2024 AUSTRALIAN SCIENCE OLYMPIAD EXAM

PHYSICS

TO BE COMPLETED BY THE STUDENT. USE CAPITAL LETTERS.

First Name: ……………….…..………… Last Name………………………………….

Date of Birth: ……/…../…….

□ Male □ Female □ Unspecified Year 10 □ Year 11 □ Other: …….

Name of School: ……………………………………….……………..**State:** ……...

Examiners Use Only:

2024 AUSTRALIAN SCIENCE OLYMPIAD EXAM
PHYSICS

Time Allowed

Reading Time: 10 minutes
Examination Time: 120 minutes

INSTRUCTIONS

- *Attempt all questions in ALL sections of this paper*.
- Permitted materials: non-programmable, non-graphical calculator, pens, pencils, erasers and a ruler.
- Marks will not be deducted for incorrect answers.
- Ensure that diagrams are clear and labelled
- All numerical answers must have correct units

MARKS

▪ Section A: Digging Disaster	18 marks
▪ Section B: Slithering Snake	31 marks
▪ Section C: Violin Vibrations	32 marks
▪ Section D: Reflection Replicas	5 marks
▪ Section E: Twisting Torques and Leaning Lego	24 marks
TOTAL	**110 marks**

Integrity of Competition

If there is evidence of collusion or other academic dishonesty, students will be disqualified. Markers' decisions are final.

Section A: Digging Disaster

Suggested Time: 25 minutes

You believe that you have a broken pipe in your backyard. The problem is that the broken pipe is under the ground. In order to find the break you will have to dig a hole. Assume that the hole you dig will be a perfect square pyramid of depth h_1. Assume that the side length of the square base is equal to the depth. Note that the apex of the pyramid is deep under the ground and the base is at the surface. The dirt that you have dug out will form a perfect square pyramid pile next to the hole. The height of this pyramid pile is also equal to the side length of its square base.

Centre of mass is the average position of all parts of an object, for a regular shape like a cube or a sphere the centre of mass is in the geometric centre of the object. Centre of mass is useful for force and energy calculations because it is often possible to treat all of the mass as being at the centre of mass rather than needing to take into account the entire distribution of mass. The centre of mass of a pyramid is located one quarter of the way between its base and its vertex. The volume of a square pyramid is given by $V = \frac{hb^2}{3}$ where h is the height of the pyramid and b is the length of the side of the base.

When the dirt is in the ground, its density is given by ρ_1. As you dig out the dirt it becomes less compact (some air gaps appear). This causes the density of the dirt to decrease to ρ_2.

1. Which of the following statements are true? (2 marks)
    a. The centre of mass of an upright pyramid is higher than half its height.
    b. $\rho_1 > \rho_2$

2. Find an algebraic expression the height of the dirt pile (pyramid) that you have dug out. Show your working. (3 marks)

3. You must do work against gravity to lift dirt from the ground into the pile. How much work do you have to do against gravity to dig this hole? Give your answer as an algebraic expression in terms of ρ_1, h_1, g and ρ_2. Show your working. (5 marks)

4. Assuming that the depth of the hole is 1.50m, the density of compacted dirt is $1600 kg/m^3$ and the density of uncompacted dirt is $1200 kg/m^3$. How much work is done (in joules) against gravity to lift the dirt? Please assume that the acceleration due to gravity is $9.81 m/s^2$ for this question. (1 mark)

5. You are wondering how long it would take you to dig the hole from question 4. The average daily energy consumption for a human is 7000kJ. If a human uses a spade the digging process is about 20% efficient. Assume that a human uses their energy evenly throughout the day and uses 10% of their energy expenditure to dig the hole while digging. Explain the process that you would use to determine the amount of time that it would take them to dig the hole. Based on your process find an estimate for how long it would take for them to dig the hole (in hours). Show your working. (2 marks)

6. A tradie has a 3.00kW digging tool that is 10% efficient. Explain the process that you would use to determine the amount of time that it would take them to dig the hole from Question 4. Based on your process find an estimate for how long it would take for them to dig the hole (in seconds). Show your working. (2 marks)

