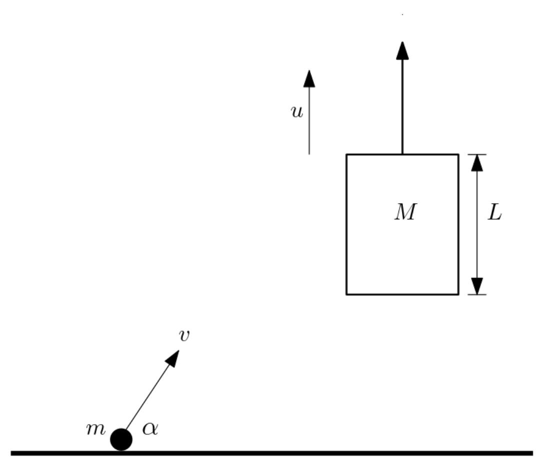
b) Throw it horizontally (v_B)

c) Throw it downwards (v_C)

d) A and C produce a faster final speed than B

e) A, B, and C all produce the same final speed

5) A very heavy box of mass M is being lifted upwards by a crane at a constant velocity u. A ball of mass $m \ll M$ is thrown at the box with velocity v at angle α.



If the ball hits the box at some time t, what are the x and y components of the velocity of the ball $(v_x(t), v_y(t))$ after the collision? Assume a perfectly elastic collision.

a) $(-v\cos\alpha,\ |v\sin\alpha - gt|)$

b) $(-v\cos\alpha, -|v\sin\alpha - gt|)$

c) $(-v\cos\alpha,\ 2u + |v\sin\alpha - gt|)$

d) $(-v\cos\alpha,\ 2u - |v\sin\alpha - gt|)$

e) Either a or b.

f) Either c or d.

6) A sphere of mass 0.2 kg is suspended from the ceiling by a light spring whose force constant is 3.2 N/m. It is projected vertically downwards with a speed of 0.5 m/s from its equilibrium position. What would be its maximum acceleration in subsequent motion?

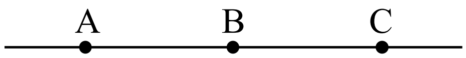
a) 2.0 m/s

b) 8.0 m/s

c) 10.0 m/s

d) 12.0 m/s

7)



A block accelerates uniformly along a straight line from A to C as shown above. Its speed at point A is v_A and that at point C is v_C. What is its speed at point B, which is the mid-point between point A and C?

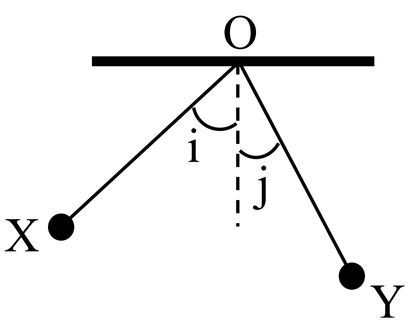
a) $\frac{2v_A v_C}{v_A+v_C}$

b) $\frac{v_A+v_C}{2}$

c) $\sqrt{\frac{v_A^2+v_C^2}{2}}$

d) $\sqrt{v_A v_C}$

8) Two charged spheres X and Y are suspended from the ceiling by identical strings as shown below. When the system is in equilibrium, the angles between string OX and the vertical is i and that between OY and the vertical is j. If $i > j$, which of the following statement must be correct?



a) Both X and Y carry positive charges.

b) The charges on X and Y are opposite.

c) The magnitude of charges on Y is greater than that on X.

d) The mass of Y is larger than that of X.

9) When two ends of a circular uniform wire are joined to the terminals of a battery, what is the strength of the magnetic field at the center of the circle?

a) Zero

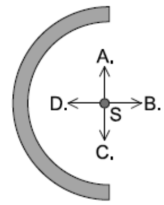
b) Infinite

c) Depends on the amount of e.m.f. applied

d) Depends on the radius of the circle

e) Both c and d.

