HSC Physics Topic 1

SPACE

What is this topic about?

To keep it as simple as possible, (K.I.S.S.) this topic involves the study of:

1. GRAVITY & GRAVITATIONAL POTENTIAL ENERGY

2. PROJECTILES & SATELLITES

3. NEWTON'S LAW OF UNIVERSAL GRAVITATION

4. EINSTEIN'S THEORY OF RELATIVITY

...all in the context of the universe and space travel

but first, an introduction...

Mass, Weight & Gravity
were covered briefly in the Preliminary Course. In this topic you will revise these concepts, and be introduced to the concept of "Gravitational Potential Energy".

Then, you move on to study two important forms of motion that are controlled by gravity...

Projectiles...

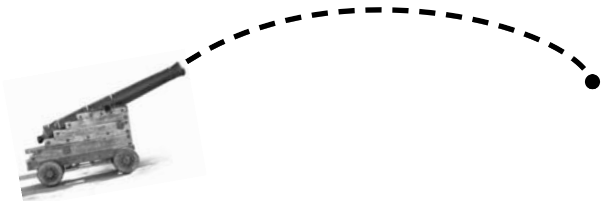


Photo by Davide

...and Satellites

Photo: Michael Diekmann

You will study how **Gravity** is responsible for holding the Solar System together...

