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Department of Physics and
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**2024 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·m²/kg²
Acceleration due to gravity $g = 9.81$ m/s²
Standard atmospheric pressure $P_0 = 1.01 \times 10^5$ Pa
Density of fresh water $\rho = 1.00 \times 10^3$ kg/m³
Density of ice $\rho_i = 916$ kg/m³

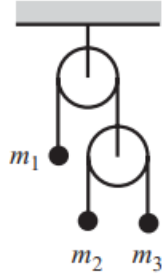
Specific heat of water $C_w = 4186$ J/(kg·K)
Specific heat of ice $C_i = 2050$ J/(kg·K)
Latent heat of water $L_w = 2260$ kJ/kg
Latent heat of ice $L_i = 334$ kJ/kg
Fundamental charge $e = 1.60 \times 10^{-19}$ C
Mass of an electron $m_e = 9.11 \times 10^{-31}$ kg
Mass of a proton $m_p = 1.67 \times 10^{-27}$ 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·m²/C²
Permittivity of free space $\epsilon_0 = 8.854 \times 10^{-12}$ C²/N·m²
Boltzmann's constant $k_B = 1.38 \times 10^{-23}$ J/K
Stefan-Boltzmann constant $\sigma = 5.67 \times 10^{-8}$ W/m²·K⁴
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
H₂ Molar mass 2.016 g/mol
O₂ Molar mass 31.998 g/mol
N₂ Molar mass 28.013 g/mol

Section A

- Black holes have a very strong gravitational field from which nothing can escape, including light. Approximately, what is the radius of a black hole having mass equal to the sun?
Hint: Use Newtonian mechanics.
 - 1.5 km.
 - 3 km.
 - 15 km.
 - 30 km.
 - The mass is too small to be a black hole.
- Surface tension is defined as the force per unit length acting on the surface of a liquid. Due to the presence of it, the surface of a liquid can be thought of having a "stretchy" property like a piece of rubber. Assume that a soap bubble of radius R has a surface tension T . What is the difference in pressure between the pressure inside the bubble and the atmospheric pressure?
 - $\frac{T}{2R}$
 - $\frac{T}{R}$
 - $\frac{2T}{R}$

- D. $\frac{4T}{R}$
 E. $\frac{8T}{R}$

3. Consider the setup below.



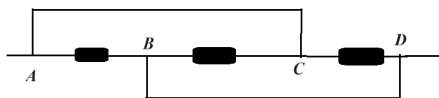
Let a_1, a_2, a_3 be the accelerations of m_1, m_2, m_3 respectively. Which of the following is true?

- A. $a_1 = -\frac{1}{2}(a_2 + a_3)$
 B. $a_1 = -\frac{1}{2}(a_2 - a_3)$
 C. $a_1 = \frac{1}{2}(a_2 + a_3)$
 D. $a_1 = a_2 + a_3$
 E. $a_1 = a_2 - a_3$
 F. $a_1 = -(a_2 + a_3)$
4. A ring of radius r is given an initial velocity v_0 . The ball slides for a little while and then starts to roll. What's the velocity of the ball when it rolls without slipping?
- A. $0.5v_0$
 B. v_0
 C. $1.5v_0$
 D. $2.5v_0$
 E. $3.5v_0$
5. The speed of a falling raindrop is 10 m/s. The weather forecast predicts 10mm of rain in the next hour. If you go out with an umbrella of radius 70 cm, approximately what is the force of the rain hitting your umbrella?
- A. 0.0002 N
 B. 0.0004 N
 C. 0.002 N
 D. 0.004 N
 E. 0.02 N
 F. 0.04 N

