وزارة التعليم
Ministry of Education

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National Science and Mathematics Olympiad

Learning Materials for the Fourth Stage Finals of "NSMO"2026

Physics

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chaptre1 Gravity

Before 1687, astronomers had meticulously recorded centuries of data on the motions of the Moon, Sun and planets. They could predict where celestial bodies would appear in the night sky, yet a fundamental question remained unanswered: *What forces govern these motions?* In that pivotal year, Isaac Newton provided the breakthrough that would transform our understanding of the universe.

Newton recognized, through his first law of motion, that the Moon's curved orbital path required a net force acting upon it—without such a force, the Moon would drift away in a straight line into space. He proposed that this force was the gravitational attraction between the Earth and Moon. But Newton's true genius lay in a more profound realization: the force governing the Earth-Moon system was not unique to celestial mechanics. Rather, it was a *universal* phenomenon—the same fundamental force that operated throughout the cosmos.

This insight was revolutionary. For the first time in human history, "earthly" and "heavenly" phenomena were unified under a single framework. Outer space was not governed by different laws from Earth—the entire universe operated according to the same physical principles. Newton published these ideas in 1687 in his monumental work Mathematical Principles of Natural Philosophy, often called simply the *Principia*.

In this chapter, we will explore Newton's law of universal gravitation and its profound implications. We will examine how this single elegant law explains planetary motion, and we will see how Johannes Kepler's empirical laws of planetary motion—discovered through painstaking analysis of astronomical observations—emerge naturally from Newton's laws. Finally, we will develop the concept of gravitational potential energy and use it to analyze the motion of planets, moons, and artificial satellites.

As you work through this material, remember that you are studying one of the greatest intellectual achievements in human history: a simple mathematical law that governs everything from falling objects to orbiting planets to the motion of galaxies themselves.

In this chapter, you will need some astronomical constants, and we list some here for reference.

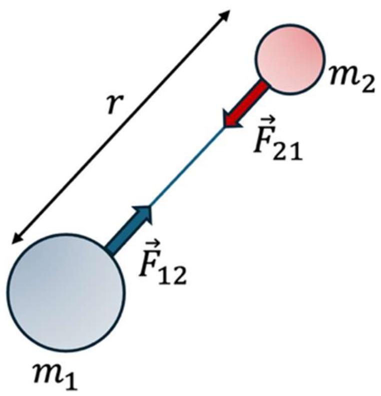
- Sun mass $M_E = 1.99 \times 10^{30}$kg

- Earth mass $M_E = 5.98 \times 10^{24}$kg
- Moon mass $M_M = 7.36 \times 10^{22}$kg
- Earth radius $R_E = 6.37 \times 10^{6}$m
- Average Earth to Sun separation $d_E = 1.50 \times 10^{11}$m
- Average Eart to moon separation $d_E = 3.83 \times 10^{8}$m
- Universal gravitational constant $G = 6.67 \times 10^{-11}$N · m^2/kg^2

1.1 Newton's Law of Universal Gravitation

The inverse square law for universal gravitation:

Every particle in the universe attracts all others with a force proportional to the product of the two masses and inversely with the square of the distance between their centers.



$$\left|\vec{F}_{12}\right| = \left|\vec{F}_{21}\right| = G\frac{m_1 m_2}{r^2} \quad (1)$$

G: universal gravitational constant $6.673 \times 10^{-11} N.m^2/kg^2$.

Notes:

- The gravitational force is a field force. Field forces are forces that do not require contact between the two bodies such as gravity, as opposed to contact forces such as friction.
- This law applies to point particles, as in their size is much smaller than the distance r. In this chapter, you can use this law for all bodies, and in the future, you will be introduced to ways of calculating gravity forces when the bodies are extended objects.

Example 1.1: a body of mass 20.0 kg was transported to height 160.0 km above the Earth surface. Calculate the ratio between its current weight and its weight when it was on the surface.

Solution: The weight is the same as the gravitational force between the body and Earth. The weight on the surface of the Earth is

$$W_i = \frac{GM_E m}{R_E^2}$$

The weight at height h is calculated by the separation $r = R_E + h$

$$W_f = \frac{GM_E m}{(R_E + h)^2}$$

The ratio between them is

$$\frac{W_f}{W_i} = \frac{R_E^2}{(R_E + h)^2} = 0.952$$

Note that the answer does not depend on the masses of the Earth or the body since it is a ratio between weights.

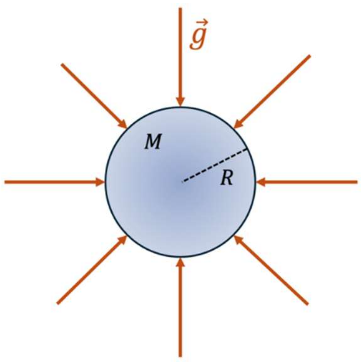
Exercise 1.1: calculate the average gravitational force between the Sun and Earth. Compare it with the average force between the Earth and Moon.

Search: look up Cavendish experiment, which is the first experiment to determine the value of the universal gravitational constant G.