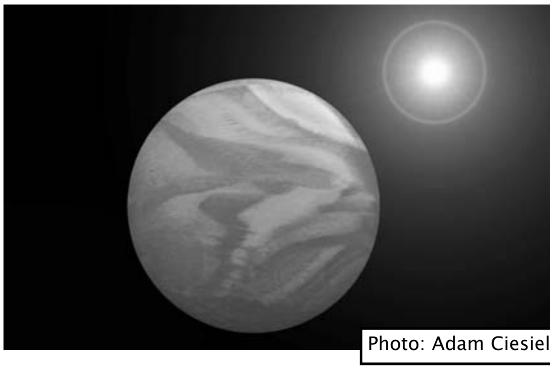


Photo: Adam Ciesielski

... and study a variety of aspects of Physics that relate to **Space Travel**

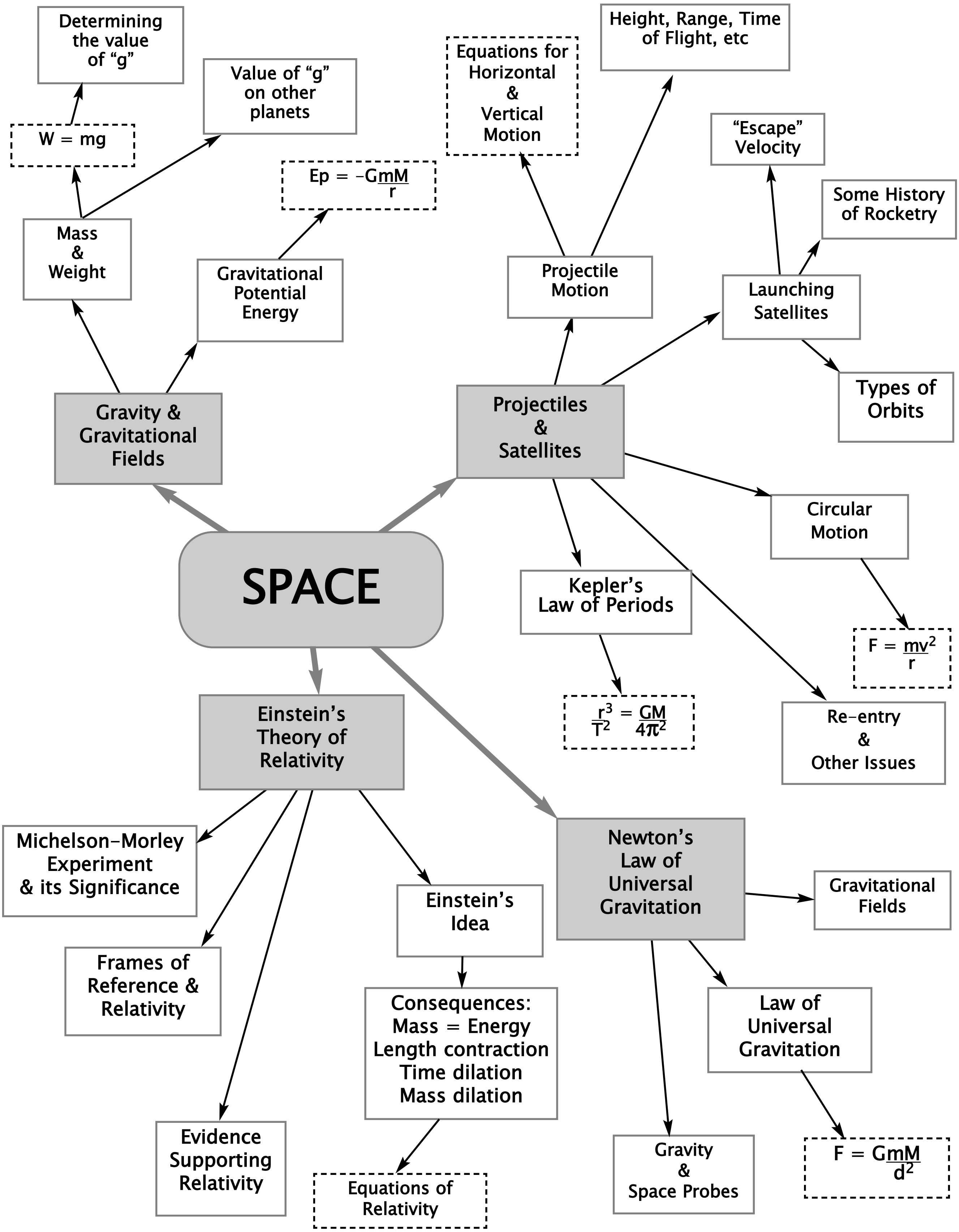
Photo: Onur Aksoy

In the final section you will study one of the most famous (and least understood) theories of Science:

Einstein's Theory of Relativity

CONCEPT DIAGRAM ("Mind Map") OF TOPIC

Some students find that memorizing the OUTLINE of a topic helps them learn and remember the concepts and important facts. As you proceed through the topic, come back to this page regularly to see how each bit fits the whole. At the end of the notes you will find a blank version of this "Mind Map" to practise on.



1. GRAVITY & GRAVITATIONAL POTENTIAL ENERGY

Weight & Gravity

You should already be aware that the "Weight" of an object is the Force due to gravity, attracting the object's mass toward the Earth. You also know that (ignoring air resistance) all objects near the Earth will accelerate downwards at the same rate. This acceleration rate is known as "g", and is approximately $10ms^{-2}$.

Weight = Mass x Acceleration due to Gravity

$$W = mg$$

Weight is in newtons (N)
Mass in kilograms (kg)
"g" is acceleration in ms^{-2}.

Gravitational Field

In one way, Gravity resembles electrical charge and magnetism... it is able to exert a force on things without touching them. Such forces are explained by imagining that there is an invisible "Force Field" reaching through space.

Gravitational fields are imagined to surround anything with mass... that means all matter, and all objects. The field exerts a force on any other mass that is within the field.

Unlike electro-magnetism, gravity can only attract; it can never repel.

Of the various "field forces", Gravity is by far the weakest, although when enough mass is concentrated in one spot (e.g. the Earth) it doesn't seem weak!

Measuring "g"

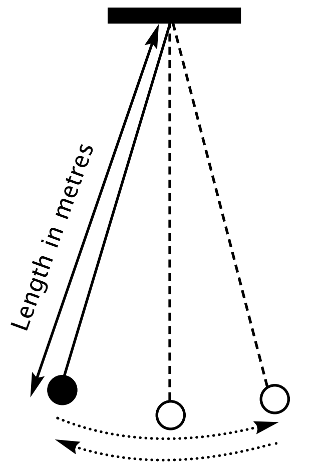
One of the first activities you may have done in class would have been to determine the value of "g", the acceleration due to gravity.

A common experimental method to do this involves using a pendulum.