10) Negative charge is uniformly distributed on a semi-circular plastic rod. What is the direction of the electric field strength at point S?



a) A

b) B

c) C

d) D

11) Suppose that a positron (charge $+e$, mass m_e) is fired at a non-relativistic velocity v_0 towards a proton (charge $+e$, mass m_p) at rest. What is the minimum separation between the two particles as they approach each other?

a) $\frac{e^2}{2\pi\epsilon_0 m_e v_0^2}$

b) $\frac{e}{2\pi\epsilon_0 m_e v_0^2}$

c) $\left(\frac{e^2}{2\pi\epsilon_0 m_e v_0^2}\right)^{1/2}$

d) $\frac{e^2}{2\pi\epsilon_0 v_0^2}\frac{m_e+m_p}{m_e m_p}$

12) An electron enters the space inside an infinite current-carrying solenoid. The velocity of the electron is parallel to the solenoid's axis. The electron will:

a) Deflect outwards

b) Slow down

c) Speed up

d) Stay parallel to the axis of the solenoid

13) An ion follows a circular path in a uniform magnetic field. Which single change increases the radius of the path?

a) Decrease the mass of the ion

b) Decrease the charge of the ion

c) Decrease the speed of the ion

d) Increase the magnetic flux density of the field

14) The number of field lines crossing a given area is given by the electric flux. For a closed surface (like a cube or sphere) the total electric flux is given by Gauss's law:

$$\text{Electric flux through a closed surface} = Q/\epsilon_0, \qquad (1)$$

where Q is the net charge *inside* the closed surface. A point charge $Q = 24q$ is placed somewhere inside a cube. The electric flux through the bottom surface of the cube is measured to be $\phi = \frac{3.98q}{\varepsilon_0}$. What is the approximate location of the charge?

a) Slightly off center.

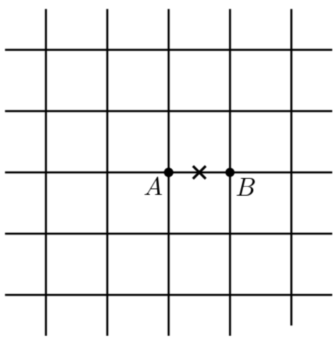
b) Slightly off center, towards the top surface.

c) Slightly off center, towards the bottom surface.

d) Far from the center, closer to the bottom surface.

e) At the center of the cube.

15)



Consider an *infinite* grid made of identical wires of resistance 1 Ω. The equivalent resistance between two adjacent points A and B is R_{AB}. If the wire connecting A and B (marked with x) is cut, R_{AB}:

a) will increase.

b) will decrease.

c) will not change.

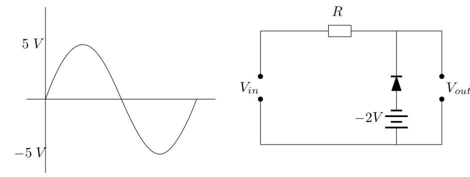
d) will become zero.

e) will become infinity.

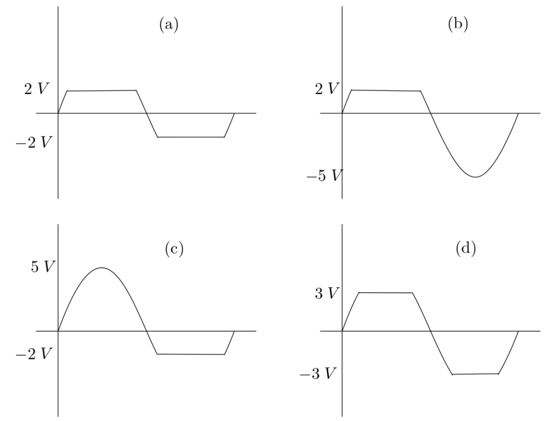
f) can not be determined.

16) A diode conducts current only when the potential of point A is higher than the potential of point B, otherwise it doesn't allow the current to pass. When it conducts, the voltage drop across an ideal diode is zero.

Consider a circuit with an ideal diode as shown below. The input voltage V_{in} is shown on the left.



What is the output voltage V_{out}?



a) a

b) b

c) c

d) d

17) One mole of an ideal gas ($C_p = 5R/2$) in a closed cylindrical piston is expanded from $T_i = 300$ K, $P_i = 0.5$ MPa to $P_f = 0.1$ MPa by an adiabatic pathway. The energy supplied to the system ΔQ, change in internal energy ΔU, and work done by the gas ΔW are:

a) ΔU=0 J, ΔQ=4014 J, ΔW =-4014 J

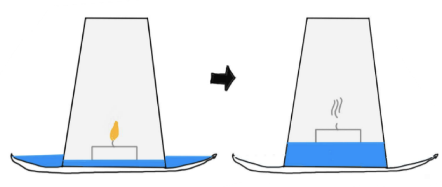
b) ΔU=-4270 J, ΔQ=0 J, ΔW =4270 J

c) ΔU=4270 J, ΔQ=0 J, ΔW =-4270 J

d) ΔU=-5487 J, ΔQ=0 J, ΔW =-5487 J

e) ΔU=-5487 J, ΔQ=-5487 J, ΔW =0 J

18) A plate is filled with a layer of water and a lit candle is placed in the centre. A cup is overturned and placed to fully cover the candle. The flame is extinguished, and the cup seems to 'drink the liquid' — the water is sucked from the plate into the cup.