Gravitational field:

The gravitational acceleration generated by an object is its gravitational field, and its magnitude for a celestial body of mass M and radius R at a height h from its surface is given by

$$g = \frac{GM}{(R + h)^2} \qquad (2)$$



Example 1.2: at what height above the surface of Earth would its gravitational acceleration be one quarter of its magnitude at the surface?

Solution: the acceleration at the surface of the Earth is given by

$$g = \frac{GM_E}{R_E^2}$$

We want to find the height at which the acceleration is one quarter of this value

$$\frac{1}{4}g = \frac{GM_E}{(R_E + h)^2}$$

Dividing the two equations, we find

$$\frac{(R_E + h)^2}{R_E^2} = 4 \Rightarrow R_E + h = 2R_R$$

Therefore, the height is

$$h = R_E$$

Exercise 1.2: a mass $m = 1.0$ kg weighs on the moon sixth of its weight on Earth. Calculate the mass of the Moon using this information and the radius of the moon provided at the beginning of the chapter. Check that your result agrees with the known mass of the Moon.

Exercise 1.3: a satellite of mass m orbits Earth in a circular orbit with a speed v. Prove the following relation

$$v = \sqrt{\frac{GM_E}{R_E + h}}$$

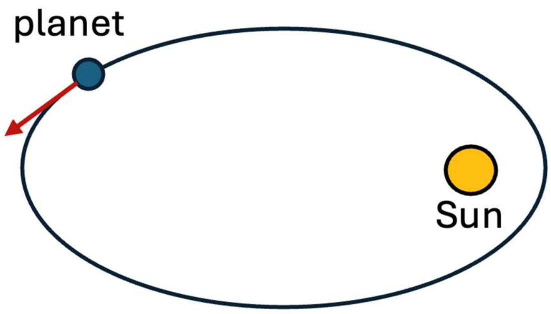
Where M_E is the Earth mass, R_E is the radius of the Earth, and h is the height of the satellite above the surface of the Earth.

1.2 Kepler's Laws

Long before Newton formulated his law of universal gravitation, German mathematician and astronomer Johannes Kepler (1571-1630) made a discovery that would lay the groundwork for understanding planetary motion. Through years of painstaking analysis, Kepler developed three mathematical laws that accurately described how planets move around the Sun—though he did not know *why* they moved this way.

First law: Law of Orbits

Every planet has an elliptical orbit, with the Sun at one of its foci.

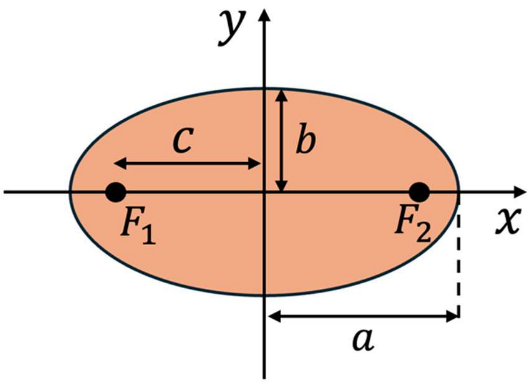


Notes:

- Most planets orbit the sun in nearly circular orbits.
- Many comets follow Kepler's laws like Halley's comet.

Geometric description of the ellipse:

The figure depicts the geometric description of an ellipse



a is the semi-major.

b is the semi-minor.

There are two foci F_1 and F_2 at a distance c from the center of the ellipse along the major axis. The Sun is at one of the foci.

$$a^2 = b^2 + c^2 \qquad (3)$$

Exercise 1.4: Circles are a special case of ellipses. Find a, b and c for a circle of radius r. What happens to the two foci in the case of the circle?

In the future, you will prove this law using Newton's second law and the universal gravitational law.

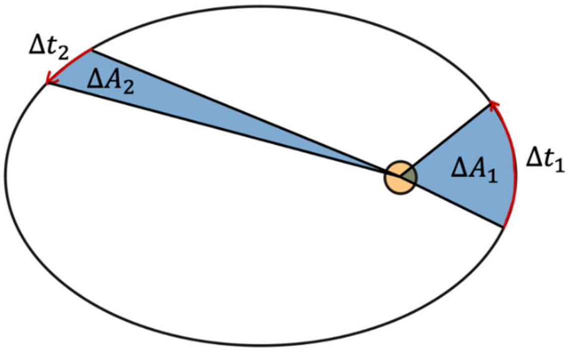
Second law: Law of Areas

The vector connecting a planet and the sun sweeps equal areas across equal time intervals. Mathematically, this law can be expressed as

$$\frac{\Delta A}{\Delta t} = \text{constant} \qquad (4)$$

so, the ratio between covered area and time interval is a constant

$$\frac{\Delta A_1}{\Delta t_1} = \frac{\Delta A_2}{\Delta t_2} \qquad (5)$$



Think: Why does a planet's speed increase as it gets closer to the Sun?

Exercise 1.5: Find the constant in Kepler's second law in the case of a planet of mass m orbiting a star of mass M in a circular orbit or radius R.

You will see in future trainings that Kepler's second law can be deduced from the conservation of angular momentum.

