2013 Joseph Henry Physics Competition

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Instructions: The competition lasts for two hours, please try to solve as many problems as you can. All questions carry equal weight. You do not have to solve all problems to win the competition! Good luck!

1. Spherical particles with radius \( r = 1.2\mu m \) form a cloud with density \( n = 4 \cdot 10^{-9} m^{-3} \). Assuming that the particles absorb all light that reaches their surface, estimate the depth of penetration of light into the cloud.

2. Neglect the effect of air resistance for this problem.
   Consider a person of mass \( m \) who runs at speed \( v \). Is there a power difference between running on the ground and running on a treadmill? If there is, then estimate the power difference. If there is not, then clearly justify your answer.

3. (a) A volume of water \( v \) is poured straight down onto the center of a flat, smooth table as shown in the left side of the figure. Estimate the fraction of the water that will fall through a hole 1 cm in diameter located 1 m from the center of the table.
   (b) Repeat part a, but now assume that the water hits the table at a 45° angle and is aimed toward the hole (as shown in the right side of the figure).
4. Consider a spherical balloon of radius $r$ and mass $m$, and a spherical rock of radius $r$ and mass $10^4m$. Both are dropped from a height $h$. Do they hit the ground at the same time? If yes, the clearly show why. If no, state which lands first and calculate the time difference. Take the density of air to be $\rho$.

5. Consider a pyramid made of eight metal rods. Assuming that the rods are uniform, and each of them has resistance $R$, determine the resistance between points A and B.

![Diagram of a pyramid made of metal rods]

6. Consider a region in space that contains constant and uniform electric and magnetic fields. If electrons enter this region with velocity $v$ pointing in the directions 1 or 2, they keep moving with constant velocity. Assuming that the absolute value of the electric field is $|E| = E \neq 0$, determine the vectors $\mathbf{E}$ and $\mathbf{B}$ (absolute values and directions).

![Diagram showing electric and magnetic fields]

7. Estimate the temperature in the center of the Sun using the following assumptions:

(1) The Sun has a constant density

(2) The Sun is made of the proton–electron plasma with molar mass $\mu = 0.5$ g/mole. Assume that this plasma obeys the equation of state for the ideal gas.

(3) The escape velocity from the surface of the Sun is $v = 618$ km/s.

You may also need the value of the gas constant, $R = 8.3$ J/(mole·K).
8. A simple force diagram will show why a person cannot lift herself into the air by running a rope under her feet and then pulling up on the ends.

(a) The left panel of the figure shows the same person trying to lift herself by running the rope halfway around a fixed horizontal bar and then pulling downwards. Now can she lift herself? Show a force diagram and either justify why she cannot, or calculate the minimum force needed (take her mass to be $m$).

(b) The middle panel of the figure shows the same person trying to lift herself by running the rope completely around a fixed horizontal bar and then pulling upwards. Now can she lift herself? Show a force diagram and either justify why she cannot, or calculate the minimum force needed (take her mass to be $m$).

(c) The right panel of the figure shows the same person trying to lift herself, but now the bar is attached to the tops of her shoes (don't try this at home). The figure shows the rope running upwards to a pulley and shows that she pulls upwards on the rope. Now can she lift herself? Show a force diagram and either justify why she cannot, or calculate the minimum force needed (take her mass to be $m$).
9. Consider a uniformly charged loop and a bead with charge $q$ and mass $m$ that can slide along a string without friction. If the string is located as shown in figure (a), then the bead undergoes small oscillations with period $T$. Find the period of small oscillations of a bead with charge $(-q)$ for the configuration depicted in figure (b).

**Hint** Use Gauss' law to determine the electric field near the center of the loop.

10. Entanglement is a fascinating phenomenon in quantum physics that seem to contradict special relativity and imply an "action at a distance". If two electrons happen to be in an entangled state, then a measurement performed on one of them immediately affects the state of the other, even if they are separated by a large distance.

Consider two electrons which are emitted in an entangled state at point O, then they travel to points A and B separated by one light year. An experimentalist at point A wants to send information to point B by making one of the two choices:
(a) measure the $x$–projection of the spin $S_x^{(A)}$,
(b) measure the $y$–projection of the spin $S_y^{(A)}$.

In quantum mechanics only one of these two measurements can be performed, and they lead to different consequences for the particle at point B:
(a) particles has a fixed $x$–projection of the spin $S_x^{(B)} = -S_x^{(A)}$, but each of the two values $S_y^{(B)} = \pm \frac{1}{2}$ can be observed with 50% probability.
(b) particles has a fixed $y$–projection of the spin $S_y^{(B)} = -S_y^{(A)}$, but each of the two values $S_x^{(B)} = \pm \frac{1}{2}$ can be observed with 50% probability.

The electron at point B jumps from the entangled state to the state (a) or (b) exactly at the time of the experiment performed at point A, so it appears that the information about the decision made by A travels from point A to point B faster than light, in contradiction to special relativity. Assuming that the problem faithfully represents all quantum mechanical facts, resolve this paradox.