Recall that $PV = nRT$. Which of the following explains why the cup sucks up the liquid?

a) T decreases so V decreases

b) P decreases so V decreases

c) n decreases so V decreases

d) n decreases so P decreases

e) T decreases so P decreases

19) An ideal gas goes through a process such that

$$PV^3 = \text{const.}$$

If the volume doubles during this process the temperature:

a) remains constant.

b) increases four-fold.

c) decreases four-fold.

d) increases eight-fold.

e) decreases eight-fold.

20) The temperature of a gas is increased by the same amount in two difference processes.

Process A: The volume is kept constant.
Process B: The pressure is kept constant.

Which of the following is correct?

a) The heat required in process A is greater.

b) The heat required in process B is greater.

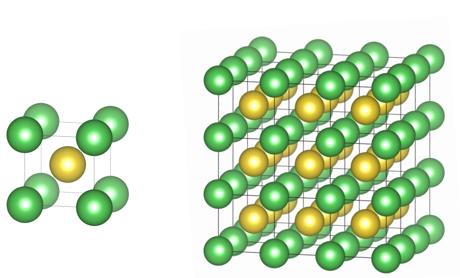
c) The same heat is required in both cases.

d) The change in entropy is the same for both processes.

e) The change in internal energy is the same for both processes.

f) c, d and e.

21) Sodium has a crystal structure (right) which can be thought of as a repetition of a *unit cell* shown on the left. The different colors just represent different relative positions in the unit cell.



Given that sodium's unit cell is a cube with edge $a = 0.428$ nm and its atomic weight is 23 g/mol, what is the density of sodium?

a) 0.47 g/cm^3

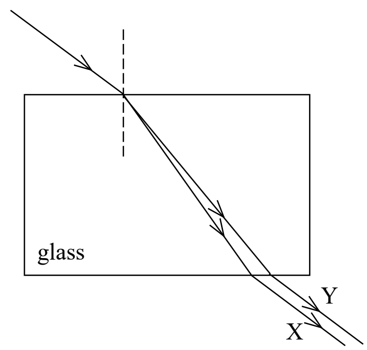
b) 0.94 g/cm^3

c) 1.41 g/cm^3

d) 4.23 g/cm^3

22) A light beam with two monochromatic components X and Y passes into a glass block and splits into two monochromatic beams when it comes out of the glass block. If the frequency of component X is smaller than that of Y, which of the following ray diagrams is correct?

a)



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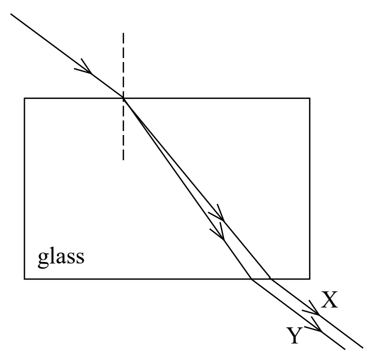
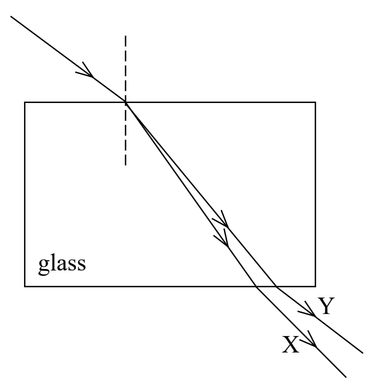
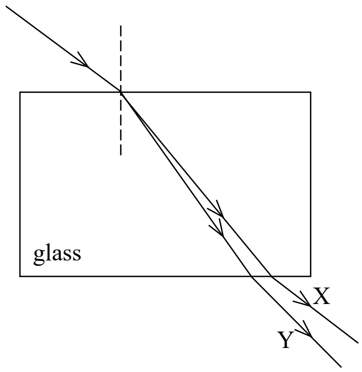


c)



d) 

