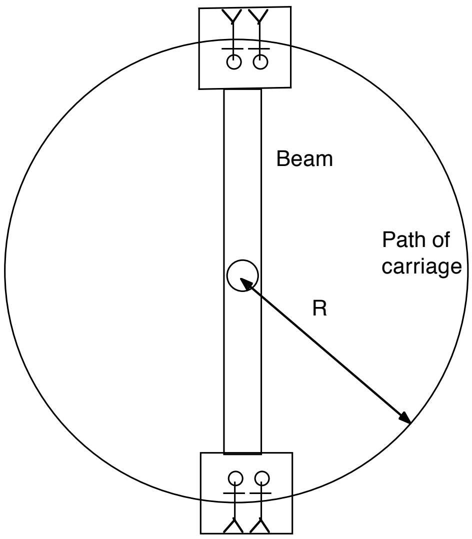
Question 1. [Marks 20]

(a) An unmarked police car P is, travelling at the legal speed limit, v_P, on a straight section of highway. At time $t = 0$, the police car is overtaken by a car C, which is speeding – ie travelling at constant speed $v_C > v_P$. At $t = 0$, the police car begins to accelerate at constant acceleration, a, for time T_1. It then decelerates, at constant acceleration, $-a$, for a time T_2. The police car driver judges T_1 and T_2 so that, at time $t = T_1 + T_2$, the police car is alongside the speeding car and travelling at the same speed, v_C.

Draw a displacement-time graph to show this sequence. Clearly mark the displacements x_P and x_C of the two cars and the time intervals T_1 and T_2. Please make the drawing clear (and draw a second one if the first one is too messy). Make sure you indicate on the graph the relative size of the time intervals, T_1 and T_2.

(b) State Newton's second law of motion for a particle, defining carefully each term used.

(c)



This is a sketch of a circus ride. A beam connects two carriages, in which people ride, secured by seatbelts. The beam rotates about a horizontal axis through its centre, so that the path of the carriages is a circle, radius R, in a vertical plane (as shown). The mass of the carriage (passengers included) is m. The mass of the beam is negligible compared to that of the carriages and the size of the carriages is negligible compared to the length of the beam.

The beam rotates at constant angular velocity with period T. Consider the moment when the beam is vertical, as shown.

(i) Derive one expression for the tension F_{top} in the top half of the beam *and another expression* for the tension F_{bottom} in the bottom half of the beam, in terms of T and other quantities.

(ii) Derive an expression for the value of T for which the tension in the beam is zero in the top half of the beam, when vertical.

(iii) Describe the behaviour of unsecured objects in the upper carriage during condition described in part (ii). How would they appear to someone inside the carriage?

Question 2. **[Marks 14]**

A spacecraft (with mass m) is in circular orbit (with radius r) around the earth (mass M), above the equator. With respect to a point below it on earth, it is travelling towards the East at speed v.

(i) Write an expression for the mechanical energy of the spacecraft in terms of M, m, v, r and G. Specify the reference state for potential energy.

(ii) Using Newton's second law, relate v and r to the gravitational force between the earth and the satellite.

(iii) Hence or otherwise derive an expression for kinetic energy K as a function of M, m, r and G.

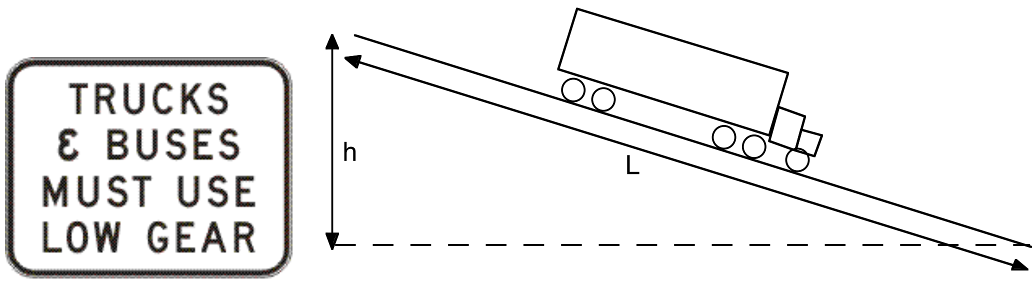
(iv) Using the previous results or otherwise, derive an expression for the mechanical energy of the orbit as a function of M, m, r and G.

(v) Write an expression for v as a function of M, m, r and G.

Question 3. **[Marks 22]**

(a) State the definition of work as an equation. Define all terms used. Use differential notation: do not assume that the quantities involved are constant.

