School ID

2025 AUSTRALIAN SCIENCE OLYMPIAD

PHYSICS

TO BE COMPLETED BY THE STUDENT. USE CAPITAL LETTERS.

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

Home Address:

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Phone Number: ……………………………………………………………………...

Email: ……………………………………………………………………………...

Date of Birth: ……/……/...….

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

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

Student ID (issued by your school): …………………………………………………..

To be eligible for selection for the Australian Physics Olympiad Summer School, students must be Australian citizens.

If you do not complete your contact details above it may not be possible for you to get an offer of a place at the Australian Physics Olympiad Summer School. The Australian Physics Olympiad team will be selected from students participating in the Australian Physics Olympiad Summer School.

Please note - students in Year 12 in 2025 are not eligible to attend the 2026 Australian Physics Olympiad Summer School.

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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.
- You are not allowed to access the internet or any notes.
- Ensure that diagrams are clear and labelled
- All numerical answers must have correct units
- This is not an exam, it is a challenge. Don't worry too much about the final answers, have fun thinking about the problems and show us how you think. Enjoy!
- The challenge consists of four questions, these are all equally weighted. Therefore it is recommend that you spend 30 minutes on each one.

Integrity of Competition

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

Question 1 – Sliding Snails

Imagine a human walking on perfectly flat ground. With each step they accelerate and decelerate.
1a) Which force is responsible for this acceleration and deceleration?

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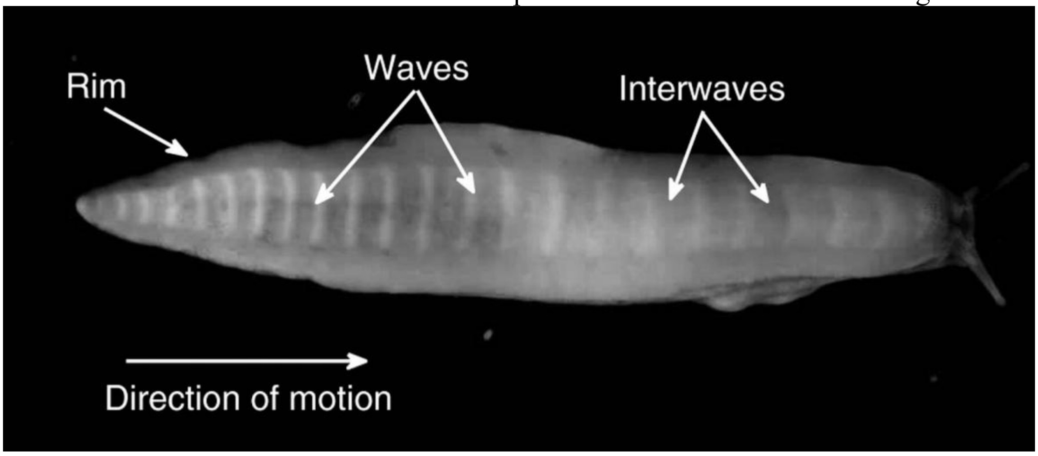
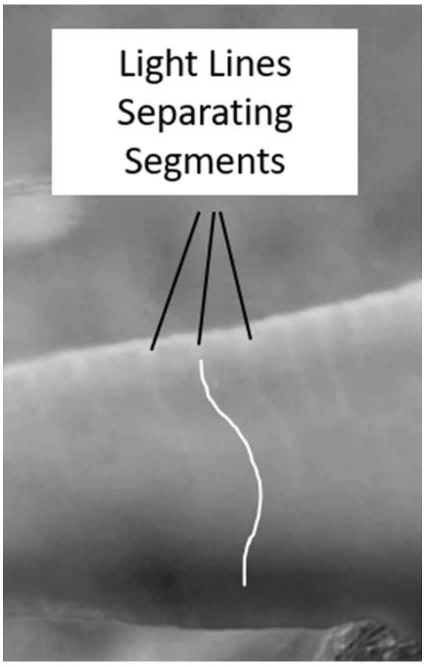
The underneath of a snail is called a foot. When a snail is backlit and travels across a surface, light regions called 'waves' and dark regions called interwaves can be observed in the snail's foot moving from its tail to its head. The rim refers to the outer part of the snail's foot. See the diagram below.



The snail is made up of segments separated by thin lines. These can be seen in the diagram to the right. In the diagram a white line highlights one of these thin lines between segments.