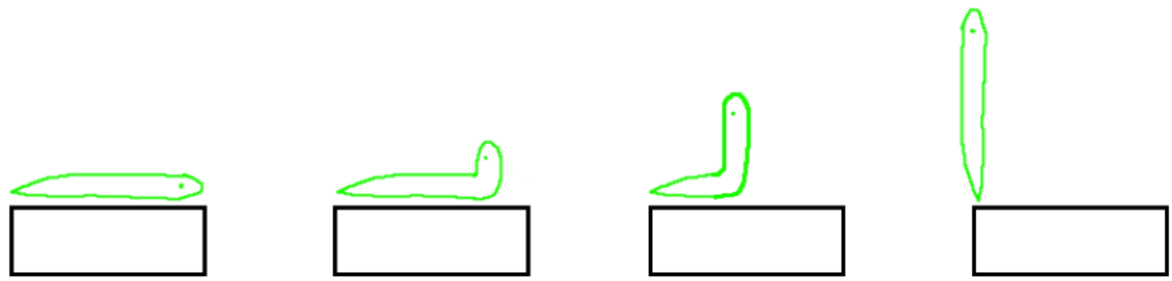
7. Electricity prices are skyrocketing to \$0.44 per KiloWatt hour (kWh). How much will the electricity cost to dig this hole using the machine (in dollars)? What fraction is this of the tradie's wage (\$100 per hour)? (3 marks)

Section B: Slithering Snake

Suggested time: 30 minutes

A class is asked to investigate and model the motion of snakes.

Student A sees a video of a snake rising to stand on the tip of its tail in the following way.



They are curious about what would happen if the snake did this on an electronic scale. They decide to model the snake as cylinder of mass $m = 1.0$ kg and length $L = 1.3$ m with a uniform mass distribution.

1. If the vertical velocity of the snake's head is $v = 0.15$ m/s, calculate an expression for the magnitude of the snake's vertical momentum at a time $t = 4$ s after the snake has started rising. (4 marks)

2. For an object to change its momentum in a given direction, it must have a net force with a component in that direction. By considering the forces on the snake and the electronic scale, sketch a graph of the reading on the electronic scale over time. Include the reading on the scale before the snake starts rising. (4 marks)

3. Student A now wants to validate their model to see if it matches with the real world. However, they have a fear of snakes and don't want to handle a real snake. They instead use a rope with the same length and mass to mimic the snake. Holding the end of the rope, they lift the rope up such that the rope's motion exactly matches the motion of the snake. Explain why the reading on the electronic scale would not match the answer in part 2. (4 marks)

Student B sees a video of a snake's motion. They notice that the snake's motion consists of two distinct phases: a 'closing' phase where the snake compresses together and an 'opening' phase where the snake expands. By alternating between closing and opening phases, the snake can travel forward.

To explore this behaviour, student B models the snake as two blocks of mass $m = 0.5$ kg which represent the two ends of the snake. They are connected by a rod which can change its length from an initial length $L = 1.3$ m. The model snake is initially stationary.

During the closing phase, a constant force $F_c = 1.4$ N is exerted on both masses until the distance between the two masses is 0. During the opening phase, a constant force $F_o = 1.4$ N is exerted on both masses until the distance between the two masses is L. A closing phase immediately followed by an opening phase will be referred to as a 'closing-opening cycle'. For parts 4 and 5, we will assume there is no friction between the model snake and the ground.

4. Calculate the time it takes for the model snake to undergo one closing-opening cycle. (4 marks)

5. Explain why the centre of the model snake does not move forward after each cycle. (2 marks)

After doing some research, Student B finds that the kinetic friction coefficient between the snake and the ground is $\mu_f = 0.15$ when the snake moves forwards, but $\mu_b = 0.25$ when the snake moves backwards. This allows the model snake to move forward after each closing-opening cycle.

6. Draw force diagrams which show the forces acting on each mass during the closing and opening phases. (4 marks)

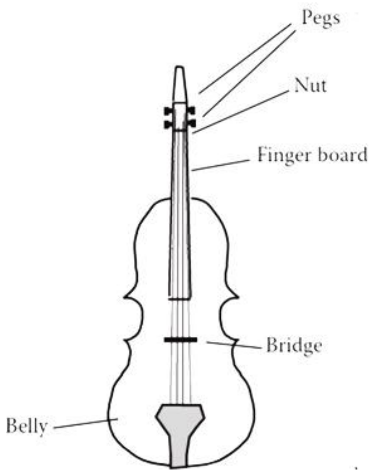
7. Calculate the distance which the centre of the model snake moves forward by after one closing-opening cycle. (7 marks)

8. Describe the movement of the model snake if the static and kinetic friction coefficients are large when the model snake moves backward and are 0 when it moves forward. (2 marks)

Section C: Violin Vibrations

Suggested time: 30 minutes

This question uses concepts from waves and motion. If you have studied waves before you may have seen diagrams which show waves on strings as sinusoids.
One aspect of these diagrams which is correct and useful for this question is that they show points of no movement (nodes) at the ends of the strings. This must be true for the ends of a violin string because they are held in place at these points.
However, the sinusoidal shape can be misleading because it indicates that there is only one pure musical note. In reality there could be many different notes at the same time resulting in very different shapes.
Below is a diagram of a violin. Take note of the location of the nut and the bridge, between which the string can vibrate. The bow moves the string transversely in the section between the bridge and the start of the fingerboard.



