Harvard Undergraduate Science Olympiad 2025

Final Round

Physics Syllabus: 9th-10th Grade

Reference Material: You will be provided with a list of fundamental constants that may be useful during the exam. Any formulas that you are not expected to know will be given in relevant questions.

Format: Students are allowed a non-programmable, non-graphing calculator for the physics exam. The exam will be 1.5 hours and will consist primarily of multiple choice questions, but may also contain free-response explanation and calculation questions. Multiple choice questions are graded +1 pt for a correct answer and -0.25 for an incorrect answer. No justification needed for the multiple choice part. Free-response questions require all work to be shown and will be given partial credit for answers making progress towards a full solution. All free-response problems are weighted the same.

Potential Topics Covered on the Exam:

Please note that not necessarily every topic on this list will be on the exam, don't get overwhelmed! The syllabus is meant to be exhaustive of all *potential* topics that could be on the exam. A great place to start is with making sure you're comfortable with the ICSE curriculum for 9th–10th grade. It will be a difficult exam, but remember you don't need to (nor do we expect you to) get a 100%! Just do your best and show us all that you've learned! Good luck and happy studying!

The final round exam will broadly cover two main subjects: **Mechanics**, **Electromagnetism**, and **Thermodynamics**. More specific topics will be listed below. It is expected that fundamental knowledge (such as concepts and formulas) from these topics will be known, and will not be provided in the exam. Formulas and constants that will be provided in the exam are in the reference sheet at the back of this syllabus.

Part A Multiple Choice

A1) Atwood machine (dynamics). Two masses m and $2m$ hang over a light, frictionless pulley. Neglect the pulley mass and axle friction. What is the magnitude of the acceleration of the system?

(a) $\dfrac{g}{3}$

(b) $\dfrac{g}{2}$

(c) $\dfrac{2g}{3}$

(d) g

A2) Energy with friction + spring. A block of mass m slides into a spring of constant k placed on a rough horizontal surface with kinetic friction coefficient μ_k. The block enters the spring region with speed v_0 and compresses the spring a maximum distance x before coming to rest momentarily. Which equation correctly determines x?

(a) $\frac{1}{2}mv_0^2 = \frac{1}{2}kx^2$

(b) $\frac{1}{2}mv_0^2 = \frac{1}{2}kx^2 + \mu_k mgx$

(c) $\frac{1}{2}mv_0^2 + \mu_k mgx = \frac{1}{2}kx^2$

(d) $\frac{1}{2}kx^2 = \mu_k mgx$

A3) Torque & angular acceleration. A uniform rod of mass m and length L pivots about one end in a vertical plane. It is initially horizontal and released from rest. What is the magnitude of its *initial* angular acceleration?

(a) $\dfrac{3g}{2L}$

(b) $\dfrac{g}{L}$

(c) $\dfrac{2g}{3L}$

(d) $\dfrac{3g}{L}$

A4) Conservation of angular momentum. A skater with moment of inertia I spins at angular speed ω. She pulls in her arms so her moment of inertia becomes $I/2$, with no external torque. What is her new angular speed?

(a) $\omega/2$

(b) ω

(c) 2ω

(d) 4ω

A5) SHM energy fraction. A mass executes simple harmonic motion with amplitude A. At displacement $x = A/2$, what fraction of the total mechanical energy is kinetic energy?

(a) $\dfrac{1}{4}$

(b) $\dfrac{1}{2}$

(c) $\dfrac{3}{4}$

(d) 1

A6) Escape speed scaling. The escape speed from a planet is $v_e = \sqrt{\dfrac{2GM}{R}}$, where M is the planet's mass and R is its radius. A planet has the *same density* as Earth but *twice* Earth's radius. How does its escape speed compare to Earth's?

(a) same

(b) $\sqrt{2}$ times larger

(c) 2 times larger

(d) $2\sqrt{2}$ times larger

A7) RC transient. A capacitor of capacitance C discharges through a resistor R from an initial voltage V_0. How long does it take for the capacitor voltage to drop to $V_0/2$?

(a) $RC/2$

(b) $RC \ln 2$

(c) $2RC$

(d) $RC/\ln 2$

A8) Thermodynamics: adiabatic ideal gas. For a reversible adiabatic process in an ideal gas, which relation is true?

(a) $PV = \text{const}$

(b) $PV^\gamma = \text{const}$

(c) $PT = \text{const}$

(d) $V^\gamma T = \text{const}$

A9) Entropy sign. A hot object at temperature T_h transfers heat Q to a cold object at temperature $T_c < T_h$, and the combined system is isolated. What is the sign of the total entropy change ΔS_{total}?

(a) 0

(b) negative

(c) positive

(d) depends on the masses of the objects

A10) Special relativity: time dilation. A spaceship moves at speed $0.6c$ relative to Earth. A clock on the ship measures $10\,\text{s}$ between two events that occur at the same place in the ship's frame. How much time elapses between these events according to Earth?