The following can be observed as the snail moves forwards.

- The thin lines move toward the front of the snail when a wave passes.
- The thin lines move towards the back of the snail when an interwave passes.
- There is significantly less movement in the rim.

b) Based on these observations, which part(s) of the snail's foot are stationary with respect to the glass as it slides? Using evidence, justify your answer.

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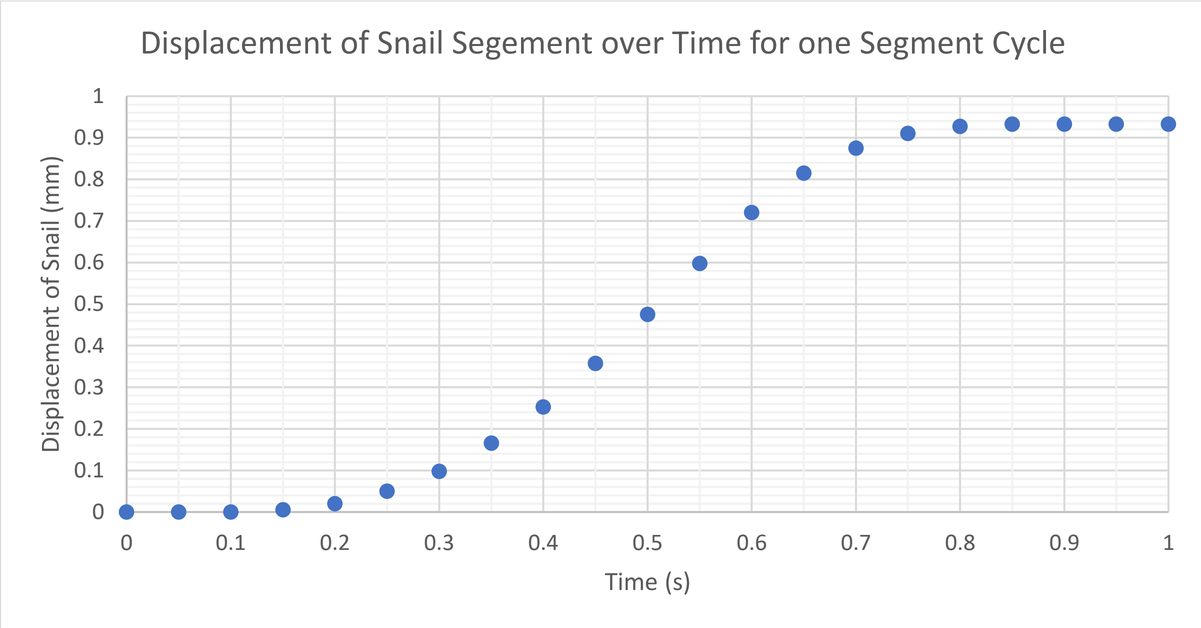
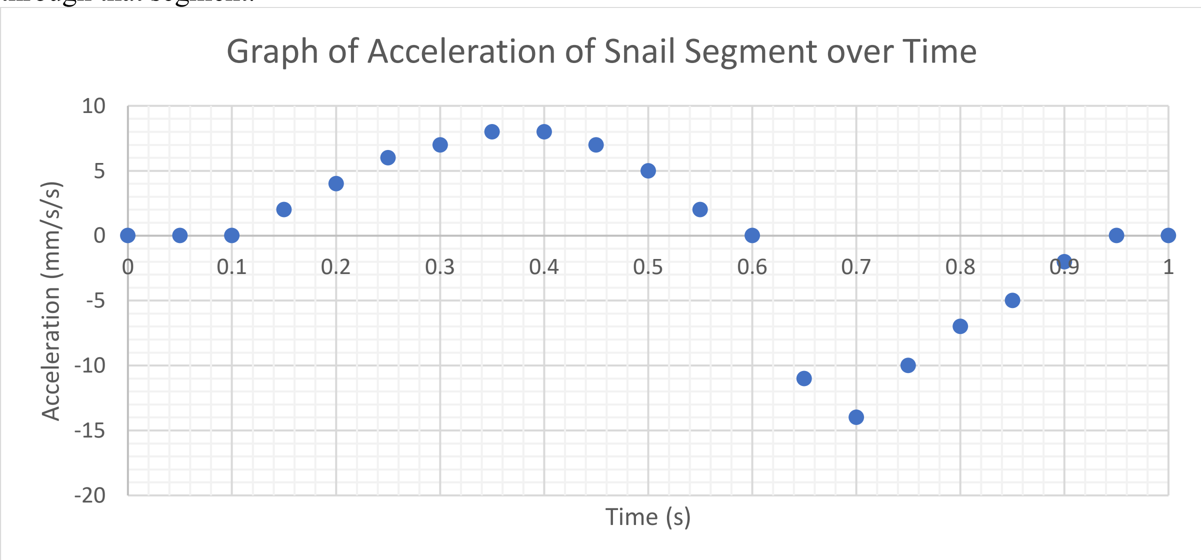
Scientists have measured the displacement, velocity and acceleration of a segment of a snail foot relative to the glass as a wave passes through it. The graph below shows the displacement over time for one segment cycle.



