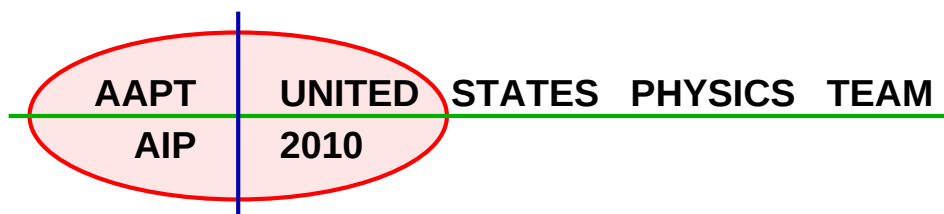


Semifinal Exam

DO NOT DISTRIBUTE THIS PAGE

Important Instructions for the Exam Supervisor

- This examination consists of two parts.
- Part A has four questions and is allowed 90 minutes.
- Part B has two questions and is allowed 90 minutes.
- The first page that follows is a cover sheet. Examinees may keep the cover sheet for both parts of the exam.
- The parts are then identified by the center header on each page. Examinees are only allowed to do one part at a time, and may not work on other parts, even if they have time remaining.
- Allow 90 minutes to complete Part A. Do not let students look at Part B. Collect the answers to Part A before allowing the examinee to begin Part B. Examinees are allowed a 10 to 15 minute break between parts A and B.
- Allow 90 minutes to complete Part B. Do not let students go back to Part A.
- Ideally the test supervisor will divide the question paper into 3 parts: the cover sheet (page 2), Part A (pages 3-4), and Part B (pages 6-7). Examinees should be provided parts A and B individually, although they may keep the cover sheet.
- The supervisor *must* collect all examination questions, including the cover sheet, at the end of the exam, as well as any scratch paper used by the examinees. Examinees may *not* take the exam questions. The examination questions may be returned to the students after March 31, 2010.
- Examinees are allowed calculators, but they may not use symbolic math, programming, or graphic features of these calculators. Calculators may not be shared and their memory must be cleared of data and programs. Cell phones, PDAs or cameras may not be used during the exam or while the exam papers are present. Examinees may not use any tables, books, or collections of formulas.



Semifinal Exam

INSTRUCTIONS

DO NOT OPEN THIS TEST UNTIL YOU ARE TOLD TO BEGIN

- Work Part A first. You have 90 minutes to complete all four problems. Each question is worth 25 points. Do not look at Part B during this time.
- After you have completed Part A you may take a break.
- Then work Part B. You have 90 minutes to complete both problems. Each question is worth 50 points. Do not look at Part A during this time.
- Show all your work. Partial credit will be given. Do not write on the back of any page. Do not write anything that you wish graded on the question sheets.
- Start each question on a new sheet of paper. Put your school ID number, your name, the question number and the page number/total pages for this problem, in the upper right hand corner of each page. For example,

School ID #

Doe, Jamie

A1 - 1/3

- A hand-held calculator may be used. Its memory must be cleared of data and programs. You may use only the basic functions found on a simple scientific calculator. Calculators may not be shared. Cell phones, PDAs or cameras may not be used during the exam or while the exam papers are present. You may not use any tables, books, or collections of formulas.
- Questions with the same point value are not necessarily of the same difficulty.
- **In order to maintain exam security, do not communicate any information about the questions (or their answers/solutions) on this contest until after March 31, 2010.**

Possibly Useful Information. You may use this sheet for both parts of the exam.

$$g = 9.8 \text{ N/kg}$$

$$k = 1/4\pi\epsilon_0 = 8.99 \times 10^9 \text{ N} \cdot \text{m}^2/\text{C}^2$$

$$c = 3.00 \times 10^8 \text{ m/s}$$

$$N_A = 6.02 \times 10^{23} (\text{mol})^{-1}$$

$$\sigma = 5.67 \times 10^{-8} \text{ J}/(\text{s} \cdot \text{m}^2 \cdot \text{K}^4)$$

$$1\text{eV} = 1.602 \times 10^{-19} \text{ J}$$

$$m_e = 9.109 \times 10^{-31} \text{ kg} = 0.511 \text{ MeV}/c^2$$

$$\sin \theta \approx \theta - \frac{1}{6}\theta^3 \text{ for } |\theta| \ll 1$$

$$G = 6.67 \times 10^{-11} \text{ N} \cdot \text{m}^2/\text{kg}^2$$

$$k_m = \mu_0/4\pi = 10^{-7} \text{ T} \cdot \text{m/A}$$

$$k_B = 1.38 \times 10^{-23} \text{ J/K}$$

$$R = N_A k_B = 8.31 \text{ J}/(\text{mol} \cdot \text{K})$$

$$e = 1.602 \times 10^{-19} \text{ C}$$

$$h = 6.63 \times 10^{-34} \text{ J} \cdot \text{s} = 4.14 \times 10^{-15} \text{ eV} \cdot \text{s}$$

$$(1+x)^n \approx 1+nx \text{ for } |x| \ll 1$$

$$\cos \theta \approx 1 - \frac{1}{2}\theta^2 \text{ for } |\theta| \ll 1$$

Part A

Question A1

An object of mass m is sitting at the northernmost edge of a stationary merry-go-round of radius R . The merry-go-round begins rotating clockwise (as seen from above) with constant angular acceleration of α . The coefficient of static friction between the object and the merry-go-round is μ_s .