(b)



The sign above is often seen on steep descents. It requires the drivers to use the engine to retard the descent. Let's see why.

A truck with mass 36 tonnes is travelling at the top of a straight descent with constant slope. Over a distance travelled of L = 4.0 km, the altitude of the road decreases by h = 400 m. (This is called a 10% slope and is fairly steep.)

The truck has 10 brake drums, which we'll treat as identical, each with a mass of 30 kg, made from steel with a specific heat of 490 $J.kg^{-1}.K^{-1}$.

(i) Suppose that the truck descends the slope at a constant speed of 30 kilometres per hour. Showing your argument and working explicitly, calculate the work done by gravity acting on the truck as it descends this section of road.

(ii) If the truck is traveling at 30 kilometres per hour, what is the rate at which gravity is doing work?

(iii) If all of the work done by gravity were converted into heat in the brake drums only, and if their temperature were 20°C at the start of the descent, what would be their temperature at the bottom? Show your working.

(iv) The heat generated by the brakes is ultimately lost to the air (some of it passing via the wheels and axles). As an estimate, let's assume that the air passing near the brakes, wheels and axles is heated by 20°C. What volume of air must be heated by 20°C to carry away the heat produced in the brakes in part (iii)? Take atmospheric pressure as 100 kPa and treat the air as a diatomic ideal gas with molecular mass 0.029 kg/mol and the temperature as 20°C.

Question 4. **[Marks 20]**

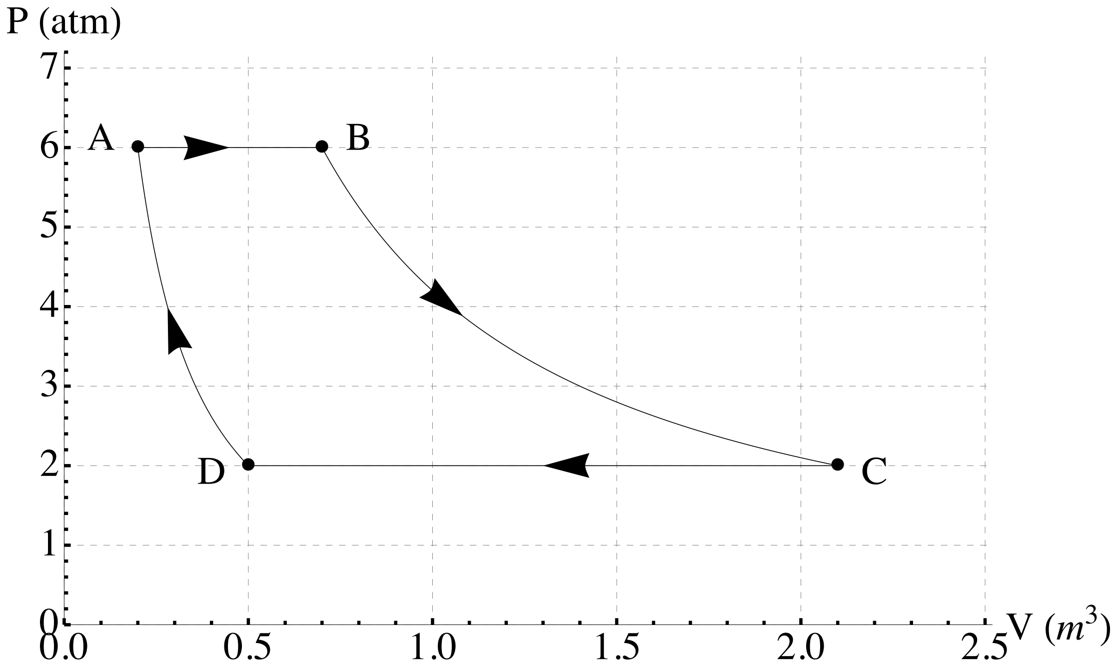
(a) (i) Explain what is meant by ‘absolute zero’.

(ii) Using an equation, state the relationship between temperature and molecular translational kinetic energy. Define the terms used in your equation.

(iii) Calculate the temperature of oxygen gas (O_2) consisting of oxygen molecules moving with v_{rms} = 393 m/s. The atomic mass of oxygen atoms is 16.0 g/mol.

(iv) State the theorem of equipartition of energy, and explain what is meant by a “degree of freedom”.

(b)



A sample of ideal gas undergoes the process shown in the diagram above. From A → B the process is isobaric and 100 kJ of heat enters the system. From B → C the process is isothermal. From C → D the process is isobaric and 200.0 kJ of heat energy leaves the system. From D → A the process is adiabatic.