c) Using this graph calculate the maximum velocity of the snail relative to the glass throughout this motion. Show your working.

The graph below shows the acceleration of a segment of snail relative to the glass as a wave passes through that segment.



d) Using this acceleration graph calculate the maximum velocity of the snail relative to the glass throughout this motion. Show your working. Does your answer agree with your answer to part c?

e) Create a sketch of the snail segment velocity of the snail over time.

For questions f and g, evaluate if the following statements are true or false. Provide evidence for your claims.

f) The pressure associated with the normal force between the snail and the glass is maximum in the wave regions and minimum in the interwave regions.

g) The average speed of the snail relative to the glass is faster than the average speed of the waves passing through the snail relative to the glass.

You may use the rest of this page and the following page as working space for question 1.

Question 2 – Practicals with Paper

This exam booklet is (hopefully) made of A4 paper. Typical office paper has a thickness defined by 80 grams per square meter. An A4 sheet of paper has a defined size and is part of the A-series of paper, which also includes A3 or A5 paper. These paper size regulations are defined by the ISO 216 standard. The A-series of paper has a few intriguing properties:

- Every size in the series has the same ratio of long edge to short edge
- If you join two sheets of the same size along the long edge, you get the paper that is the next up in the series. For example, two A4 pieces of paper joined along the long edge gives an A3 page
- A0 paper has an area of exactly 1 square meter

2a) Calculate the length and width of an A4 piece of paper to 4 significant figures.

2b) The mass of a typical A4 sheet of paper is 5×10^{a} kg. What is the integer exponent a?

2c) Estimate the density of the paper comprising this exam booklet. Briefly explain your method and calculations, and include an estimate of the uncertainty in your measurement.

When two surfaces move past each other while in contact, they experience a friction force that acts to oppose the motion. The magnitude of the frictional force between two surfaces sliding past one another is given by

$F = \mu N$ … (1)

Where N is the normal force between the two surfaces and μ is the coefficient of kinetic friction, a measure of 'roughness' between the two surfaces.

2d) Austin has designed an experiment to measure the coefficient of kinetic friction between paper and paper. The method he used is outlined below.

1. Take a wooden plank with the top surface covered with paper and place it against the wall at some angle to the ground.
2. Place paper along the ground after the ramp.
3. Wrap a 500 g mass in paper and let it slide from rest, starting at the top of the plank.
4. Measure the distance d between the end of the ramp and the final position of the mass.
5. Repeat for different angles of the ramp.

The data Austin collected is shown in the table below. Unfortunately, he did not get time to finish the analysis of the data. Complete the following table (there are more columns than needed) and plot an appropriate graph to determine the coefficient of friction. Briefly comment on the validity of the result. If you can, also determine the length of the ramp used, s.

Hint: Derive an equation linking θ and d, and other constants, and linearise by writing it in the form $y = mx + b$ where x, y depend on θ and d, and m and b are constants.

θ (°)	d (cm)			
35	6			
40	23			
45	47			
50	61			
55	75			
60	94			
65	120			
70	129			
75	142			
80	162			

An object, like an A4 piece of paper, moving through a fluid such as air, experiences a drag force that acts opposite to the direction of motion with magnitude given by the equation below

$$F_D = \frac{1}{2}\rho A v^2 C_D \ldots (2)$$

where ρ is the density of the fluid, A is the surface area of the object perpendicular to the motion, v is the speed of the object and C_D is the dimensionless drag coefficient, which depends on the material and geometry.