(a) $6\,\text{s}$

(b) $8\,\text{s}$

(c) $10\,\text{s}$

(d) $12.5\,\text{s}$

A11) Rotating rod. A rod of mass m, uniform density, and length ℓ rotates in a horizontal plane about a vertical axis through one end with angular speed ω_0. The rod's angular momentum about the pivot is:

(a) $L = \frac{1}{2}m\ell^2\omega_0$

(b) $L = \frac{1}{3}m\ell^2\omega_0$

(c) $L = m\ell^2\omega_0$

(d) $L = \frac{2}{3}m\ell^2\omega_0$

A12) Perfectly inelastic collision A block of mass m slides with speed v_0 on a frictionless table and sticks to a second block of mass $2m$ initially at rest. The kinetic energy after the collision is:

(a) $\frac{1}{2}mv_0^2$

(b) $\frac{1}{3}mv_0^2$

(c) $\frac{1}{6}mv_0^2$

(d) $\frac{1}{9}mv_0^2$

A13) Variable force work. A particle moves along the x-axis under a force $F(x) = kx$ from $x = 0$ to $x = a$. The work done by the force is:

(a) ka

(b) $\frac{1}{2}ka^2$

(c) ka^2

(d) $\frac{1}{2}k^2a^2$

A14) Electrostatics: field of an infinite line of charge. An infinite line of charge has linear charge density λ. The magnitude of the electric field at distance r from the line is:

(a) $E = \frac{\lambda}{4\pi\varepsilon_0 r^2}$

(b) $E = \frac{\lambda}{2\pi\varepsilon_0 r}$

(c) $E = \frac{\lambda r}{2\pi\varepsilon_0}$

(d) $E = \frac{\lambda}{\varepsilon_0}$

A15) Capacitors: half-filled by area with a dielectric. A parallel-plate capacitor (plate area A, separation d) is divided into two equal regions *side by side* (each of area $A/2$). One region is completely filled with a dielectric of constant κ across the full gap d, and the other region is vacuum. The equivalent capacitance is:

(a) $C = \kappa\varepsilon_0 \frac{A}{d}$

(b) $C = \varepsilon_0 \frac{A}{d}\left(\frac{1+\kappa}{2}\right)$

(c) $C = \varepsilon_0 \frac{A}{d} \left(\frac{2\kappa}{1+\kappa} \right)$

(d) $C = \varepsilon_0 \frac{A}{d} \left(\frac{1}{2} + \frac{1}{2\kappa} \right)$

A16) Thermodynamics: maximum heat-engine efficiency. A heat engine operates between a hot reservoir at temperature T_h and a cold reservoir at temperature T_c. The maximum possible efficiency is:

(a) $\eta_{\text{max}} = 1 - \frac{T_h}{T_c}$

(b) $\eta_{\text{max}} = 1 - \frac{T_c}{T_h}$

(c) $\eta_{\text{max}} = \frac{T_c}{T_h}$

(d) $\eta_{\text{max}} = \frac{T_h}{T_c}$

A17) Waves: standing wave on a string. A string of length L fixed at both ends supports standing waves. If the wave speed is v, the frequency of the n-th harmonic is:

(a) $f_n = \frac{nv}{L}$

(b) $f_n = \frac{v}{nL}$

(c) $f_n = \frac{nv}{2L}$

(d) $f_n = \frac{v}{2nL}$

A18) Special relativity: length contraction. A rod has proper length L_0. It moves past an observer at speed v. The observer measures its length to be:

(a) $L = L_0 \sqrt{1 - \frac{v^2}{c^2}}$

(b) $L = \frac{L_0}{\sqrt{1 - \frac{v^2}{c^2}}}$

(c) $L = L_0 \left(1 - \frac{v}{c}\right)$

(d) $L = L_0 \left(1 + \frac{v}{c}\right)$

Part B Free-response questions

Problem B1

Three kids are playing by throwing balls. Kid A throws a ball horizontally with initial velocity $v_A = 5m/s$. Kid B throws it at a $30°$ angle with the horizontal with initial velocity $v_B = 10m/s$ (where we measure the angle trigonometrically, so the kid is throwing the ball towards up-right). Kid C lets their ball fall from their hands with no initial push. You can assume that all kids have the same height of $h = 125cm$.

You can assume that $g = 10m/s^2$. Denote the times that the balls are in air with t_A, t_B, and t_C. You can use the fact that the solutions for a quadratic equation $ax^2 + bx + c = 0$ are $x = \frac{-b \pm \sqrt{b^2-4ac}}{2a}$.

(a) Denoting the final horizontal displacements of the balls from the kids that throwed them by d_A, d_B, and d_C, compare these displacements by calculating them.

(b) Calculate and compare the times that are balls are in air.