The following information may be useful.

A violin consists of four strings, each of different thickness and tension. They are held still on one end and connected to the (tuning) pegs on the other. Turning the pegs allows the tension in each of the strings to be adjusted independently. A violin is played by sliding the bow on the string between the bridge and the fingerboard.

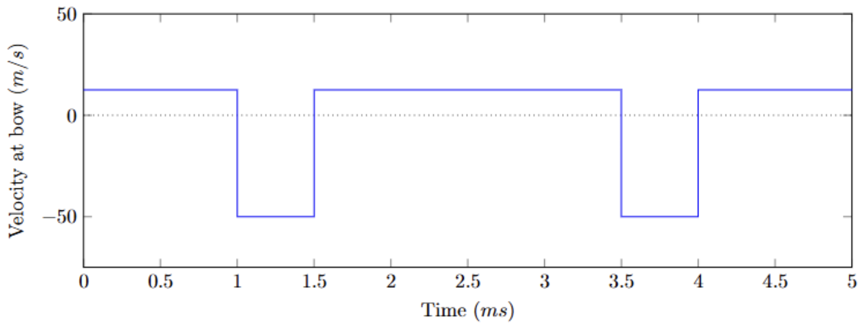
Near the end opposite to the pegs, there is a 'bridge' which elevates the strings. On the other end, there is the 'nut', or a raised bump similar to the bridge (but much shorter). The bridge and nut mark the two fixed ends of the string, and only the length of string in between can oscillate.

In this question, we model a violin as a single string fixed at both ends, the bridge and the nut.

Sound is a vibration of particles in some medium (such as air). To produce sound, the violin string forms waves. If these waves have a resonant frequency they can travel up and down the length of the string without decaying over time. While all higher overtones are possible (and give rise to the violin's unique sound), in this question you may assume that only the lowest frequency wave occurs. When the string oscillates, it transfers that oscillation to the air inside the hollow body of the violin which is amplified by the body and transmitted to our ears.

Placing a finger along the string shortens the effective length of the string that can oscillate to produce different pitches/frequencies. Ignore the change in tension due to pressing down on the string.

A bowed violin string oscillates rather strangely. The bow alternates between 'sticking' to the string and allowing it to 'slip'. Below is a graph showing the velocity of the string at the point of contact with the bow over time.



The period T (in seconds) is the time taken between two consecutive occurrences of a repeating event (like a vibration on a string). It is related to the frequency f (in Hertz) by the formula:

$$f = \frac{1}{T}$$

1. Using the graph above, determine the frequency of the sound produced by this bowed violin string. (1 mark)

2. Sketch a graph of the displacement of the string at the point of contact with the bow over time. Label the amplitude of the motion. Hint: The displacement must return to 0 after each period. (7 marks)

3. Using your answer to part 2, or otherwise, sketch a graph of the displacement of the string over its length at t=1 ms. Hint: think about what the string would look like if you took a picture. For this question assume that the note played is the lowest note that the violin can play for this string length. (6 marks)

4. The speed of a wave v in a string depends on the tension force, T, and the linear mass density μ (mass per unit length) of the string. It is given by $v=T^a\mu^b$ where a and b are constants. Using dimensional analysis, determine the exponents a and b. (3 marks)

One technique that violinists can use is known as 'harmonics'. To play a 'harmonic', the violinist will place their finger lightly on the string in certain points. Instead of shortening the effective length of the string, the finger forces that point to be a node (zero displacement), while still allowing the entire string to oscillate.

5. Draw a scale diagram of the violin string and label the nut and bridge. Indicate clearly on the diagram exactly three points where a violinist could place their finger lightly to achieve 'harmonics'. (2 marks)

6. The wavelength of a wave is the distance between consecutive peaks. A wave moving at a constant speed travels one wavelength in one period. For each of the positions in part 5, determine the frequency that would be heard, as a multiple of f_{open} the frequency of the open string. Show your working and justify your answer. (3 marks)

An ‘octave’ is an interval between two frequencies where one is twice the frequency of the other. Because the octave sounds harmonious, almost all musical systems around the world split the octave into notes that ‘repeat’ each octave. In Western classical and pop music, the octave is split into 12 notes. The frequency of the next highest note is a constant multiple of the previous note’s frequency.