An object which experiences a significant drag force will accelerate more slowly, eventually reaching a maximum speed called the terminal velocity.

2e) We are interested in performing an experiment to determine the drag coefficient of a flat rectangle. Design an experiment to measure the drag coefficient of a A4 piece of paper, which uses only the materials allowed in this exam, a tape measure and a stopwatch. Your answer should include (i) an explanation of the method in detail, (ii) any assumptions you made, (iii) how you would analyse your data to find the drag coefficient, and (iv) any significant sources of uncertainty and how you would mitigate them. You do not need to complete this experiment, but it might help to perform some tests!

(Additional space for writing/working for Question 2)

Question 3 – Fun with Friction

Friction forces oppose the relative motion between two surfaces in contact. The maximum force due to friction depends on the normal force N between the two surfaces (i.e. how strongly they are pressed together) and also the coefficient of friction (which depends on what the surfaces are made of).

The maximum force due to friction is given by:

$F = \mu N$ ... (1)

A cylinder of height h and radius r is placed upright on a ramp that is inclined at angle θ to the horizontal. This means that the circular face of the cylinder is against the ramp. The cylinder is of uniform density and has mass M. The coefficient of friction between the cylinder and the ramp is μ.

3a) Draw a free body diagram of the cylinder (that is, a diagram showing all of the forces acting on the cylinder).

3b) Stephen slowly tilts the ramp to increase its steepness. As the angle θ increases, eventually the cylinder will tip over. What is the angle of the ramp when the cylinder begins to tip over? Assume that the coefficient of friction between the ramp and cylinder is large, so that the cylinder does not slide on the ramp.

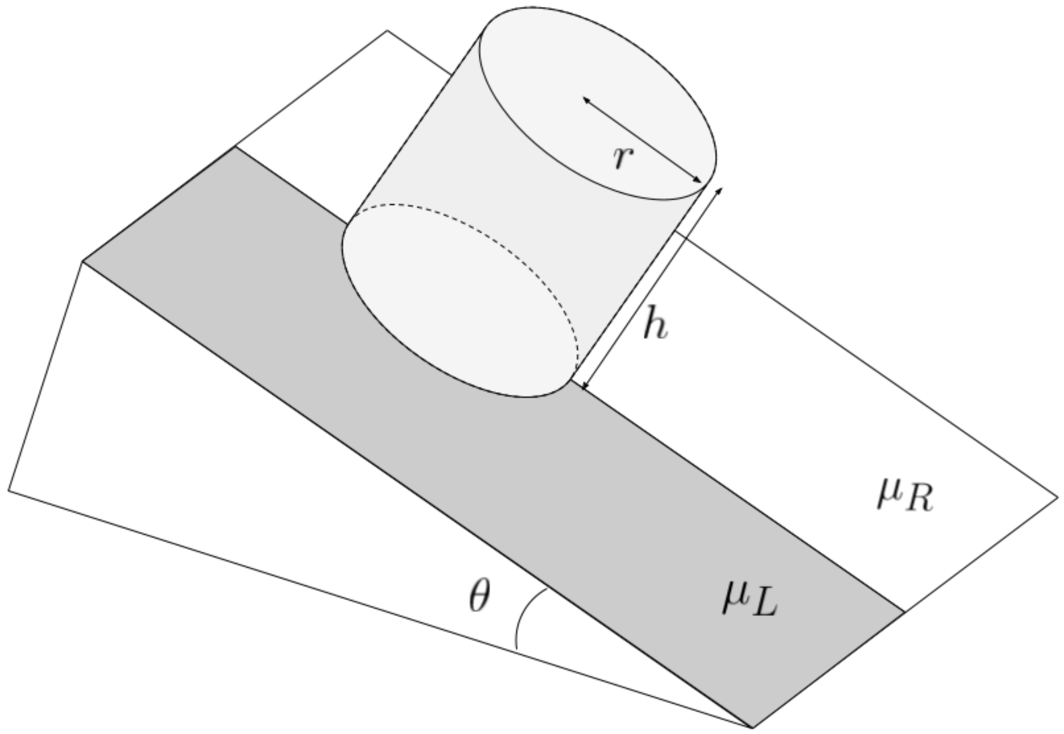
Next we will consider what happens if the coefficient of friction μ is lower, so that the cylinder slides down the ramp instead of tipping.