By accurately timing (say) 10 swings of the pendulum, and then dividing by 10, the Period (T) can be measured. This value needs to be squared for graphing.

The length of the pendulum (L) is also measured as accurately as possible.

Typically, the measurements are repeated for several different lengths of pendulum, then the results are graphed as shown.



Time taken for 1 complete (back-and-forth) swing is called the "**Period**" of the pendulum ("**T**")

How This Relates to "g"

It turns out that the rate at which a pendulum swings (its Period) is controlled by only 2 things:

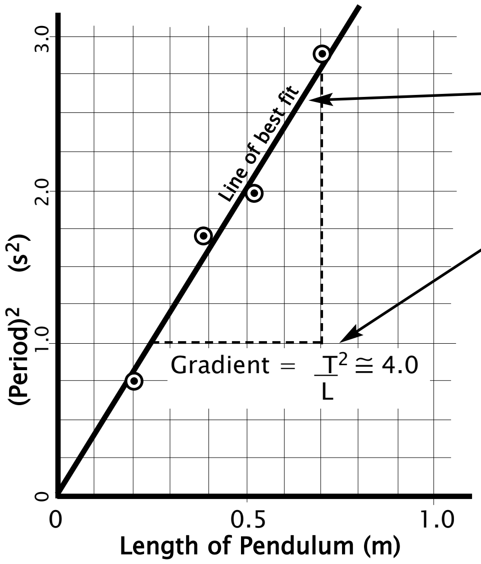
- its length, and
- the acceleration due to gravity

Mathematically,

$$T^2 = \frac{4\pi^2 L}{g}$$

so, $$\frac{T^2}{L} = \frac{4\pi^2}{g}$$

You are NOT required to know this equation.



Analysis

- The straight line graph shows there is a direct relationship between the Length (L) and the (Period)^2.
- Gradient, $\frac{T^2}{L} = \frac{4\pi^2}{g} \cong 4.0$

Therefore, $g \cong 4\pi^2/4.0 = 9.9\ ms^{-2}$.

Accepted value, g = $9.81ms^{-2}$

Explanations for Not Getting Exact Value:

The main causes of experimental error are any jerking, stretching or twisting in the string, which causes the pendulum swing to be irregular. This is why the most accurate results will be obtained with very small, gentle swings.

Gravitational Potential Energy (GPE)

Potential Energy is commonly defined as the energy "stored" in an object. In the case of any object on or near the Earth, the amount of GPE it contains depends on

- its mass
- its height above the Earth

If that object is allowed to fall down, it loses some GPE and gains some other form of energy, such as Kinetic or Heat. To raise the object higher, you must "do work" on it, in order to increase the amount of GPE it contains.

However, for mathematical reasons, the point where an object is defined to have zero GPE is not on Earth, but at a point an infinite distance away. So GPE is defined as follows:

Gravitational Potential Energy is a measure of the work done to move an object from infinity, to a point within the gravitational field.

This definition has an important consequence:
it defines GPE as the work done to bring an object towards the Earth, but we know that you need to do work to push an object (upwards) away from Earth.

Therefore, GPE is, by definition, a negative quantity!

$$GPE = \frac{-GmM}{R}$$

G = Gravitational Constant ($=6.67 \times 10^{-11}$)
m = mass of object (kg)
M = mass of Earth, or other planet (kg)
R = distance (metres) of mass "m" from centre of the Earth

Note: the HSC Syllabus does NOT require you to carry out calculations using this equation. You ARE required to know the definition for GPE.

In the interests of better understanding, here is an example of how the equation could be used:
How much GPE does a 500kg satellite have when in orbit 250km (= 250,000m) above the Earth's surface?
(Earth's mass = 5.98×10^{24}kg, Earth radius = 6.38×10^{6}m)

Solution
$$GPE = \frac{-GmM}{R}$$
$$= \frac{-6.67 \times 10^{-11} \times 500 \times 5.98 \times 10^{24}}{(6.38 \times 10^{6} + 250{,}000)}$$
$$= -3.00 \times 10^{10} \text{ J.}$$

The negative value is due to the definition of GPE.