Third law: Law of Periods

The square of the period of any planet is proportional to the cube of the semi-major of its elliptical orbit around the sun.

$$T^2 = \frac{4\pi^2}{GM_S} a^3 \qquad (6)$$

T is the period.

M_S is the mass of the Sun or the star.

a is the semi-major of the orbit.

Example 1.3: Two moons orbit the same planet in circular orbits. The radius of of the first moon's orbit is r and it takes 20 days to complete a full rotation, and the radius of the second orbit is $4r$. What is the orbital period of the second moon?

Solution: Using the proportionality between T^2 and r^3, we find

$$\frac{T_2^2}{T_1^2} = \frac{r_2^3}{r_1^3} = \left(\frac{4r}{r}\right)^3 = 64$$

$$\Rightarrow T_2 = 8T_1 = 160 \text{ days}$$

Exercise 1.6: Prove Kepler's third law when the orbit is circular. Assume the mass of the star to be much larger than that of the planet.

You will prove this law for the case of an elliptic orbit in the future.

1.3 Gravitational Potential Energy

The potential energy due to gravity between two bodies is given by

$$U = -G\frac{m_1 m_2}{r} \tag{7}$$

and it is a negative value since it represents a bonding energy due to gravitational attraction.

Notes:

- The potential energy approaches zero when the two bodies are far away from each other and r goes to infinity.
- A body needs an external input of energy equal to the bonding energy in order to be freed from the bond, and any excess will be turned into kinetic energy.
- The equation $U = -Gm_1m_2/r$ does not result from multiplying force by distance, since this force is not a constant as a function of separation. It results from the process of integration, which you will face in the future.

Example 1.4: a meteor moves toward Earth at a speed 12.0 km/s when it was at a distance equal to ten times the radius of Earth from the Earth center. Find its speed when it reaches the Earth surface, ignoring air friction.

Solution: we will use energy conservation

$$E_i = E_f$$

$$\frac{1}{2}mv_o^2 - \frac{GM_E m}{10R_E} = \frac{1}{2}mv_f^2 - \frac{GM_E m}{R_E}$$

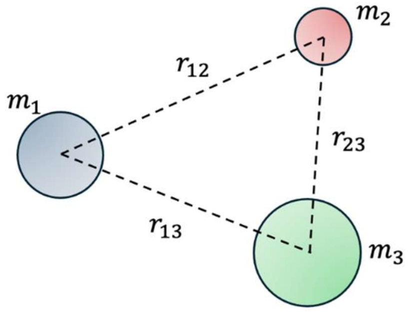
This can be solved algebraically (note that the mass of the meteor m cancels out)

$$v_f = \sqrt{v_o^2 + \frac{9GM_E}{5R_E}} = 16.0\text{km/s}$$

The total Potential energy for a system of gravitationally attracted bodies

When there are three masses, the total potential energy will be the sum of the pairwise potentials between all pairs

$$U_{total} = U_{12} + U_{13} + U_{23} = -G\left(\frac{m_1m_2}{r_{12}} + \frac{m_1m_3}{r_{13}} + \frac{m_2m_3}{r_{23}}\right) \quad (8)$$



Think: how would you express the total potential energy if there were four masses?

The total energy for the motion of planets and satellites:

Consider an isolated system where a body of mass m orbits a heavy object M such that $M \gg m$. If the semi-major was a, then the total energy of the system is

$$E = K + U = -\frac{GMm}{2a} \quad (9)$$

Exercise 1.7: Prove this equation in the case when the orbit is circular.

Escape velocity from Earth's gravity:

Since there is a bonding energy between bodies, such as between a space shuttle and Earth, if we launch the shuttle with high speed, it will succeed in escaping Earth's gravity. The needed velocity to escape the gravitational attraction is called escape velocity.

The escape velocity from a spherical planet of radius R and mass M is given by

$$v_{esc} = \sqrt{2GM/R} \qquad (10)$$

which you will derive in a following exercise. Note that the escape velocity does not depend on the mass of the object.

Example 1.5: calculate the escape velocity from Earth for a space shuttle of mass $m = 5.0$ Mg and calculate the kinetic energy it needs to gain at the surface of Earth to escape its gravity.

Solution: using the escape velocity formula and the known data of the Earth:

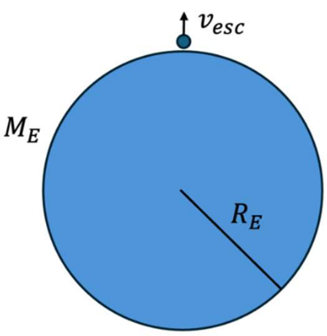
$$v_{esc} = \sqrt{\frac{2GM_E}{R_E}} = 11.2\text{km/s}$$

The kinetic energy ca be found by substituting in the kinetic energy formula

$$K = \frac{1}{2}mv_{esc}^2 = 3.1 \times 10^{14}\text{J}$$

Exercise 1.8: a body of mass m was launched vertically away from Earth's surface with an initial speed v_i. Prove that the smallest speed needed for it to escape from Earth's gravity is

$$v_{esc} = \sqrt{2GM_E/R_E}$$



Think: is there an escape velocity in the case of a body connected with an ideal spring? What is the difference between these two cases?

