THE UNIVERSITY OF SYDNEY
FACULTIES OF ARTS, EDUCATION & SOCIAL WORK,
ENGINEERING AND SCIENCE

PHYS 1901 PHYSICS 1A (ADVANCED)

JUNE 2008

Time allowed: THREE Hours

MARKS FOR QUESTIONS ARE AS INDICATED
TOTAL: 90 MARKS

INSTRUCTIONS
• All questions are to be answered.
• Use a separate answer book for section A and section B.
• All answers should include explanations in terms of physical principles.

DATA

Density of fresh water \( \rho = 1.00 \times 10^3 \text{ kg.m}^{-3} \)
Free fall acceleration at earth's surface \( g = 9.81 \text{ m.s}^{-2} \)
Gravitational constant \( G = 6.67 \times 10^{-11} \text{ N.m}^2 \text{ .kg}^{-2} \)
Speed of light in a vacuum \( c = 3.00 \times 10^8 \text{ m.s}^{-1} \)
Speed of sound in air \( v = 344 \text{ m.s}^{-1} \)
Avogadro constant \( N_A = 6.023 \times 10^{23} \text{ mol}^{-1} \)
Universal gas constant \( R = 8.314 \text{ J.mol}^{-1}.\text{K}^{-1} \)
Boltzmann constant \( k = 1.380 \times 10^{-23} \text{ J.K}^{-1} \)
Stefan–Boltzmann constant \( \sigma = 5.67 \times 10^{-8} \text{ W.m}^{-2} \text{ K}^{-4} \)
SECTION A

Question 1

A mass of $2m$ is connected to two masses of mass $m$ and $3m$ as shown below. The strings connecting the masses are light. The pulleys and the slopes are frictionless.

(a) Draw separate free body diagrams for each of the masses, taking care to identify all forces acting.

(b) If the angle of the slope $\theta = 30^\circ$, and the system is released from rest, does the hanging mass $2m$ remain where it is, accelerate upwards or accelerate downwards? Justify your answer.

(5 marks)

Question 2

A stone of mass $m$ is moving in a circle of radius $r$ at constant speed $v$ on a horizontal plane at the end of a light string. Assume friction is negligible and that the stone is a point mass.

(a) What is the angular momentum of the stone?

(b) What is the kinetic energy of the stone?

The length of the string from the stone to the centre is now halved (i.e. radius is now $r/2$) by pulling the stone inwards while it continues to move.

(c) What is the change in the angular momentum of the stone?

(d) What is the change in the kinetic energy of the stone?

(e) Recalling that the tension in the string does no work while the stone is moving in a circle, how do you explain the change in kinetic energy in (d)?

(5 marks)
Question 3

While jogging, a 70.0 kg Paul generates thermal energy at a rate of 1200 W. To maintain a constant body temperature of 37.0°C this energy must be removed by perspiration or other mechanisms. If these mechanisms fail and heat does not transfer from Paul’s body, irreversible body damage could occur. Protein structures in the body are irreversibly damaged if the body temperature rises to 44°C or above.

The specific heat capacity of a typical human body is 3480 J.kg⁻¹ K⁻¹.

(a) If there is no heat transfer from his body, how much heat generation is needed to cause irreversible damage to Paul’s body?
(b) For how long a time $t$ could he jog with no heat transfer from his body before irreversible damage occurs?
(c) When a person suffers from heat stroke, the body stops sweating. Why is sweating a particularly effective way for heat transfer from the body to occur?

(5 marks)

Question 4

Initially, a hot cup of coffee at a temperature $T_H$ is sitting on a table. The environment surrounding the coffee is at a lower temperature $T_C$. The temperature of the coffee drops until it is in equilibrium with the surroundings. It is assumed that the change in temperature of the environment is negligible.

(a) Show that the change in entropy of the cup of coffee is negative.
(b) If the initial temperature of the coffee was 80°C and the temperature of the surroundings was 20°C, show that the second law of thermodynamics is not violated in the cooling of the coffee.

(5 marks)

Question 5

A loudspeaker emits a pure sinusoidal sound of frequency $f$, which can be varied. The loudspeaker is placed in front of a wine glass and the sound wave from the loudspeaker makes the glass oscillate. If the frequency is set at a particular value, $f_1$, there is a high chance that the glass will break.

(a) Explain in just a few words why the glass could break when the frequency of the emitted sound wave is “just right”.

Assume that you have two wine glasses that “ring” (i.e. they vibrate with a ringing sound when you tap them gently with your finger) with the same frequency. However, one of them “rings” for much longer than the other.