(i) Define the term ‘adiabatic process’. Include an equation in your definition.

(ii) Calculate the work done *on* the gas as it goes from state A to state B.

(iii) Determine the change in internal energy of the sample between states A and B.

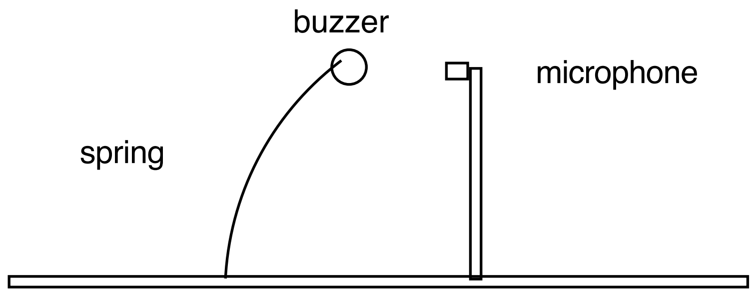
(iv) Determine the change in internal energy as the sample moves from state B to state C.

(v) How much work is done on the sample as it moves from state D to state A? State any assumptions you make.

Question 5. [11 Marks]

(a) A 7.00 kg object is hung from the bottom end of a vertical spring fastened to an overhead beam. When the object is set into a vertical oscillation, it is found to have a period of 2.60 s. Find the force constant of the spring.

(b) Refer to the figure below. A piezo-electric buzzer, emitting a frequency of 3.00 kHz, is mounted on a vertical cantilever spring so that it oscillates horizontally at 10 Hz with simple harmonic motion. The amplitude of this simple harmonic motion is 40 cm. A microphone is mounted on the horizontal line of the buzzer's motion.

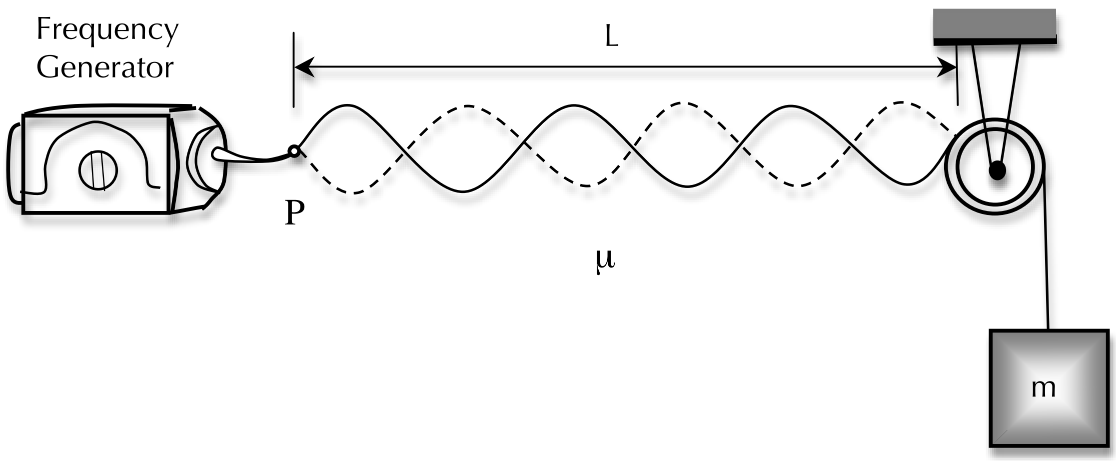


Determine the highest and lowest frequencies received by microphone.

Assume that the speed of sound is 343 m/s, and ignore reflections from the floor.

Question 6 [Marks 13]

(a) As shown in the Figure below, an object is hung from a string (with linear mass density $\mu = 0.00200$ kg/m) that passes over a light pulley. The string is connected to a vibrator (of constant frequency *f*), and the length of the string between point *P* and the pulley is $L = 2.00$ m. When the mass *m* of the object is either 16.0 kg or 25.0 kg, standing waves are observed; however, no standing waves are observed with any mass between these values. Note: The amplitude of the vibrator is much smaller than that of the standing waves produced, so you may treat the vibrator as a displacement node.



(i) What is the frequency of the vibrator? (*Note*: The greater the tension in the string, the smaller the number of nodes in the standing wave.)

(ii) What is the largest object mass for which standing waves could be observed?

(b) A piccolo is a musical instrument with an overall length of 32.0 cm. The resonating air column can be approximated as a cylindrical pipe, ideally open at both ends. Find the frequency of the lowest note that a piccolo can play, assuming that the speed of sound in air is 343 m/s.