23) A photocell emits electrons when it is illuminated with green light. We are uncertain whether it emits electrons when it is illuminated with:

a) ultra-violet radiation

b) X-rays

c) red light

d) blue light

24) One of the two slits in a Young's experiment is painted over so that it transmits only one-half the intensity of the other slit. As a result:

a) The fringe system disappears

b) The bright fringes get brighter and the dark ones get darker

c) The bright fringes get dimmer

d) The dark fringes get brighter

e) The dark fringes get brighter and the bright ones get darker

25) A double slit system is located in water ($n_w = 1.33$). What is the approximate spacing between two bright fringes? Assume that $R \gg d$ and that λ is the wavelength in vacuum.

a) $\frac{\lambda d}{R n_w}$

b) $\frac{\lambda R n_w}{d}$

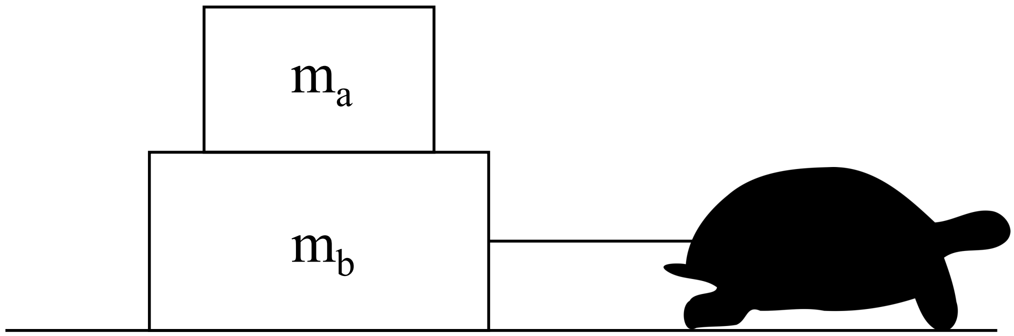
c) $\frac{\lambda R}{d n_w}$

d) $\frac{\lambda R}{d}$

End of Section A

Section B starts on next page

1)



A turtle is pulling two stacked boxes as shown in the above figure. The string attached to the bottom box is parallel to the ground. The mass of the bottom box is m_b and that of the top box is m_a. The tension in the string is T. The coefficient of static friction between the bottom box and the ground is μ_b and that between the two boxes is μ_a. Find the range of T with sufficient justification and mathematical reasoning when:

a) two boxes are static

b) the bottom box is moving relative to the ground with the box on top resting on it

c) the bottom box is moving relative to the ground but there is also relative motion between the top and the bottom box

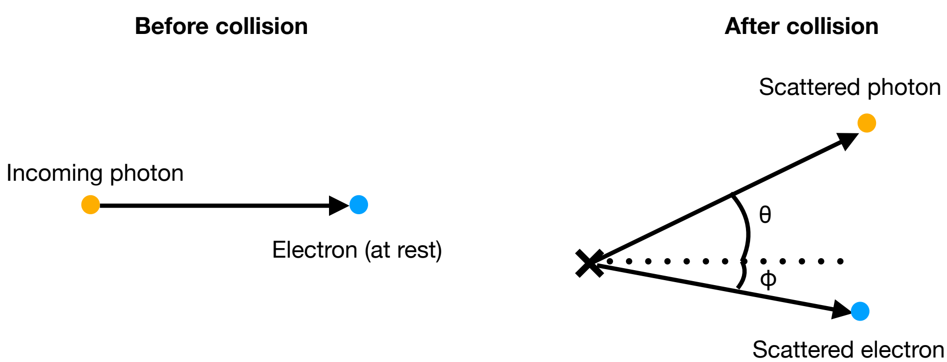
2)

A linear accelerator is a machine used to deliver radiation therapy to cancer patients. It shoots very precise beams of high energy photons into the patient's body, and those photons interact with electrons and atoms in the cancer cells to kill it. There are several different ways a photon can interact with electrons and atoms. In this question, we're going to explore a Compton interaction between a photon and an electron. Historically accepted relativistic equations are provided[1].