Gravity and Weight on Other Planets

We are so used to the gravity effects on Earth that we need to be reminded that "g" is different elsewhere, such as on another planet in our Solar System.

Since "g" is different, and **W = mg**
it follows that things have a different weight if taken to another planet.

Values of "g" in Other Places in the Solar System

Planet	**g** (ms^{-2})	**g** (as multiple of Earth's)
Earth	9.81	1.00
Mars	3.8	0.39
Jupiter	25.8	2.63
Neptune	10.4	1.06
Moon	1.6	0.17

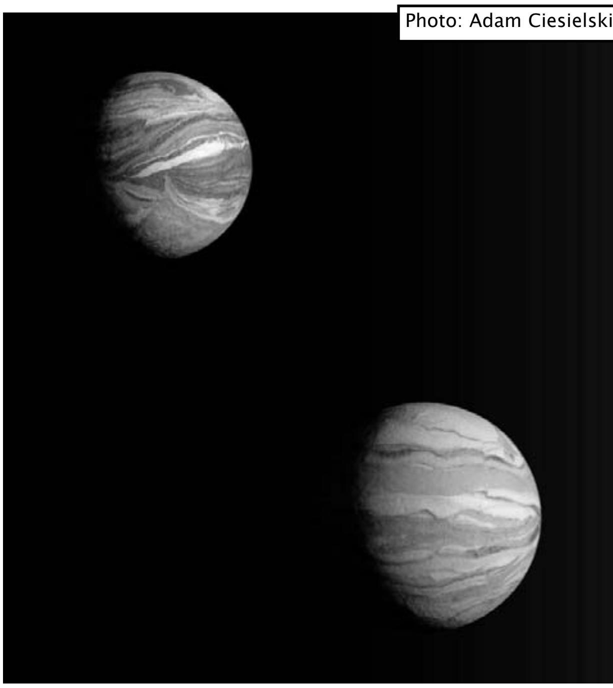


Photo: Adam Ciesielski

Calculating a Weight on another Planet

Example
If an astronaut in his space suit weighs 1,350N on Earth, what will he weigh on Mars where $g=3.84ms^{-2}$?

Solution **W = mg**
On Earth, 1,350 = m x 9.81
∴ mass = 1,350/9.81
= 137.6 kg

So on Mars, W = mg = 137.6x3.84 = 528kg.

TRY THE WORKSHEET, next page.

Worksheet 1

Part A Fill in the blanks.
Check answers at the back

The weight of an object is the a)........................... due to b).. Near the Earth, all objects will c)... at the same rate, approximately d).................ms^{-2}

Experimentally, "g" can be easily determined by measuring the length and e).................................... of a pendulum. When the results are graphed appropriately, the f)................................... of the graph allows calculation of "g".

Gravity acts at a distance by way of a g)............................ .... the same as electro-magnetism, but the force only h).. and can never i)... Gravity is a property of "mass"; every object is surrounded by a j).. which will attract any other k).............................. within the field.

Any mass within a gravitational field possesses "Gravitaional Potential Energy" (GPE). This is defined as "the amount of l).. to move an object from m)............................... to a point within the field." In reality, work must be done to move any mass in the opposite direction, so the definition means that the value for GPE is always a n)... quantity.

The value of "g" at the surface of the Earth is o)..................ms^{-2}, but has a different value in other places, so the p)................................ of any object will be different on a different planet. However, the q)............................ will remain the same.

COMPLETED WORKSHEETS BECOME SECTION SUMMARIES

Remember that for full marks in calculations, you need to show FORMULA, NUMERICAL SUBSTITUTION, APPROPRIATE PRECISION and UNITS

Part B Practice Problems
Mass & Weight on Earth & Elsewhere

Refer to the previous page for values of "g".

1.
A small space probe has a mass of 575kg.
a) What is its <u>mass</u> i) in orbit?
ii) on the Moon?
iii) on Jupiter?
b) What is its <u>weight</u> i) on Earth?
ii) in orbit?
iii) on the Moon?
iv) on Jupiter?

2.
If a martian weighs 250N when at home, what will he/she/it weigh:
a) on Earth? (hint: firstly find the mass)
b) on Neptune?
c) on the Moon?