Think: Why do some planets have atmospheres, but some other do not?

Think: when calculating the escape velocity, we ignored many factors that would affect the real value for the escape velocity. Mention one factor that would help the body at escaping, and one effect that would make it more difficult for it to escape.

1.4 Additional Questions

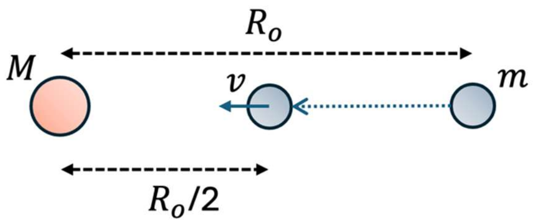
Question 1.1: The mass of Mars equals 0.11 of Earth's mass. If the weight of an object on Earth is 2.0×10^2 N, what will its weight be on Mars? The radius of Mars is 3.44×10^6m.

Question 1.2: Some satellites appear to be suspended at a fixed point relative to an observer on Earth's surface. Find the altitude of these satellites above Earth's surface, as well as their orbital velocity.

Question 1.3: Two objects with masses m and $4m$ are fixed at a distance d from each other. Where can we place a third object so that it will remain stationary under the influence of the gravitational forces acting on it?

Question 1.4: Halley's Comet completes one orbit in its elliptical path around the Sun every 76 years. In 1986, it was at its closest distance to the Sun in its orbit (between the planets Mercury and Venus), equal to $d_{min} = 8.90 \times 10^{10}$m. Calculate the farthest distance of Halley's Comet from the Sun.

Question 1.5: A mass m is attracted toward another fixed mass M starting from rest at a distance R_o from it. What will be the velocity of the mass m when it is at a distance $R_o/2$?

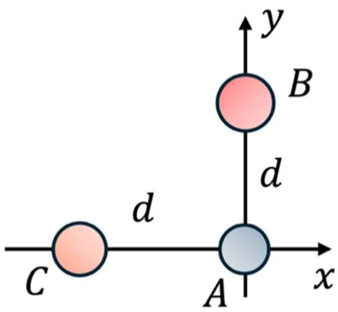


Question 1.6: An asteroid whose mass equals 2.0×10^{-4} of Earth's mass orbits the Sun in a circular orbit at a distance equal to twice Earth's distance from the Sun.

a) Find the orbital period of the asteroid in years.

b) What is the ratio of the asteroid's kinetic energy to the kinetic energy of Earth's revolution around the Sun?

Question 1.7: In the figure, three point particles are placed on the xy plane. The first body A has mass m_A, the second body B has mass $3m_A$, and the third body C has mass $4m_A$. Where should a fourth point particle D with mass $5m_A$ be placed so that the net gravitational force acting on body A equals zero?



Question 1.8: A satellite with mass 220.0 kg orbits in a circular orbit around Earth at an altitude 640.0 km above Earth's surface. Assuming the satellite loses mechanical energy at a rate of 1.4×10^5 J per orbital revolution, calculate its new orbital radius after completing 1500 revolutions.

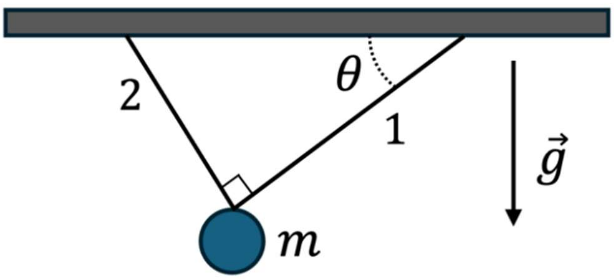
1.5 Simulation test

Question 1: Fahad will go from the first floor to the sixth floor at his work. The elevator ascends with uniform acceleration a for a time period T, then stops accelerating and continues its motion at constant speed for $4T$, then begins to decelerate with the same magnitude as the initial acceleration a for T until it stops. If the height of the sixth floor above the first is h, answer the following:

a) Draw graphs for the elevator's acceleration $a(t)$, velocity $v(t)$, and height $H(t)$ as functions of time from $t = 0$ to $t = 6T$.

b) Express a in terms of h and T.

Question 2: A mass m is suspended by two massless strings hung from the ceiling. The two strings form a right angle at the mass, and the first string makes an angle θ with the ceiling. What is the tension T_1 and T_2 in each of the two strings?

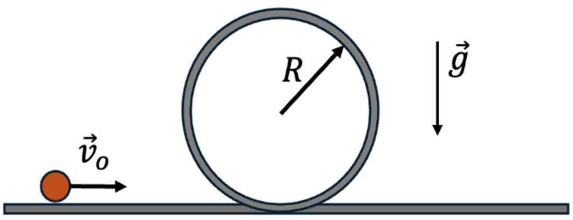


Question 3: A small ball with mass m is released from the top of a tall building. This ball falls due to Earth's gravitational acceleration $\vec{g}$, but it is affected by air resistance. If we assume that the air resistance force on the ball's motion is linearly proportional to the ball's velocity $\vec{v}$ with a positive proportionality constant b, then the force is given as follows:

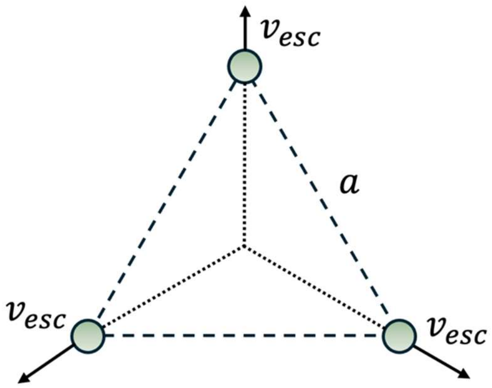
$$\vec{F}_d = -b\vec{v}$$

What is the maximum (terminal) velocity that the ball will reach in its fall? Assume g is uniform.