6. A kitchen towel hangs off a table. The coefficient of friction between towel and table is μ . What is the maximum fraction of the towel that can hang before the towel falls?
- A. $\frac{\mu}{1+\mu}$
 B. $\frac{\mu}{1-\mu}$
 C. $\frac{1-\mu}{\mu}$
 D. $\frac{\mu}{2+\mu}$
7. Neglecting air resistance, a baseball player on Earth can throw a baseball a distance of 100 m. If gravity is 5 times weaker on the moon, how far could he throw the ball if he were on the moon?
- A. 20 m
 B. 100 m
 C. 500 m
 D. 2500 m
8. You live on the 20th floor of a building with two elevators, A and B, of the same mass. To go to floor 20, elevator A accelerates for the first 10 floors, then decelerates for the last 10. Meanwhile elevator B accelerates for 5 floors, moves at a constant speed for 10 floors, then decelerates for 5 floors. Both elevators complete the trip in the same amount of time. You are environmentally conscious, so you want to take the elevator which uses the least electricity. Assume friction in the motors and air drag are negligible. Which elevator should you take?
- A. Elevator A.
 B. Elevator B.
 C. Both elevators use the same amount of electricity.
 D. Can't say without more information.
9. A mass hangs from the ceiling, held up by two springs in series. The upper spring has spring constant k_1 , and the bottom spring has spring constant k_2 . If the mass is displaced from equilibrium by a small amount x , it has a maximum speed v . If instead the mass is displaced by $x/2$, what is the maximum speed?
- A. $\frac{1}{4}v$
 B. $\frac{1}{2}v$
 C. v
 D. $\frac{k_1+k_2}{2\sqrt{k_1k_2}}v$
 E. $\frac{k_1-k_2}{2\sqrt{k_1k_2}}v$
 F. $\frac{|k_1-k_2|}{2\sqrt{k_1k_2}}v$

10. A car is speeding up as it goes in a circle. When it is at the northernmost point of the circle, what are the possible directions for its acceleration.
- Exactly north
 - Between north and west
 - Between north and east
 - Exactly south
 - Between south and west
 - Between south and east
11. A regular n -gon is a polygon with n equal edges as well as equal angles. Positive charges each of magnitude q sit on the corners of a regular 2024-gon. The distance from each charge to the center of the 2024-gon is a . If one of the charges is removed, what is the magnitude and the direction of electric field at the center?
- $\frac{q}{4\pi\epsilon_0 a^2}$, directed away from the removed charge.
 - $\frac{q}{4\pi\epsilon_0 a^2}$, directed towards the removed charge
 - $\frac{1}{2024} \frac{q}{4\pi\epsilon_0 a^2}$, directed away from the removed charge.
 - $\frac{1}{2024} \frac{q}{4\pi\epsilon_0 a^2}$, directed towards the removed charge
 - $\frac{1}{2023} \frac{q}{4\pi\epsilon_0 a^2}$, directed away from the removed charge.
 - $\frac{1}{2023} \frac{q}{4\pi\epsilon_0 a^2}$, directed towards the removed charge

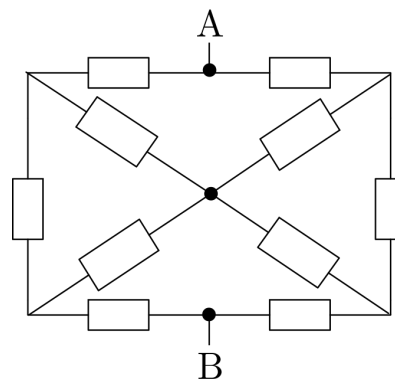
12. In the circuit below each resistor has equal resistance.



Where should a battery be connected so that each resistor has voltage equal to the emf of the battery?

- Between A and B
- Between B and C
- Between C and D
- Between A and C
- Between B and D
- Between A and D

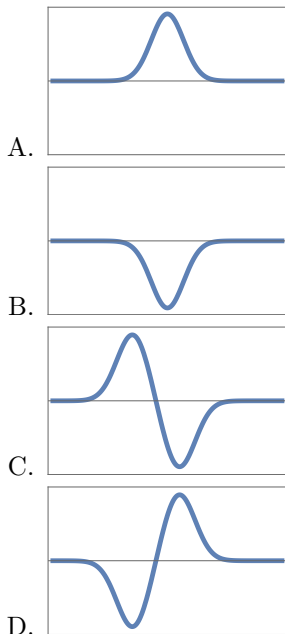
13. An electron with an initial velocity v enters a uniform magnetic field making an angle α with the magnetic field B . It then hits a screen located at a distance D from the entrance point. Assuming $0 < \alpha < 90^\circ$, which of the following statement is true?
- The time to hit the screen increases if B increases.
 - The time to hit the screen increases if B decreases.
 - The time to hit the screen increases if α increases
 - The time to hit the screen increases if α decreases.
 - The time to hit the screen is independent of α .
14. In the following circuit, each resistor has resistance $1\ \Omega$. Find the equivalent resistance of the circuit between point A and B.



- $\frac{3}{2}\ \Omega$
- $\frac{6}{2}\ \Omega$
- $\frac{4}{3}\ \Omega$
- $\frac{8}{3}\ \Omega$
- None of these.