3.
A rock sample, weight 83.0N, was collected by a space probe from the planet Neptune.
a) What is its mass?
b) What will it weigh on Earth?
c) On which planet would it weigh 206N?

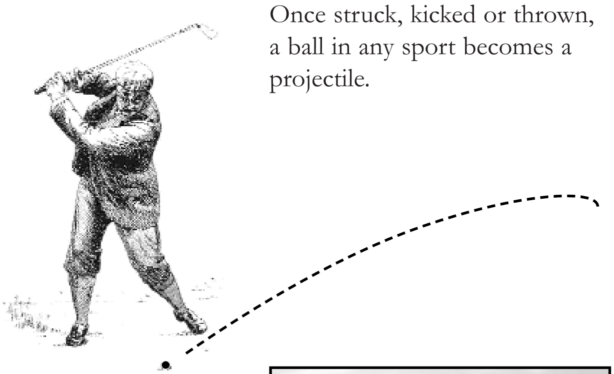
FULLY WORKED SOLUTIONS IN THE ANSWERS SECTION

2. PROJECTILES & SATELLITES

What is a Projectile?

A projectile is any object that is launched, and then moves only under the influence of gravity.

Examples:



Once struck, kicked or thrown, a ball in any sport becomes a projectile.

Any bullet, shell or bomb is a projectile once it is fired, launched or dropped.

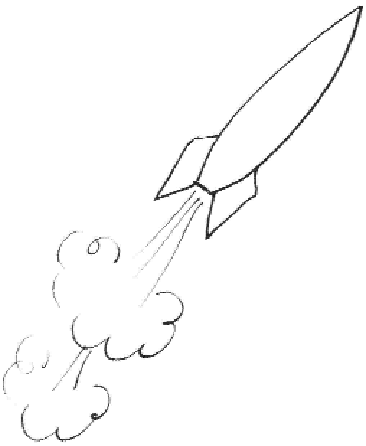
Photo: Keith Syvinski

An example which is NOT a Projectile:

A rocket or guided missile, while still under power, is NOT a projectile.

Once the engine stops firing it becomes a projectile.

Projectiles are subject to only one force... **Gravity**!



When a projectile is travelling through air, there is, of course, an air-resistance force acting as well. For simplicity, (K.I.S.S. Principle) air-resistance will be ignored throughout this topic.

In reality, a projectile in air, does not behave quite the way described here because of the effects of air-resistance. The exact motion depends on many factors and the Physics becomes very complex, and beyond the scope of this course.

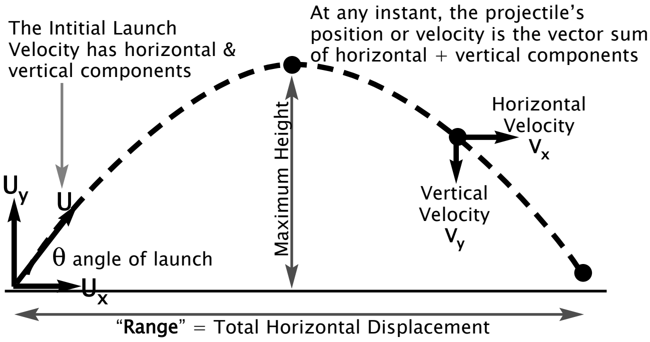
Projectile Motion

By simple observation of a golf ball trajectory, or a thrown cricket ball, the motion of any projectile can be seen to be a curve. It is in fact a parabola, and you might think the Physics of this is going to be difficult. NOT SO... it is really very simple. Just remember the following:

Horizontal **CONSTANT VELOCITY** **Vertical** **CONSTANT ACCELERATION at "g", DOWNWARDS**

You must analyse projectile motion as 2 separate motions; horizontal (x-axis) and vertical (y-axis) must be dealt with separately, and combined as vectors if necessary.