Question 4: A skater is preparing to complete a full loop around a vertical circular track. Assuming all surfaces are frictionless, what is the minimum speed v_o that the skater must launch with to complete the loop around the circular track, if the track's radius is R and gravitational acceleration g is uniform and points downward?



Question 5: Three identical objects with mass m are placed at the vertices of an equilateral triangle with side length a. What is the minimum speed v_{esc} that must be given to each mass in the direction shown (the extension of the velocity vectors intersect at the center of the triangle) for the objects to escape from each other's gravitational influence?

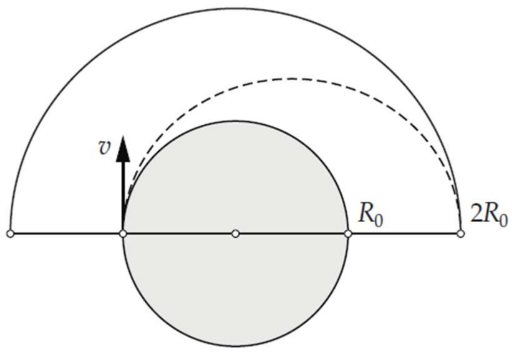


Question 6: Two stars rotate around each other in a circular orbit. Star A has mass M and star B has mass $2M$. If they are at a distance d from each other, find the orbital speed of star A, V_A.

Question 7: Astronauts on the Moon need to return to their spaceship, which orbits at a height equal to the radius of the Moon, $R_0 = 1700$ km (see Fig). The astronauts' return trajectory will be tangential to the Moon's surface and tangential with the spaceship's trajectory. The engine used by astronauts to return to the ship fires up only at the start of the journey. The acceleration due to gravity on the Moon's surface is $g = 1.7\ m/s^2$.

a) Find the initial velocity v of the astronauts on the Moon's surface after the engine fired up.

b) What will be the duration of the journey to return to the spaceship?



chaptre 2 Experiments

The famous physicist Lord Kelvin has a well-known quote: "I often say that when you measure something and express it in numbers, you know something about it, but when you cannot measure it and express it in numbers, your knowledge of it is limited and unsatisfactory."

Think: Give an example to which Lord Kelvin's quote applies.

2.1 Physics as an Experimental Science

Experimental Physics is the foundation of modern physics. It is the method by which we verify the correctness of theories and discover new phenomena. This is done through building experiments and taking measurements, where measurement is the comparison of an unknown quantity with a standard quantity.

Why do we need experiments?

- **Verifying theories:**

Physical theories explain scientific phenomena, and therefore must be tested. For example, Einstein's General Theory of Relativity predicted that light bends under the influence of gravity in 1915, and this was verified in 1919. Note that the time period between theoretical predictions and practical confirmations can reach several years or decades.

- **Discovering new phenomena:**

Many scientific discoveries came from unexpected practical observations, such as the discovery of X-rays by scientist Röntgen in 1895.

- **Developing technologies:**

Experiments lead to the development of new technologies that benefit humanity, such as the LASER which began as a theoretical prediction and then became a fundamental technology in our lives.

Research: Give examples of important experiments throughout the history of physics. What are the physical quantities that were measured in these experiments?

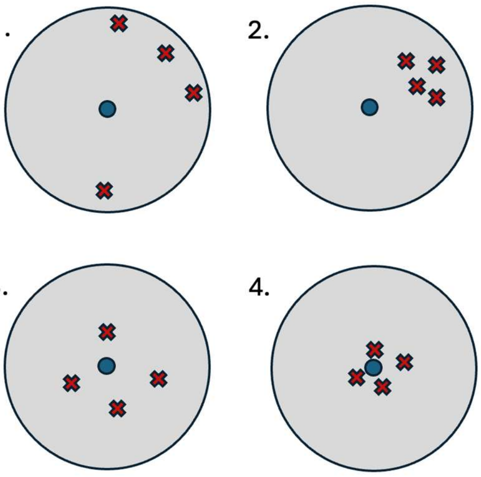
2.2 Precision, Accuracy and Errors in experiments

There is a difference between two main concepts in experiments:

Precision: Refers to how close repeated measurements are to each other. Precise measurements give closely grouped results, even if they are far from the true or reference value.

Accuracy: Refers to how close a measurement is to the true or accepted value of the measured quantity.

Look at the figure below which illustrates the difference using the image of targeting the center of a circle with arrows. Case 1 is neither accurate nor precise. Case 2 is precise due to close results but not accurate due to distance from the target. Case 3 is somewhat accurate but not precise. Case 4 is both precise and accurate.