A more advanced technique is known as ‘artificial harmonics’. To play an ‘artificial harmonic’, the violinist will place one finger on the string, as if to play a note normally, and another finger in front (closer to the bridge) of the first lightly, as if to play a harmonic. If the interval between these two fingers is appropriate, the effective length of the string is shortened and a point is forced to be a node.

Suppose the violinist places their first finger on the A-string (440.00 Hz) and plays the note B (493.88 Hz). Then, they lightly place their pinky, as if to play a harmonic. An artificial harmonic is heard two octaves above the note B.

7. What frequency should sound if the first finger is lifted and the pinky is placed firmly down? (5 marks)

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Being an avid contemporary musician, our violinist wants to create a new musical system called the ‘decimal scale’. It is based on the Western system but splits the octave into only 10 tones instead of 12. The notes in the octave are now numbered 0 to 9, which each successive octave is encoded by the ten’s digit. The lowest note 0 in the new system corresponds to a low C in the Western system (f_0=16.35 Hz).
For example, the note 10 would be exactly one octave about the note 0 and would correspond to 32.70 Hz. The note 43 would be two octaves above the note 23.

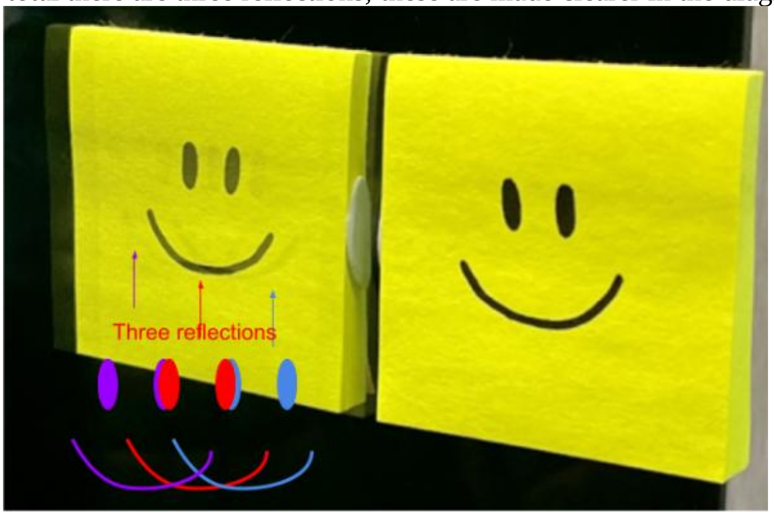
8. Find a relationship between the note number N and the frequency f in Hz in terms of f_0. What frequency in Hz would the note 27 correspond to? (5 marks)

Section D: Reflection Replicas

Suggested time: 5 minutes

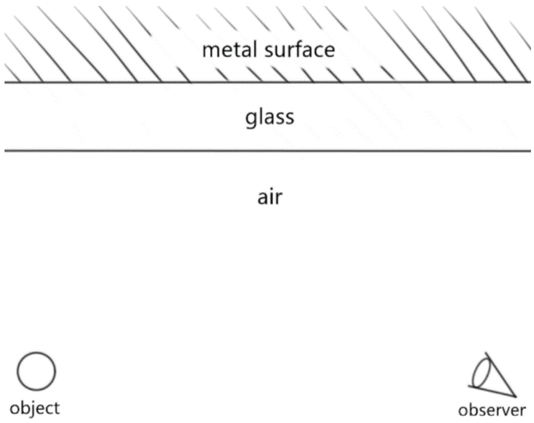
Jane was looking in the mirror one day when she noticed that her reflection had two very faint copies:

This means that in total there are three reflections, these are made clearer in the diagram below:



Her mirror is made up of a layer of glass backed by a reflective metal layer, as shown in the question below. The glass reflects about 4% of the light that hits its surface, and transmits the rest into/out of the mirror.