The Trajectory (Path) of a Projectile

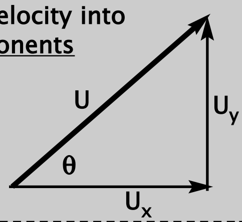


Equations for Projectile Motion

1. Resolve the Initial Launch Velocity into Vertical & Horizontal Components

$\sin\theta = \frac{U_y}{U}$ & $\cos\theta = \frac{U_x}{U}$

$\therefore U_y = U.\sin\theta, \quad U_x = U.\cos\theta$



2. **Horizontal Motion** is constant velocity, so

$V_x = \frac{S_x}{t}$ is all you need

3. Vertical Motion is constant acceleration at "g"

To find vertical velocity:

$V_y = U_y + g.t$ (from $v=u+at$)

To find vertical displacement:

$S_y = U_y.t + \frac{1}{2}.g.t^2$ (from $S=ut+\frac{1}{2}at^2$)

The syllabus specifies a 3rd equation as well, but its use can be avoided. (K.I.S.S. Principle)

Analysing Projectile Motion

Example 1

The artillery cannon shown fires a shell at an initial velocity of 400ms^{-1}.
If it fires at an angle of 20^o, calculate:

a) the vertical and horizontal components of the initial velocity.

b) the time of flight. (assuming the shell lands at the same horizontal level)

c) the range. (same assumption)

d) the maximum height it reaches.

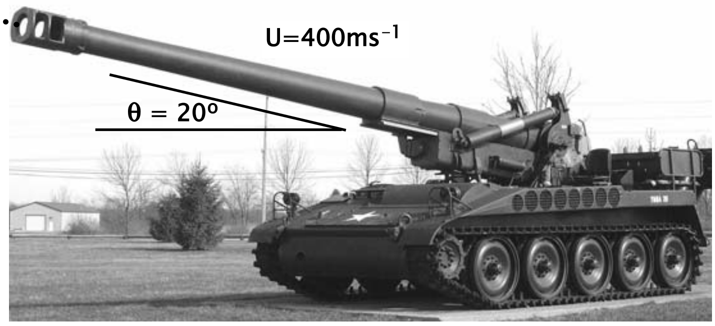


Photo: Keith Syvinski

a)

U_y = U.Sinθ
= 400.Sin20
=138.8ms^{-1}
(upwards)

U_x = U.Cosθ
=400Cos20
=375.9ms^{-1}
(horizontal)

b) The shell is fired upwards, but acceleration due to gravity is downwards.
You must assign up = (+ve), down = (−ve).

At the top of its arc, the shell will have an instantaneous vertical velocity= zero.

$V_y = U_y + g.t$

0 = 138.8 + (−9.81)xt

∴ t = −138.8/−9.81

= **14.1s**

This means it takes 14.1s to reach the top of its arc. Since the motion is symmetrical, it must take twice as long for the total flight.

∴ time of flight = 28.2s

c) Range is horizontal displacement

Remember

$V_x = U_x$ = constant velocity

$V_x = \dfrac{S_x}{t}$

∴ $S_x = V_x.t$ (use time of flight)

= 375.9 x 28.2

= 10,600m

Range = 1.06x10^{4}m
(i.e. 10.6 km)

d) Vertical Height (up =(+ve), down =(−ve))

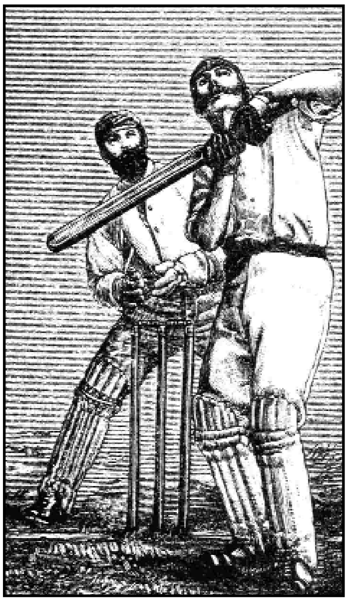
$S_y = U_y.t + \frac{1}{2}.g.t^2$

= 138.8x14.1 + 0.5x(−9.81)x(14.1)^2

= 1957.1 + (−975.2)

= 982m = **9.82x10^{2}m.**

Note: the time used is the time to reach the top of the arc... the time at the highest point



Analysing Projectile Motion

Example 2

The batsman has just hit the ball upwards at an angle of 55°, with an intial velocity of 28.0ms^{-1}. The boundary of the field is 62.0m away from the batsman.