Exercise 2.1: Ahmed and Hussam measured the speed of light. Ahmed obtained $(3.001 \pm 0.001) \times 10^8$m/s, and Hussam obtained $(2.999 \pm 0.006) \times 10^8$m/s. Which is more precise and why? Which is more accurate, given that the standard value for the speed of light is 2.99792458×10^8 m/s?

There are generally two types of errors we face when conducting experiments: **statistical errors** and **systematic errors**. Systematic errors stem from limitations in the precision of measurement instruments in the experiment and other factors that limit the precision and accuracy of measurements. Statistical errors come from variation in measurement results when repeating measurements many times, and can be reduced by taking additional data.

You will not estimate errors in your results at this stage, but you will work on strategies to reduce them, such as repeating measurements to avoid statistical errors and being careful to build and execute experiments properly to avoid systematic errors.

2.3 Data Recording

There are three basic stages for every experiment in the Physics Olympiad. The first is construction, the second is measurement, and the third is analysis.

In the construction stage, you will need to follow certain steps to build your experiment. For example, in electrical circuit experiments, you will need to connect measuring devices and other electrical circuit elements to the rest of the circuit. Sometimes, most steps for building the experiment will be given, but in some experiments, you will need to think about how to build the experiment yourself. In some experiments, it's easy to do this step, but in others, this stage may be the main challenge in the experiment.

In the measurement stage, you will start conducting the experiment, and during this time you will take various measurements that will help you find what is required.

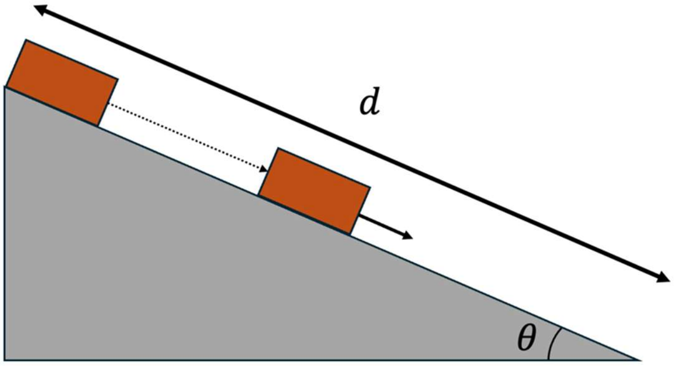
Note:

- You must review the rules of significant figures.
- Remember that the precision of a measuring instrument equals half the value of the smallest graduation on the instrument, so when writing your measurement results, make sure not to use significant figures that exceed the measurement precision of your instruments.

Example 2.1: Reema conducts an experiment sliding a cube on a smooth inclined plane to measure gravitational acceleration. She will use the known result from Newton's laws that acceleration is related to the distance covered d and time duration t as follows:

$$d = \frac{1}{2}at^2$$

In the case of a smooth inclined plane: $a = g\sin\theta$.



Let's assume she measured the angle θ and the length of the slope d. She will need to record these values in a table showing units and measurement precision.

θ [degree]	$d[cm]$	$t_1[s]$	$t_2[s]$	$t_3[s]$	$t_4[s]$	$t_5[s]$
10.	150.0	1.38	1.28	1.33	1.20	1.34

The question now is how do we use this data to obtain gravitational acceleration?

2.4 Data Analysis and Graphs

After you have tabulated your data, you will begin the third stage, which is the data analysis stage. In this stage, you must perform some calculations on the data you have collected. In case of repeated measurements, one of the simplest operations is taking the average.

$$\bar{x} = \frac{x_1 + x_2 + \cdots + x_N}{N} = \frac{1}{N}\sum_i x_i \qquad (1)$$

Calculating the average helps you reduce the effect of statistical error.

Example 2.2: calculate the average length from the list $\{10,15,18,25\}$ given that they are all measured in cm.

Solution: The formula for the average is given by the sum of the values over their number:

$$\bar{L} = \frac{10 + 15 + 18 + 25}{4}\text{cm} = 17\text{cm}$$

Exercise 2.2: Calculate the average time in Reema's experiment, then calculate the gravitational acceleration based on this result.

Note: You don't always need to repeat measuring all data. For example, you will need to repeat measuring the cube's sliding time several times, but you don't need to repeat measuring the length of the inclined slope or the angle several times.

When conducting an experiment like the cube sliding on an inclined plane experiment, it's useful to repeat the experiment with different distances and angles so we can extract unknowns through graphing. Often you will need to plot your data on a graph to find the value of some unknown. In simple cases, the theoretical prediction for the relation between variable x and variable y is often given by a function like:

$$y = ax^n + b \qquad (2)$$

where n is given and the requirement is to find the two unknowns a and b. The easiest way to do this is to transform the equation into a linear equation by calculating and plotting x^n on the horizontal axis instead of x. For example, if $n = 2$, you will calculate the squares of x values from the data table, then plot them. Then the slope of the straight line will be a, and the y-intercept will be b.