15. Wires A and B lie in the $x - y$ plane. The wires carry equal currents in the same direction. A charged particle passes precisely between the two wires, heading in the $+\hat{z}$ direction. What happens to the velocity \vec{v} of the particle over time?
- The direction and magnitude change.
 - The direction changes but the magnitude remains constant.
 - The direction remains constant but the magnitude changes.
 - The direction and magnitude both remain constant.

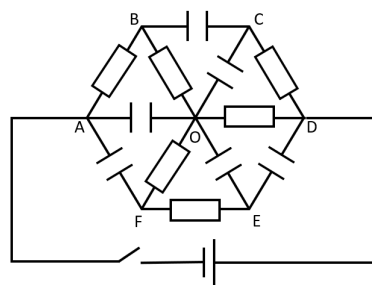
16. A permanent magnet is dropped north-first through a conducting loop. Which diagram could represent the current in the loop as a function of time? (A positive value indicates a clockwise current, and a negative value a counterclockwise current, when viewed from above.)



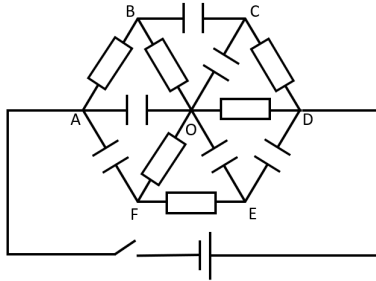
17. Two charges A and B are held at a fixed distance apart. A material M is placed between the charges, where M is either a block of aluminum or a block of rubber. M does not touch the charges. What happens to the magnitude of the electromagnetic force on charge A as a result of the presence of the material?
- A. Decreases substantially for both materials.
 B. Increases substantially for both materials.
 C. Remains approximately the same for both materials.
 D. Increases for one material, decreases for the other.
 E. Increases for one material, remains same for the other.
 F. Decreases for one material, remains same for the other.
18. Two permanent magnets A and B are held at a fixed distance apart. A material M is placed between the magnets, where M is either a block of aluminum or a block of rubber. M does not touch the magnets. What happens to the magnitude of the electromagnetic force on magnet A as a result of the presence of the material?

- A. Decreases substantially for both materials.
 B. Increases substantially for both materials.
 C. Remains approximately the same for both materials.
 D. Increases for one material, decreases for the other.
 E. Increases for one material, remains same for the other.
 F. Decreases for one material, remains same for the other.

19. In the circuit below, all resistors are identical with resistance R and all capacitors are identical with capacitance C . A battery with voltage V is connected between points A and D. Initially, the switch is opened and all of the capacitors are uncharged. Which of the following options is true right after the switch is closed? Assume the internal resistance of the battery is negligible.



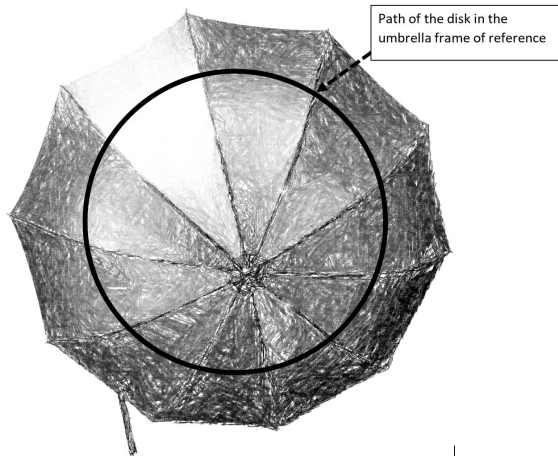
- A. Most of the current only flows through all resistors.
 B. Most of the current only flows through resistors AB, FE, and CD.
 C. Most of the current only flows through resistors OB, OF, and OD.
 D. Almost no current flows through any resistor.
20. In the circuit below, all resistors are identical with resistance R and all capacitors are identical with capacitance C . A battery with voltage V is connected between points A and D. Initially, the switch is opened and all of the capacitors are uncharged. Which of the following options is true a long time after the switch is opened? Assume the internal resistance of the battery is negligible.