1. Explain using a drawing of light ray paths how these three reflections may have been formed. You may wish to use a diagram similar to the one below. (5 marks)



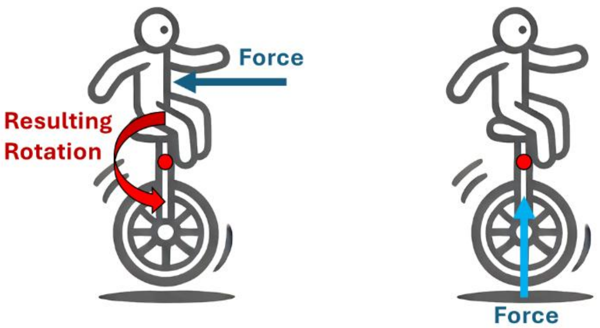
Section E: Twisting Torques and Leaning Lego

Suggested time: 25 minutes

When studying Newton's laws you will have learned that for an object to remain at rest, the forces on it must be balanced. However it is possible for an object with balanced forces on it to twist. There is a rotational equivalent of force that we use to determine if an object will twist or rotate which is called torque.

For this question we will define a clockwise torque as a torque which makes the unicycle-human system rotate clockwise.

For the following questions we will think about torques around the centre of a unicycle-human system. In the two diagrams below there are two unicyclists both with a single force depicted.



The force on the left unicyclist is an anticlockwise torque around the red dot (centre of the unicycle human system). The force on the right unicyclist points directly at the red dot therefore there is no off-centre force and no torque. For each of the unicyclists in the questions below determine whether the force depicted corresponds to a clockwise torque, an anti-clockwise torque or no torque with respect to the red dot.

1. For each of the three diagrams below indicate whether the force on the unicyclist corresponds to a clockwise, anti-clockwise torque or no torque. (3 marks)

The torque caused by a force is given by the following formula: $\tau = rF\sin(\theta)$
Where: τ is the magnitude of the torque, r is the distance between the point about which we are calculating the torque and the force's location on the object, F is the magnitude of the force. θ is the angle between the force F and a line joining the force's position to the position around which we are calculating the torque. Note that this means it is possible for a small force to have an equal torque to a large force if the smaller force is significantly further away.

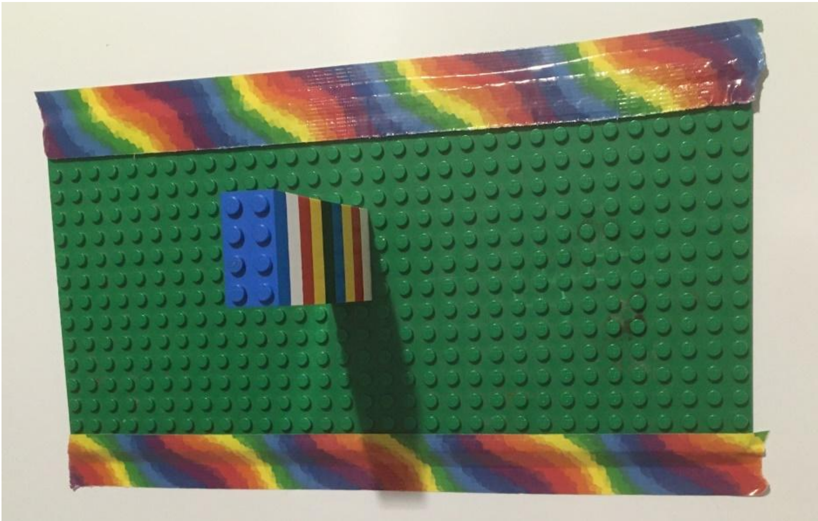
A free body diagram is a diagram where the forces are represented as straight arrows. The size of the arrow should roughly indicate the size of the force. If you wish to use an arrow to represent the direction of motion or acceleration make sure that it is clearly labelled and separate from the rest of the diagram.

Newton's Laws state that if an object has a net force it will accelerate. Similarly if an object has a net torque (around any point) then it will start to rotate or change its rotational velocity. If a unicyclist has an unbalanced torque then the unicycle will start to fall over (not desirable).