Example 2.3: Sama conducts an experiment sliding a cube on a rough inclined plane to calculate the kinetic friction coefficient μ between the cube and the rough surface. She collected the following data, using an inclination angle $\theta = 30°$. Given that gravitational acceleration at the experiment location equals 9.8 m/s^2. Sama collected data on the cube's sliding time for different distances and put them in the table below.

$d\ [cm]$	$t_1[s]$	$t_2[s]$	$t_3[s]$	$t_4[s]$	$t_5[s]$	$t_{avg}[s]$	$t_{avg}^2[s^2]$
40.	1.09	1.16	1.07	1.13	1.11	1.11	1.24
50.	1.28	1.21	1.24	1.17	1.27	1.23	1.52
60.	1.36	1.34	1.28	1.37	1.42	1.35	1.83
70.	1.56	1.45	1.42	1.61	1.40	1.49	2.22
80.	1.58	1.57	1.62	1.57	1.56	1.58	2.50

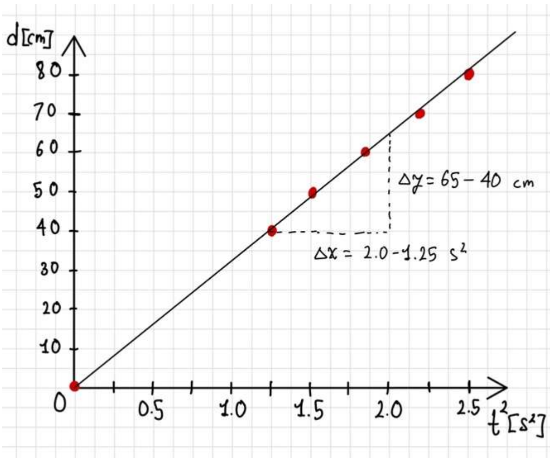
Note:

- Each column in the table starts with the measured or calculated quantity and its unit.
- The last two columns in the table were calculated using a calculator.

Sama will use her knowledge of Newton's laws to deduce that distance is related to time through:

$$d = \frac{1}{2} g(\sin\theta - \mu\cos\theta)t^2$$

So she plotted a graph of t_{avg}^2versus d:



The slope will be

$$\frac{\Delta y}{\Delta x} = 0.33\ \text{m/s}^2 = \frac{1}{2} g(\sin\theta - \mu\cos\theta)$$

And solving the equation for μ, we find that: $\mu = 0.50$.

Important notes:

- Note that the origin point was used in this analysis because it's obvious that the time duration will be zero when the displacement is zero, but using the origin point is not possible in all experiments and you must determine this.
- There are no points between $t = 0.0$ s and $t = 1.0$ s at the beginning of the graph, and this is appropriate because the precision of time measurement becomes worse when the distance covered is small because it becomes closer to reaction time.

Exercise 2.3 : In one experiment, there was an object moving with constant acceleration a in a straight line starting from rest. Saud conducted this experiment several times to measure the time the object needs to cover different distances. Saud recorded his measurements in the following table:

$d\ [m]$	$t_1[s]$	$t_2[s]$	$t_3[s]$	$t_4[s]$	$t_5[s]$	$t_{avg}[s]$	$t_{avg}^2[s^2]$
1.0	0.88	0.85	0.97	0.89	0.97		
2.0	1.32	1.23	1.24	1.21	1.24		
3.0	1.56	1.51	1.33	1.63	1.47		
4.0	1.80	1.84	1.70	1.84	1.75		
5.0	1.88	2.02	2.06	2.01	2.00		

Complete the table for the given data, then use what you know about motion with constant acceleration to find the value of acceleration a. Find the value of a by drawing an appropriate graph.

Exercise 2.4: Kayan analyzes data collected about a new star around which several planets orbit. The following table shows the semi-major axis of these planets' orbits around the star and the time period of their complete orbit.

$a[10^7\text{km}]$	T[years]
5.2	0.15
17.3	0.91
30.8	2.11
48.1	4.40
61.9	5.80
68.8	7.01
74.5	7.17

Draw an appropriate graph and use this data to calculate the star's mass. You can assume that the star's mass is much larger than the planets' masses.

Note: Notice that in this data, you cannot use the origin point $(a, T) = (0,0)$ in the analysis because it is not a case that can be obtained practically.

Important Notes: we will mention here some general useful tips for Olympiad experiments:

- While conducting experiments, it's important to think with the mindset of an experimental physicist and not a theoretical physicist. Building your experiment and taking data does not require deep and clear theoretical understanding of what happens in the experiment. Therefore, avoid spending much time trying to understand theoretical derivations of given equations and the like.
- Before building your experiment, read the steps and match the experiment tools. You will lose a lot of time if you make an error in building your experiment.
- Don't forget significant figures.
- Don't forget units in graphs and data tables.
- Always write the quantities you measured or chose in the experiment clearly.
- When taking repeated measurements, build a data table that clearly shows the measured quantities and their units.
- Leave room for data analysis in the tables you create.
- Think about how to reduce errors in your experiment.
- When drawing a graph, make sure your drawing covers more than two-thirds of the graph area.