- A. Most of the current only flows through all capacitors.
- B. Most of the current only flows through resistors OF, FE, and OD.
- C. Most of the current only flows through resistors AB, OB, and OD.
- D. Almost no current flows through any capacitors.
21. One mole of an ideal gas inside an engine goes through a process labelled by $1 \rightarrow 2 \rightarrow 3 \rightarrow 1$. The Volume vs Temperature graph during this process is shown below.
-
- Consider the following statements:
- Work done by the gas during $2 - 3$ is zero.
 - The pressure during $3 - 1$ is constant.
 - The total work done by the gas during $1 - 2 - 3 - 1$ is zero.
- Which of these statements is/are true?
- A. i
- B. ii
- C. iii
- D. i and ii
- E. ii and iii
- F. i, ii and iii
22. How does increasing the pressure affect the freezing temperature T_f and boiling temperature T_b of most liquids?
- A. It decreases T_f and T_b .
- B. It increases T_f and T_b .
- C. It decreases T_f and increases T_b .
- D. It increases T_f and decreases T_b .
23. The gas in the Earth's atmosphere is more dense closer to the Earth's surface. Based on this fact, where do you expect the sun to be when you look directly at it? (Assume the sun isn't directly above you.)
- A. Slightly higher than it appears
- B. Slightly lower than it appears
- C. Slightly right of where it appears
- D. Slightly left of where it appears
24. You want to magnify an ant using a magnifying glass with a focal length of 20 cm. How far should you place your magnifying glass from the ant?
- A. Less than 20 cm
- B. Approximately 20 cm
- C. More than 20 cm
- D. It depends on other factors
25. Two very large mirrors intersect each other at the right angle. Suppose, you are standing at an equal distance from each mirror. How many images of yourself will you see in the mirrors?
- A. 2
- B. 3
- C. 4
- D. 5
- E. More than 5

Section B

1. The juggler in the photograph rotates the umbrella in such a way that the disk rolling on the umbrella stays in the same place in the room reference frame, as shown:



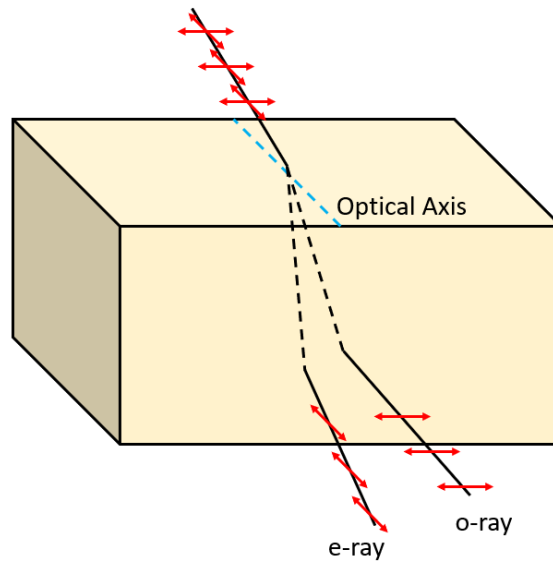
- a. The *coefficient of a rolling friction* C is a property of a rolling object and the surface on which it rolls. It is defined by the equation $F = CN$, where F is the magnitude of the applied force required for the object to roll at a constant velocity, and N is the magnitude of the normal force of the object relative to the surface. Make appropriate measurements on the photo and some approximations to figure out what is the coefficient of rolling friction of the disk over the umbrella material.
- b. Using the photo can you determine the angular velocity of the rotation of the umbrella?

2. Birefringence is an optical phenomena where a birefringent crystal refracts light in two different directions, resulting in the separation of a single incident light beam into two polarized rays with different refractive indices (n_o and n_e). These two rays are often called the ordinary ray (o-ray) and the extraordinary ray (e-ray). Each ray travels through the crystal at a different speed.

Part 1: Refraction from a birefringent crystal

When an electromagnetic wave propagates in a medium with a refractive index n , the change in oscillation phase after going through a distance d can be expressed as follows.

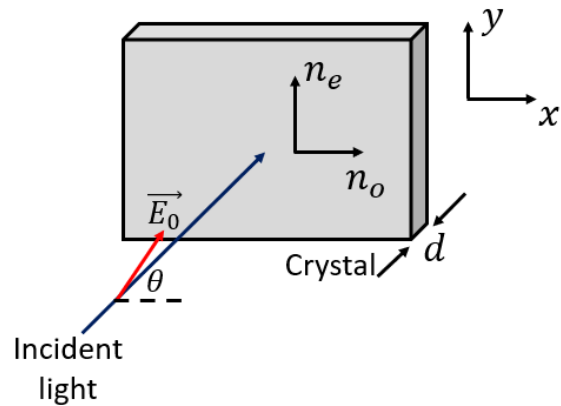
$$\phi = \frac{2\pi nd}{\lambda}$$



- a. Suppose we have a birefringent crystal with thickness d . If a beam of light with a wavelength of λ propagates through the crystal, express the phase difference between the ordinary and extraordinary ray, ϕ , in terms of λ , n_e , n_o , and d .