(b) The glasses are put next to the loudspeaker under the same conditions. Is the glass that “rings” for longer more likely or less likely to break than the other glass? Briefly explain your answer.

(5 marks)
Question 6

A string is attached to a wall. A lecturer holding the unattached end pulls with a constant force (parallel to the string) while moving his hand up and down (perpendicular to the string) to create a pulse travelling towards the wall.

The lecturer now wants to produce a pulse that takes a longer time to reach the wall. Four ways of doing this are considered below.

(a) Choose the best answer from the following and give a brief justification.
   i. He should move his hand up and down more quickly.
   ii. He should move his hand up and down more slowly.
   iii. Neither (i) nor (ii) will change the time for the pulse to reach the wall.

(b) Choose the best answer from the following and give a brief justification.
   i. He should use a heavier string of the same length, under the same tension.
   ii. He should use a lighter string of the same length, under the same tension.
   iii. Neither (i) nor (ii) will change the time for the pulse to reach the wall.

(c) Choose the best answer from the following and give a brief justification.
   i. He should displace his hand a greater distance up and down but at the same speed.
   ii. He should displace his hand a lesser distance up and down but at the same speed.
   iii. Neither (i) nor (ii) will change the time for the pulse to reach the wall.

(d) Choose the best answer from the following and give a brief justification.
   i. He should pull the string harder to increase the tension in the string.
   ii. He should pull the string less hard to decrease the tension in the string.
   iii. Neither (i) or (ii) will change the time for the pulse to reach the wall.

The lecturer now detaches the string from the wall and invites one of the students to hold that end of the string and keep it fixed. The lecturer and student both pull the string with the same force as the lecturer did before. The lecturer then moves his hands up and down in the same way as he did originally.

(e) Compared with the original travel time for the pulse, choose the best answer from the following options and give a brief justification.
   i. The travel time does not change because the tension in the rope is the same.
   ii. The travel time gets longer because the tension in the rope is greater.
   iii. The travel time gets shorter because the tension in the rope is greater.

(5 marks)
**SECTION B**

*Please use another book to answer this section*

Question 7

The potential energy of two atoms in a diatomic molecule is approximated by

\[ U(r) = \frac{a}{r^{12}} - \frac{b}{r^{6}} \]

where \( r \) is the spacing between the molecules and \( a \) and \( b \) are positive constants.

(a) Show that the force \( F(r) \) on one atom because of the other is given by

\[ F(r) = \frac{12a}{r^{13}} - \frac{6b}{r^7}. \]

(b) Show that the atoms are in equilibrium (sit at rest with respect to each other) if

\[ r = \left( \frac{2a}{b} \right)^{\frac{1}{6}}. \]

(c) With the aid of a sketch of both \( U(r) \) and \( F(r) \), comment on whether this equilibrium is stable or unstable.

(d) Show that the minimum energy required to dissociate the molecule – that is, to separate the two atoms to an infinite distance apart, is

\[ E = \frac{b^2}{4a}. \]

(e) For the molecule CO, the equilibrium distance between the carbon and oxygen atoms is \( 1.13 \times 10^{-10} \) m and the dissociation energy is \( 1.54 \times 10^{-18} \) J per molecule. Find the values of the constants \( a \) and \( b \).

(10 marks)
Question 8

You are designing a rocket for use in deep space, well away from any significant gravitational fields. Initially, the total mass of the rocket consists of the rocket itself, of mass $M$, plus 10 blocks of fuel, each with a mass $m$. To propel the rocket forward, the blocks of fuel are ejected out of the back at a speed $v$ relative to the rocket.

On your first test flight, you start from rest and eject all of the fuel at once.

(a) Using the conservation of momentum, show that the velocity of the rocket after the mass is ejected, $v_{10}$ is given by:

$$v_{10} = \frac{10m}{M} v$$

(b) Show that the impulse achieved through the ejection of all 10 blocks of fuel is the same whether they are ejected individually, or all at once. Ensure you mention the force required to eject the fuel and the time over which it acts.

Based on part (b), for your second run you start again from rest, loaded with 10 blocks of fuel of mass $m$, but now eject the fuel blocks individually at regular intervals in time. Again the fuel is ejected with a velocity $v$ with respect to the rocket.