- Derive an expression for the magnitude of the object's velocity at the instant when it slides off the merry-go-round in terms of μ_s , R , α , and any necessary fundamental constants.
- For this problem assume that $\mu_s = 0.5$, $\alpha = 0.2 \text{ rad/s}^2$, and $R = 4 \text{ m}$. At what angle, as measured clockwise from north, is the direction of the object's velocity at the instant when it slides off the merry-go-round? Report your answer to the nearest degree in the range 0 to 360° .

Question A2

A spherical shell of inner radius a and outer radius b is made of a material of resistivity ρ and negligible dielectric activity. A single point charge q_0 is located at the center of the shell. At time $t = 0$ all of the material of the shell is electrically neutral, including both the inner and outer surfaces. What is the total charge on the outer surface of the shell as a function of time for $t > 0$? Ignore any effects due to magnetism or radiation; do not assume that $b - a$ is small.

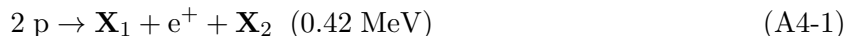
Question A3

A cylindrical pipe contains a movable piston that traps 2.00 mol of air. Originally, the air is at one atmosphere of pressure, a volume V_0 , and at a temperature of $T_0 = 298 \text{ K}$. First (process A) the air in the cylinder is compressed at constant temperature to a volume of $\frac{1}{4}V_0$. Then (process B) the air is allowed to expand adiabatically to a volume of $V = 15.0 \text{ L}$. After this (process C), the piston is withdrawn, allowing the gas to expand to the original volume V_0 while maintaining a constant temperature. Finally (process D) while maintaining a fixed volume, the gas is allowed to return to the original temperature T_0 . Assume air is a diatomic ideal gas, no air flows into, or out of, the pipe at any time, and that the temperature outside the cylinder remains constant at all times. Possibly useful information: $C_p = \frac{7}{2}R$, $C_v = \frac{5}{2}R$, $1 \text{ atm} = 1.01 \times 10^5 \text{ Pa}$.

- Draw a P-V diagram of the whole process.
- How much work is done on the trapped air during process A?
- What is the temperature of the air at the end of process B?

Question A4

The energy radiated by the Sun is generated primarily by the fusion of hydrogen into helium-4. In stars the size of the Sun, the primary mechanism by which fusion takes place is the *proton-proton chain*. The chain begins with the following reactions:



The amounts listed in parentheses are the total kinetic energy carried by the products, including gamma rays. p is a proton, e^+ is a positron, γ is a gamma ray, and $\mathbf{X}_1$, $\mathbf{X}_2$, and $\mathbf{X}_3$ are particles for you to identify.

The density of electrons in the Sun's core is sufficient that the positron is annihilated almost immediately, releasing an energy x :



Subsequently, two major processes occur simultaneously. The “pp I branch” is the single reaction

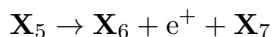


which releases an energy y . The “pp II branch” consists of three reactions:



where z is the energy released in step A4-6.

- Identify $\mathbf{X}_1$ through $\mathbf{X}_7$. $\mathbf{X}_2$ and $\mathbf{X}_7$ are neutral particles of negligible mass. It is useful to know that the first few elements, in order of atomic number, are H, He, Li, Be, B, C, N, O.
- The mass of the electron is $0.51 \text{ MeV}/c^2$, the mass of the proton is $938.27 \text{ MeV}/c^2$, and the mass of the helium-4 nucleus is $3727.38 \text{ MeV}/c^2$. Find the energy released during the production of one helium-4 nucleus, including the kinetic energy of all products and all energy carried by gamma rays.
- Find the unknown energies x and y above.
- Step (A4-6) does not proceed as follows because there is insufficient energy.



What constraint does this fact place on z ?

- In which of the reaction steps is the energy carried by any given product the same every time the step occurs? Assume that the kinetic energy carried in by the reactants in each step is negligible, and that the products are in the ground state.