The electron is originally at rest, has a mass m_o and energy m_oc^2. An incoming photon with energy $\frac{hc}{\lambda}$ and momentum $\frac{h}{\lambda}$, where λ is the wavelength of the photon, collides with this electron and transfers some of its energy, which causes the electron and the photon to scatter in different directions. The ejected electron is now travelling at speed v and has a mass $m = \frac{m_o}{\sqrt{1-\frac{v^2}{c^2}}}$ and energy mc^2.

Derive an equation that relates the wavelength (λ) of the incoming photon with the wavelength (λ') of the outgoing scattered photon and its scattering angle (θ).

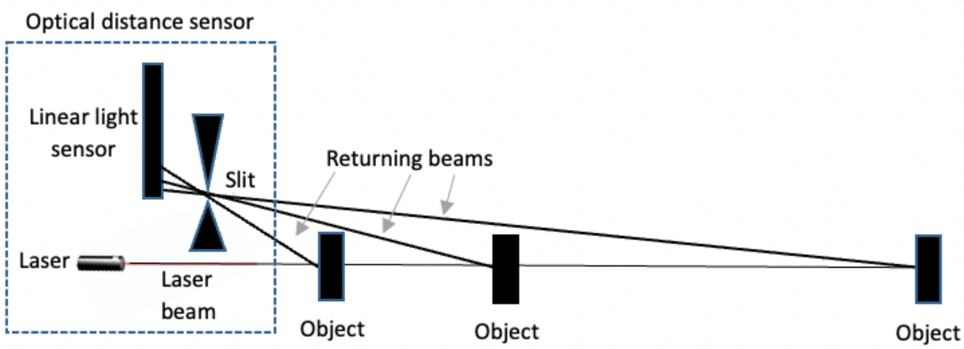
Hint: $sin^2\theta + cos^2\theta = 1$



[1] It is important to note that the historically accepted equations for the relativistic mass of an electron that are provided here are not properly correct. They imply that mass changes with velocity, when in fact mass is invariant. The proper equations of relativistic mass are much more complex and are not needed to solve this problem; the correct solution can be found with the equations provided.

3)

One way of measuring distance using optics is to send a laser beam to the object and measure the angle the scattered light makes with the original beam as shown below:



The components inside the dashed line box form the optical distance sensor. The vertical rectangle represents a linear light sensor, which measures the point of impact of the returning beam. The three lines indicate light rays reflected from objects at different distances.

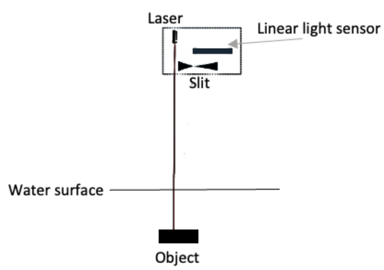
The linear sensor is 9 mm long and consists of one line of 600 pixels spaced 15 μm apart.

The slit for the returning beam is 20 μm wide and is located 5 mm above the laser beam and 2 mm away from the linear sensor. The last pixel of the linear light sensor, the one closest to the laser beam is 15 μm above the slit.

What is the shortest and longest distance this sensor can measure in air?

If we want to measure the distance to an object underwater, two pixels of the linear sensor will be activated: one corresponding to the laser scattering off the water surface and one corresponding to the laser scattering off the object. Explain how one can use these two readings to get the proper distance to the object underwater.

Start with the case when the laser beam is perpendicular to the water surface:



Question 1	a	b	c	d	e	f
Question 2	a	b	c	d	e	f
Question 3	a	b	c	d	e	f
Question 4	a	b	c	d	e	f
Question 5	a	b	c	d	e	f
Question 6	a	b	c	d	e	f
Question 7	a	b	c	d	e	f
Question 8	a	b	c	d	e	f
Question 9	a	b	c	d	e	f
Question 10	a	b	c	d	e	f
Question 11	a	b	c	d	e	f
Question 12	a	b	c	d	e	f
Question 13	a	b	c	d	e	f
Question 14	a	b	c	d	e	f
Question 15	a	b	c	d	e	f
Question 16	a	b	c	d	e	f
Question 17	a	b	c	d	e	f
Question 18	a	b	c	d	e	f
Question 19	a	b	c	d	e	f
Question 20	a	b	c	d	e	f
Question 21	a	b	c	d	e	f
Question 22	a	b	c	d	e	f
Question 23	a	b	c	d	e	f
Question 24	a	b	c	d	e	f
Question 25	a	b	c	d	e	f