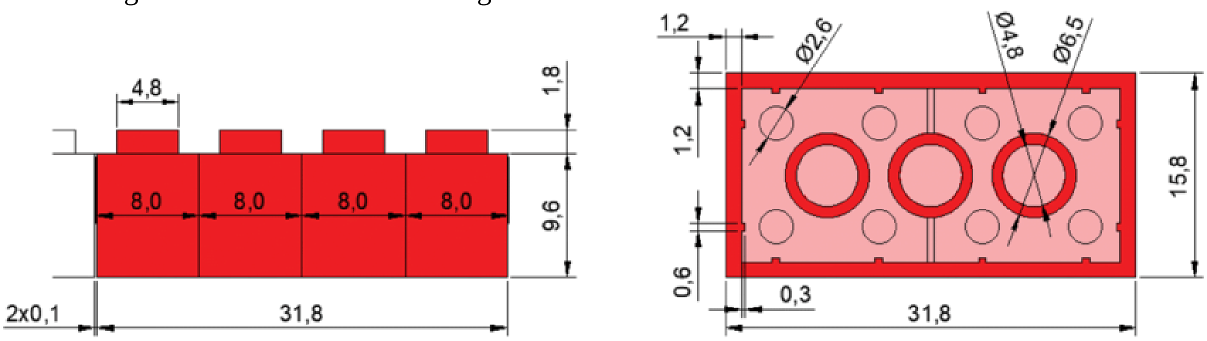
2. With this in mind, draw a free body diagram of the unicycle/ unicyclist system in each of the following circumstances. State whether the forces are balanced and whether the torques are balanced. (6 marks)
    a. The unicycle and rider are stationary.
    b. The unicycle and rider while moving at constant velocity.
    c. The unicycle and rider while accelerating forwards.

The next part of this question is called Leaning Lego Logic. It uses the information that you learned about torque from the previous parts of the question.

You suddenly decide that you are interested in determining the coefficient of static friction of Lego. So you tape a Lego baseplate to your fridge (using rainbow duct-tape) and start stacking 2x4 bricks outwards as shown in the image below.



You also accurately measure the brick weight (2.32 g) and dimensions. The dimensions of the Lego bricks are given in millimeters in the diagram below.



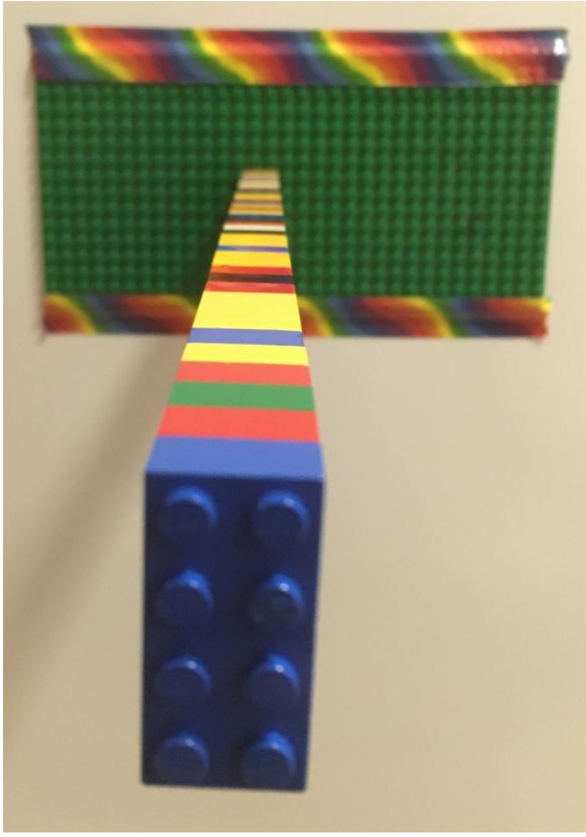
The cylindrical bumps that are on top of the Lego bricks are called studs.

Your plan is to find out how many bricks it takes before the horizontal 'tower' falls down. Assume that acceleration due to gravity is $9.8 m/s^2$.

3. Draw a free body diagram of your experiment showing the relevant forces. (4 marks)

4. Imagine you kept making the horizontal tower longer and longer until it collapsed under its own weight. Where in the tower do you expect it to fail (break)? Justify your answer. (3 marks)

You are impressed with how strongly these bricks hold!



You find that the horizontal tower was able to hold 44 Lego bricks before collapsing.

5. For this question assume that only friction from the top of each stud prevents each piece of Lego from sliding off the previous piece. Assume that the weight is distributed evenly between the studs. Assume that the normal force is caused only by the weight of the blocks hanging from the studs. Using the formula $F = N\mu$, where F is the friction force, N is the normal force and μ is the static coefficient of friction, find μ. Show your working. (4 marks)

You find that the coefficient of friction is unrealistically high. So you think long and hard and realise there must be extra forces that you hadn't considered: compressive forces from the tightly fitting Lego bricks!
So now you ask yourself a new question. What is the compressive force (the inward compressing force pushing on the 8 studs) acting on a Lego brick?
After trawling the internet, you find the coefficient of friction of ABS (Lego) is 0.09.

6. Using your experimental results, determine the compressive force acting between stacked Lego bricks. Show your working. (4 marks)

<u>END OF EXAM</u>