A beam of linearly polarized polychromatic light, whose electric field's vector makes an angle $\theta = 45^\circ$ with the x-axis, falls normally on a crystal. The refractive index for the electric field component in the x-direction is $n_o = 2.647$, and the refractive index for the electric field component in the y-direction is $n_e = 2.693$.

- b. Write down the conditions for the phase difference, ϕ , that causes the transmitted light to have:



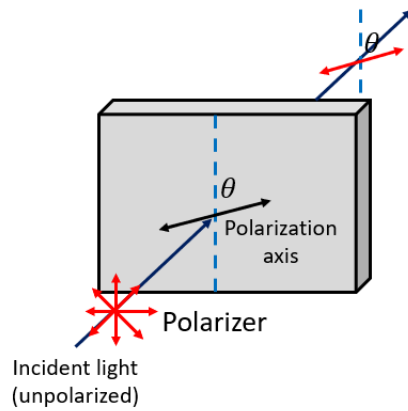
- i. Maximum intensity
 - ii. Minimum intensity
- c. It is known that the wavelengths for three primary colors are:
- $\lambda_{\text{red}} = 680 \text{ nm}$
 - $\lambda_{\text{green}} = 530 \text{ nm}$
 - $\lambda_{\text{blue}} = 470 \text{ nm}$

Find the minimum thickness of the crystal, so that the transmitted light:

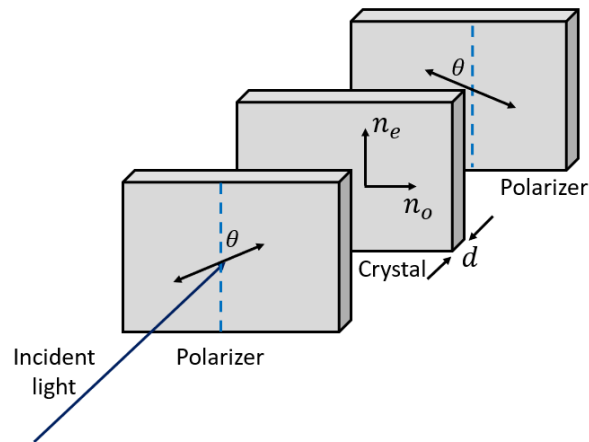
- i. Appears blue.
- ii. Appears yellow.

Part 2: Birefringent crystal and polarizers

A polarizer is an optical device that transmits electromagnetic waves with a particular orientation. For example, a linear polarizer at θ will selectively transmit the component of light oriented at θ as illustrated in the figure below.

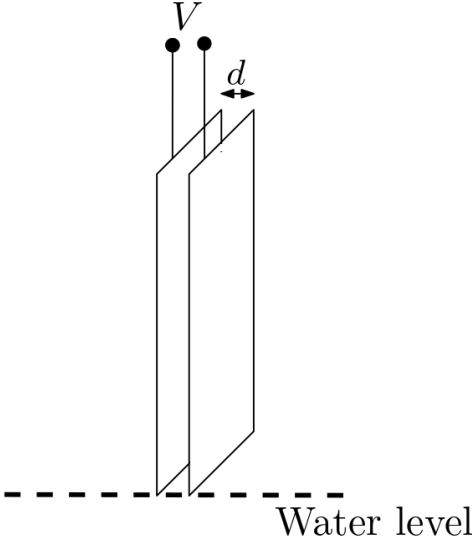


Now, our birefringent crystal is placed between two linear polarizers. The first (front) polarizer is aligned $\theta = 45^\circ$ clockwise with respect to the y-axis, while the second (rear) one is aligned $\theta = 45^\circ$ counter-clockwise with respect to the y-axis as shown in the figure below. An unpolarized light propagates normally to the first polarizer.



- d. Write down the conditions for the phase difference, ϕ , that causes the transmitted light to have:
 - i. Maximum intensity
 - ii. Minimum intensity
- e. Find the minimum thickness of the crystal, so that the transmitted light:
 - i. Appears blue.
 - ii. Appears yellow.

3. Two uncharged $10\text{cm} \times 10\text{cm}$ metal plates, separated by a distance $d = 1\text{ mm}$ are just touching the surface of water as shown in the figure. The electric permittivity of water is 10 times than that of the air. If a constant voltage difference of $V = 600\text{V}$ is applied to the plates, determine how much the water rises inside the plates.



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