3c) The cylinder begins at a distance L from the bottom of the ramp. Find an equation for the amount of time, t, that it takes for the cylinder to slide to the bottom of the ramp.

3d) Find a numerical value for t (in seconds) for the case where $L = 4$ m, $h = 20$ cm, $r = 10$ cm, $M = 1$ kg, $\theta = 30°$, and $\mu = 0.37$. Write your answer to three significant figures.

$t =$

Now consider a ramp made from two different materials. The left side of the ramp has friction coefficient μ_L and the right side of the ramp has friction coefficient μ_R. The boundary between the two halves of the ramp is perfectly straight and in the centre of the ramp.



The cylinder is initially placed in the centre of the ramp, so the centre of mass is over the boundary between the two surfaces and half of the cylinder is on each side. Then, it is released and begins to slide down the ramp.

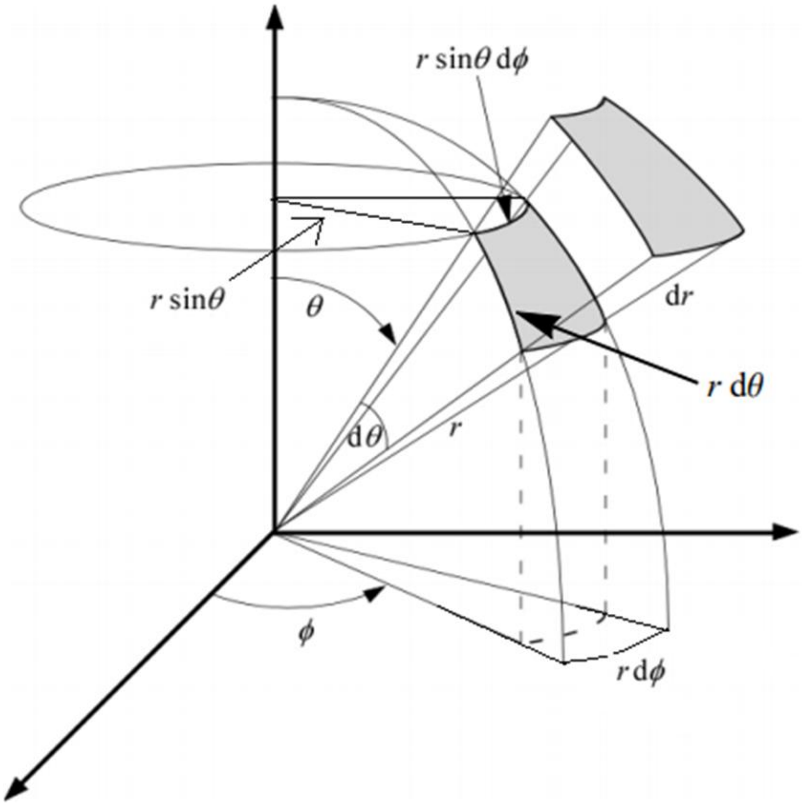
3e) Suppose that $\mu_L < \mu_R$. As the cylinder slides down the ramp, does its centre of mass move towards the left side of the ramp, the right side of the ramp, or remain in the centre? Explain your thinking using words (and diagrams if you wish).

(Additional space for writing/working for Question 3)

Question 4 – Introduction to Curved Spacetime

When a physical situation has spherical symmetry, it becomes more convenient to use a spherical polar coordinate system instead of a normal cartesian (x, y, z) coordinate system. The diagram below illustrates a polar coordinate system where any point in 3D space can be represented by three coordinates:

- a distance from the origin (r)
- an angle from the north pole (θ), we call this the ***polar angle***.
- a longitude angle moving towards the y-axis from the x-axis (ϕ), called the ***azimuthal angle.***



Note, the angular coordinates are given in radians. Also note that in this question d is not a variable, it refers to an infinitesimal (tiny) change in a variable. So in the diagram above, dr means a tiny change in radius and $d\theta$ and $d\phi$ mean tiny changes in angle.

4a) Consider two different objects. Object 1 is originally at the coordinate (r_1, θ_1, ϕ_1). Object 2 has the coordinates (r_2, θ_1, ϕ_1), where $r_2 > r_1$. Imagine that both objects are rotated around the vertical axis by the same angle. This results in a small change in ϕ_1. Which object travels further? Justify your answer.