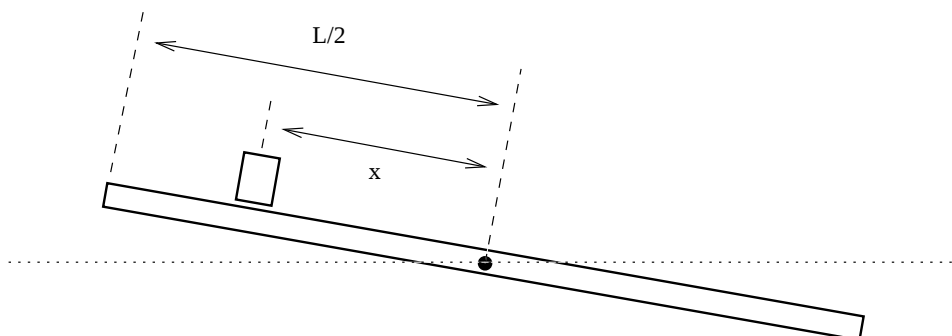
STOP: Do Not Continue to Part B

If there is still time remaining for Part A, you should review your work for Part A, but do not continue to Part B until instructed by your exam supervisor.

Part B

Question B1

A thin plank of mass M and length L rotates about a pivot at its center. A block of mass $m \ll M$ slides on the top of the plank. The system moves without friction. Initially, the plank makes an angle θ_0 with the horizontal, the block is at the upper end of the plank, and the system is at rest. Throughout the problem you may assume that $\theta \ll 1$, and that the physical dimensions of the block are much, much smaller than the length of the plank.



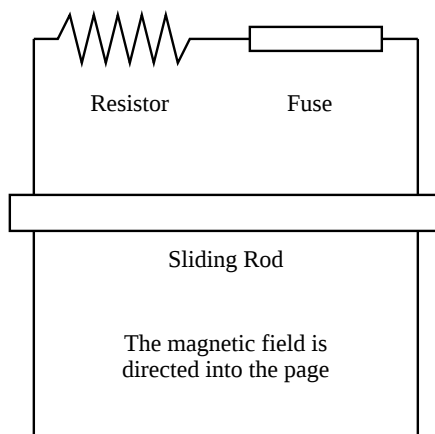
Let x be the displacement of the block along the plank, as measured from the pivot, and let θ be the angle between the plank and the horizontal. You may assume that centripetal acceleration of the block is negligible compared with the linear acceleration of the block up and down the plank.

- For a certain value of θ_0 , $x = k\theta$ throughout the motion, where k is a constant. What is this value of θ_0 ? Express your answer in terms of M , m , and any fundamental constants that you require.
- Given that θ_0 takes this special value, what is the period of oscillation of the system? Express your answer in terms of M , L , m , and any fundamental constants that you require.
- Determine the maximum value of the ratio between the centripetal acceleration of the block and the linear acceleration of the block along the plank, writing your answer in terms of m and M , therefore justifying our approximation.

Question B2

These three parts can be answered independently.

- a. One pair of ends of two long, parallel wires are connected by a resistor, $R = 0.25 \, \Omega$, and a fuse that will break instantaneously if 5 amperes of current pass through it. The other pair of ends are unconnected. A conducting rod of mass m is free to slide along the wires under the influence of gravity. The wires are separated by 30 cm, and the rod starts out 10 cm from the resistor and fuse. The whole system is placed in a uniform, constant magnetic field of $B = 1.2 \, \text{T}$ as shown in the figure. The resistance of the rod, wires, and fuse is negligible. When the rod is released it falls under the influence of gravity, but never loses contact with the long parallel wires.



- i. What is the smallest mass needed to break the fuse?
 - ii. How fast is the mass moving when the fuse breaks?
- b. A fuse is composed of a cylindrical wire with length L and radius $r \ll L$. The resistivity (*not resistance!*) of the fuse is small, and given by ρ_f . Assume that a uniform current I flows through the fuse. Write your answers below in terms of L , r , ρ_f , I , and any fundamental constants.
- i. What is the magnitude and direction of the electric field on the surface of the fuse wire?
 - ii. What is the magnitude and direction of the magnetic field on the surface of the fuse wire?
 - iii. The Poynting vector, $\vec{S}$ is a measure of the rate of electromagnetic energy flow through a unit surface area; the vector gives the direction of the energy flow. Since $\vec{S} = \frac{1}{\mu_0} \vec{E} \times \vec{B}$, where μ_0 is the permeability of free space and $\vec{E}$ and $\vec{B}$ are the electric and magnetic field vectors, find the magnitude and direction of the Poynting vector associated with the current in the fuse wire.
- c. A fuse will break when it reaches its melting point. We know from modern physics that a hot object will radiate energy (approximately) according to the black body law $P = \sigma AT^4$, where T is the temperature in Kelvin, A the surface area, and σ is the Stefan-Boltzmann constant. If $T_f = 500 \, \text{K}$ is the melting point of the metal for the fuse wire, with resistivity $\rho_f = 120 \, \text{n}\Omega \cdot \text{m}$, and $I_f = 5 \, \text{A}$ is the desired breaking current, what should be the radius of the wire r ?