Problem B2 Circuits

A 12 V battery is connected to the circuit described below:

- $R_1 = 6\ \Omega$ is in **series** with a **parallel** combination of
- $R_2 = 3\ \Omega$ and $R_3 = 6\ \Omega$.

In other words, the battery connects to R_1, and then the circuit splits into two branches: one branch contains R_2 and the other branch contains R_3, and the branches rejoin.

(a) Find the equivalent resistance R_{eq} of the circuit.

(b) Find the total current drawn from the battery.

(c) Find the voltage across the parallel section (the voltage across R_2 and across R_3).

(d) Find the current through R_2 and the current through R_3.

(e) Find the power dissipated in R_2.

(f) If R_2 burns out (becomes an open circuit), what is the new total current drawn from the battery?

Problem B3 Conical pendulum

a) A strong thread of length $l = 1\ m$ is attached to the ceiling and holds a metal ball of mass m. Suppose the ball now swings in a horizontal circle tracing out the shape of a cone with angular frequency $\omega_0 = 4$ rad/s.

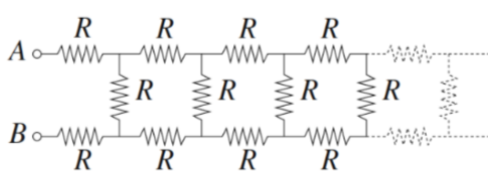
What is the radius of the circle traced by the ball?

b)Now suppose we place the conical pendulum in an elevator and the ball traces out the shape of a cone again. When the elevator is at rest, the period of oscillations is $T_0 = 1\ s$, and the ball thread is deflected by $\alpha_0 = 45°$ from the vertical. Find the period of oscillations if the elevator is going down with acceleration $a = 4.9\frac{m}{s^2}$, and the deflection angle becomes $\alpha_1 = 60°$.

Problem B4 Infinite resistor ladder

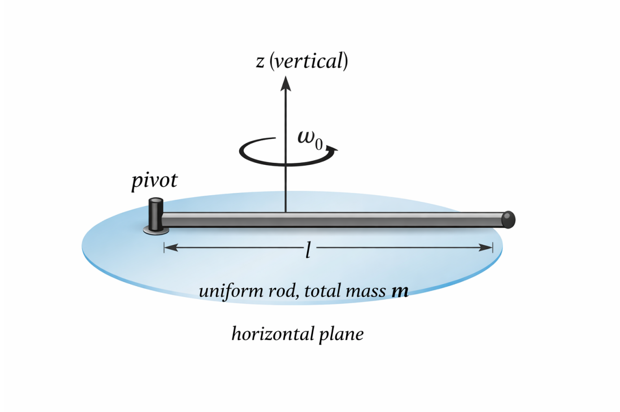
An infinite resistor ladder (picture below) consists of an infinite number of resistors, all of resistance R, arranged as shown in the figure below. Find the resistance between terminals A and B (the equivalent resistance of the ladder).

(*Hint*: Think about an invariance property of the ladder)



Problem B5 Around the world

A uniform rigid rod of mass m and length l rotates at constant angular speed ω in a horizontal plane about a vertical axis through one end (a frictionless hinge at the end). Neglect gravity (or assume it is supported so it does not affect the in-plane forces).



a) Let $T(x)$ denote the internal axial force transmitted across a cross-section of the rod at distance x from the pivot (with $0 \leq x \leq l$). Find $T(x)$.
(*Hint*: Think about the equilibrium condition of an element of length dx of the rod. The integral $\int x\ dx = \frac{x^2}{2} + C$ might be useful.)

b)Find the hinge reaction force on the rod (its magnitude and direction).

Problem B6 Thermodynamics

A sealed, insulated cylinder contains $n = 0.5$ mol of an ideal monatomic gas at initial conditions $\mathbf{T_1} = 300K$, and $\mathbf{P_1} = 10^5 Pa$. The gas is slowly compressed by a piston in two steps:

Step 1: The gas is compressed isothermally at $\mathbf{T_1} = 300\ K$, until its volume is reduced to half its initial value.

a) Find the pressure after the isothermal compression, P_2.

b) Find the work **done by the gas** during Step 1, W_1. The gas constant is $R = 8.31 \frac{kg \cdot m^2}{s^2 \cdot K \cdot mol}$.

Step 2 : After the volume of the gas has been reduced to half its initial value, the piston is locked. Then, the gas is heated until it reaches the temperature $\mathbf{T_3} = 450\ K$.

c) Find the final pressure P_3.

d) Find the work done by the gas during step 2, W_2.

e) Find the heat added during step 2, Q_2.

f) For the entire two-step process, is the net heat added Q_{net} positive, negative, or zero?

Problem B7 Rolling without slipping

A solid cylinder rolls without slipping down an incline of angle θ. What is the acceleration of its center of mass?