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In physics, the term metric refers to a formula that defines how distances are measured. In cartesian coordinates the metric is given by Pythagoras's theorem:

$(ds)^2 = (dx)^2 + (dy)^2 + (dz)^2$ ... (1)

Where ds is the distance between two points and dx, dy and dz are the differences in the x, y and z coordinates respectively. When using spherical polar coordinates the metric is given by the following formula:

$(ds)^2 = (dr)^2 + (rd\theta)^2 + (r\sin\theta\, d\phi)^2$ ... (2)

Note that this formula is only accurate for small changes in coordinates dr, $d\theta$ and $d\phi$.

4b) Suppose that r and θ are kept constant ($dr = 0$ and $d\theta = 0$). In this circumstance how does $(ds)^2$ depend on r, θ and $d\phi$? Explore what the equation predicts and explain whether the behaviour makes sense or not.

At the North Pole, ϕ can change even though nothing moves. That's not a problem with the place, it's a problem with the coordinates. We call this a ***'coordinate singularity'***: the math looks weird, but space itself is normal. You could stand or walk there with no issues. That's different from a ***'physical singularity'***, where spacetime itself breaks down, like infinite gravity in some theories of black holes.

The theory of relativity proposed by Einstein between 1905 and 1915 states that time and space are not separate but should be considered together as a four-dimensional spacetime.

The spacetime around a non-rotating mass can be described by the Schwarzschild metric. In this case, the spacetime interval (the spacetime equivalent of distance) between two nearby events (events have a time coordinate t as well as position coordinates) can be described by the following expression:

$$(ds)^2 = -\left(cdt\sqrt{1-\frac{2GM}{rc^2}}\right)^2 + \left(\frac{dr}{\sqrt{1-\frac{2GM}{rc^2}}}\right)^2 + (rd\theta)^2 + (r\sin\theta\, d\phi)^2 \quad \dots (3)$$

Where $(ds)^2$ is the spacetime interval between two events, dt is a small time interval between the two events as observed by someone far away from the mass. We will define θ and ϕ the same way that we did in spherical polar coordinates. However, now we define the r coordinate differently because it may not be possible to walk radially out from a heavy mass. Instead, we construct a giant spherical frame around the mass. We define the coordinate r for any point on the frame as the circumference of the frame divided by 2π. G is the gravitational constant, M is the mass of the heavy object and c is the speed of light.

4c) At what points do singularities (both coordinate and physical) occur in the spacetime coordinate system defined by equation 3?

Imagine that we created two spherical frames, frame 1 has radius $r = r_1$ and frame 2 has radius $r = r_2$ where $r_1 > r_2 > \frac{2GM}{c^2}$. Imagine you are on the inside of frame 1 and extend a tape measure directly towards the centre of the frame until it touches frame 2. In everyday life, you would expect to measure a distance of $r_1 - r_2$.

4d) If frames 1 and 2 were built around a very large mass, would you actually measure $r_1 - r_2$ as the distance between the frames, or would you measure a different distance? Explain what you would measure and justify your answer.

We will now define $r_1 = r_2 + \Delta r$, such that frame 1 always has an r-coordinate slightly greater than frame 2. We will now use a (perfectly rigid) tape measure to measure the distance between the two frames. If you set $t = 0$, $\theta = \frac{\pi}{2}$ and $\phi = 0$, this distance is given by $\Delta L^2 = \frac{\Delta r^2}{1 - \frac{2GM}{r_1 c^2}}$

4e) Plot a graph of $\frac{\Delta L^2}{\Delta r^2}$ against r_1. Label any singularities on your diagram.

When two events occur at the same position, the proper time between the events is defined as the time that passed for an observer who was present at both events and is given by $d\tau = \sqrt{-(ds)^2}$. This time may not be the same time that is observed by someone far away who would measure the coordinate time dt.

4f) Imagine you are at a safe distance ($r \gg \frac{2GM}{c^2}$) and you have a strobe light which is falling and getting close to a heavy mass in the centre of the frame. The light is programmed to flash once per second. Describe what you would see watching this light if you remain at the safe distance. Justify your answer.

4g) How would this compare with your observations if you were to fall with the strobe light towards the centre?

A coordinate singularity happens at the Schwarzschild radius, the point of no return around a black hole. At this boundary, nothing can escape outward, not even light. The coordinates used in the standard black hole solution become confusing at this point, but just like at the North Pole, that doesn't mean the place itself is broken. It's possible that the coordinates are the problem.