2.5 Some Simple Experiments

Experiment 1: Free Fall

In this experiment, you will calculate gravitational acceleration through free fall. You will drop small balls from different heights and calculate the fall time. This data will help you find the gravitational acceleration on Earth's surface.

Tools:

- Timer
- Length measuring tool
- Two balls with different masses

Calculate the gravitational acceleration for both balls and compare your results.

Experiemnt 2: Static Friction:

In this experiment, you will calculate the static friction coefficient between a rough surface and an object.

Tools:

- Rough inclined plane with adjustable inclination angle
- Protractor to measure angles
- Small cube or board

By changing the inclination angle, determine the static friction coefficient between the inclined plane and the object you chose.

Experiment 3: Measuring Cube Dimensions:

In this experiment, you will determine the dimensions of an unknown object using vernier calipers.

Tools:

- Small cuboid with unknown dimensions
- Vernier calipers

Learn how to use vernier calipers and record your measurements of the parallelepiped's dimensions.

2.6 Simulation test

Question 1: Calculating Spring Constant

Tools:

- Spring with unknown constant
- Length measuring tape
- Different known small weights for hanging
- Base for hanging the spring

Hang the spring vertically. Assuming that the spring's restoring force follows Hooke's law:

$$\vec{F_s} = -k\Delta\vec{y}$$

where $\Delta\vec{y}$ is the displacement from the equilibrium point.

Find the spring constant k, given that gravitational acceleration equals approximately 9.8 m/s^2.

Question 2: Simple Pendulum

Tools: Simple pendulum - Measuring tape - Timer

The oscillation of a simple pendulum has a periodic time T that relates to gravitational acceleration g and rope length L through:

$$T = 2\pi\sqrt{\frac{L}{g}}$$

Calculate the period of the simple pendulum to determine the magnitude of gravitational acceleration.

Hint: To reduce error resulting from starting and stopping the timer, calculate the time for several periods.

Note: The mathematical formula above for the period of a simple pendulum is accurate when the oscillation angle is small.

Final answers to the fourth stage

Solutions to the first chapter exercises

Exercise 1.1: $F_{ES} \approx 3.53 \times 10^{22}$N, $F_{ME} \approx 2.00 \times 10^{20} N$, $F_{ME} \ll F_{ES}$

Exercise 1.2: $M_M \approx 7.4 \times 10^{22}$kg

Exercise 1.3: final answer is given

Exercise 1.4: $a = r$ ،$b = r$، $c = 0$. The foci merge at the center of the circle.

Exercise 1.5: $\Delta A/\Delta t = \sqrt{GMR}/2$

Exercise 1.6: $T^2 = 4\pi^2 r^3/GM$

Exercise 1.7: $E = -GMm/2r$

Exercise 1.8: final answer is given

Solutions to the first chapter additional questions

Question 1.1: $W_{Mars} = 75\ N$

Question 1.2: $h \approx 36000\ km$

Question 1.3: $x = 2d/3$. x is the distance away from $4m$ toward m.

Question 1.4: $d_{max} = 5.3 \times 10^{12}\ m$

Question 1.5: $v = \sqrt{2GM/R_o}$

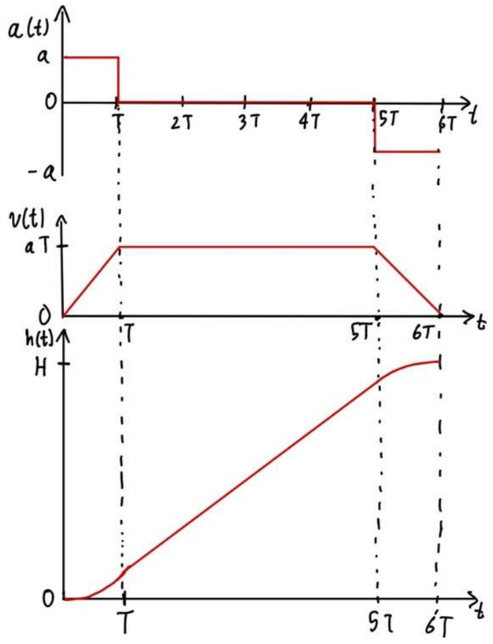
Question 1.6: $K_a/K_E = 10^{-4}$, $T_a = 2.8$ years

Question 1.7: $x_D = 4d/5$, $y_D = -3d/5$

Question 1.8: $r_f = 6.8 \times 10^6$m

Solutions to the first chapter simulation test

Question 1: $a = H/5T^2$



Question 2: $T_1 = mg\sin\theta, T_2 = mg\cos\theta$

Question 3: $v_{terminal} = mg/b$

Question 4: $v_o = \sqrt{5gR}$

Question 5: $v_{esc} = \sqrt{2Gm/a}$

Question 6: $V_A = \sqrt{4GM/3d}$

Question 7: $v = 2.0$ km/s ,$T = 96$ mins

Solutions to the second chapter exercises

Exercise 2.1: Ahmad is more precise while Hussam is more accurate

Exercise 2.2: $\bar{t} = 1.31$ s, $g = 10.1$ m/s^2

Exercise 2.3: $a \approx 2.5$ m/s^2

Exercise 2.4: $M \approx 4.0 \times 10^{30}$kg

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