(c) Show that after the first block of fuel is ejected, the velocity of the rocket, $v_1$, is given by:

$$v_1 = \frac{m}{M + 9m} v$$

(d) Remembering that the fuel speed, $v$, is relative to the rocket, show that the rocket's velocity after the second and then third blocks of fuel are ejected, $v_2$ and $v_3$ respectively, are given by:

$$v_2 = \frac{m}{M + 8m} (2v - v_1)$$

$$v_3 = \frac{m}{M + 7m} (3v - v_1 - v_2)$$

When all 10 blocks of fuel are ejected, the final velocity of the rocket is (you do not need to prove this):

$$v_{10} = \frac{m}{M} \left(10v - v_1 - v_2 - v_3 - v_4 - v_5 - v_6 - v_7 - v_8 - v_9\right)$$

where $v_i$ is the velocity after the $i^{th}$ block has been ejected. However, this is clearly different to the velocity you calculated in part (a).

(e) Although you showed in part (b) that the impulse does not depend upon the way the blocks were ejected, briefly explain, using physical principles, why the resultant velocity depends upon the method of ejection you adopt.

(10 marks)
Question 9

(a) An engine has work output $W$, transfers energy $Q_c$ to the environment, and operates between heat reservoirs at temperatures $T_c$ and $T_H$. Using the theoretical efficiency of the engine show that:

$$|Q_c| = \frac{WT_c}{T_H - T_c}$$

(b) Suppose that a deep shaft is drilled in the Earth’s crust from the surface, where the temperature is 0°C, down to a depth where the temperature is 800°C. An engine is constructed to operate between these temperatures.

(i) What is the theoretical limit to the efficiency of this engine?
(ii) The engine is used to melt surrounding ice. The ice is initially at -40°C. If 200 J of useful work is done in a thermodynamic cycle, how many cycles of operation are required to melt 1.0 kg of ice?

(iii) At what rate would liquid water at 0°C be produced from ice at -40°C by a 100 MW power station based on this principle?

$$c_{\text{ice}} = 2.10 \times 10^3 \text{ J.kg}^{-1}.\text{K}^{-1}$$
$$c_{\text{water}} = 4.19 \times 10^3 \text{ J.kg}^{-1}.\text{K}^{-1}$$
$$L_f = 3.34 \times 10^5 \text{ J.kg}^{-1}$$

(10 marks)

Question 10

A 0.12 mol sample of a diatomic ideal gas is permanently in contact with a thermal reservoir that holds the temperature of the sample fixed at a temperature of 9.80°C. The initial volume of the sample is $9.80 \times 10^{-3} \text{ m}^3$. The gas expands and does 14.0 J of work on the surroundings.

(a) What type of thermal process occurs during the expansion? Explain.
(b) Calculate the initial pressure of the gas.
(c) Calculate the final volume of the gas.
(d) Calculate the final pressure of the gas.
(e) Calculate the change in internal energy of the gas.
(f) Calculate the heat transfer. Is heat transferred to the gas or from the gas? Explain.

(g) If the gas had expanded in an adiabatic process from its initial volume to the final volume calculated in part (c), would the temperature of the gas be lower, the same as, or higher than 9.80°C? Briefly explain your answer.
(h) If the gas had expanded in an adiabatic process from its initial volume to the final volume calculated in part (c), would the work done by the gas on the surroundings be less than, equal to, or greater than 14.0 J? Briefly explain your answer.

(10 marks)
Question 11

A spring with spring constant $k$ is suspended from the ceiling. Assume that the spring has negligible mass and that the bottom of the spring is distance $L$ from the floor. You carefully attach a mass $M$ to the bottom of the spring, without stretching the spring. You hold the mass still and then release it at time, $t=0$, so that it oscillates up and down with period $T$ and amplitude $A$ (without touching the floor).

(a) Draw a graph of the height of the mass above the floor as a function of time $t$. Make sure you label both axes and indicate $L$, $A$ and $T$.

(b) Show that the amplitude $A$ of the oscillation is given by:

$$A = \frac{Mg}{k}.$$

(c) Write down the equation of motion of the mass (the height $y$ above the floor as a function of time $t$). Your answer should only contain the parameters $L$, $k$ and $M$.

(10 marks)

Question 12

Consider a damped oscillator for which the damping is proportional to speed. Such a system is described by the following differential equation:

$$m \frac{d^2x}{dt^2} + b \frac{dx}{dt} + kx = 0$$

(a) Briefly explain the physical meanings of $m$, $b$ and $k$ in the above equation.

We guess a solution of this equation to be:

$$x(t) = Ae^{-Bt} \cos(\omega t).$$

(b) Briefly explain the physical meanings of $A$, $B$ and $\omega$ in the above equation.

(c) By writing $x(t)$ as the real part of a complex quantity $z(t)$, or otherwise, show that

$$B = \frac{b}{2m}.$$  

*Hint: Recall that $e^{i\theta} = \cos \theta + i \sin \theta$.*

(10 marks)

THIS IS THE END OF YOUR QUESTIONS