Resolve the velocity into vertical and horizontal components, then use these to find:

a) the time of flight of the ball.

b) the maximum height reached.

c) whether or not he has "hit a 6" by clearing the boundary.

d) the velocity of the ball (including direction) at the instant t = 3.50s.

Remember to let UP = (+ve)
DOWN = (–ve)
acceleration = "g" = –9.81ms^{-2}

Vertical & Horizontal Components of Velocity

U_y = U.Sinθ, **U_x = U.Cosθ**
=28Sin55 =28Cos55
=**22.9ms^{-1}** =**16.1ms^{-1}**

a) Time of Flight

At highest point V_y=0, so

$V_y = U_y + g.t$
0 = 22.9 + (–9.81)xt
∴ t = –22.9/–9.81
= **2.33s**

This is the mid-point of the arc, so
time of flight = 4.66s

b) Maximum Height
is achieved at t = 2.33s, so

$S_y = U_y.t + \frac{1}{2}.g.t^2$
= 22.9x2.33+0.5x(–9.81)x(2.33)^2
= 53.5 + (–26.6)
= **26.9m**

c) Range will determine if he's "hit a 6".

$V_x = U_x$= constant velocity
$S_x = V_x.t$ (use total time of flight)
= 16.1 x 4.66
= **75.0m** That'll be 6 !

d) Velocity at t = 3.50s ?

Vertical

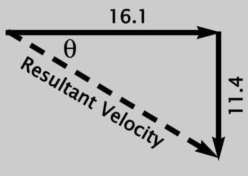
$V_y = U_y + g.t$

=22.9+(–9.81)x3.50
= **–11.4ms^{-1}**
(this means it is downwards)

Horizontal

$V_x = U_x$= constant

= **16.1ms^{-1}**



By Pythagorus,
$V^2 = V_y^2 + V_x^2$
= (–11.4)^2 + 16.1^2
∴ V = Sq.root(389.17) = **19.7ms^{-1} at an angle 35° below horizontal**

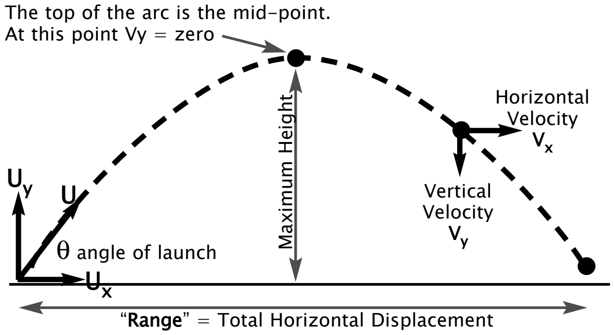
Tan θ = 11.4/16.1
∴ θ ≅ 35°

Analysing Projectile Motion (cont)

If you find solving Projectile Motion problems is difficult, try to learn these basic rules:

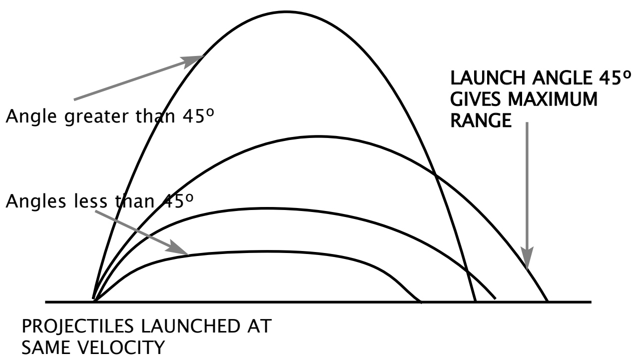
• The "launch velocity" must be <u>resolved</u> into a horizontal velocity (U_x) and a vertical velocity (U_y). Once you have these, you can deal with vertical and horizontal motion as 2 separate things.

• The motion is symmetrical, so at the highest point, the elapsed time is exactly half the total time of flight.



• Also, at the highest point, V_y = zero.
The projectile has been rising to this point.
After this point it begins falling. For an instant $V_y = 0$.
Very useful knowledge!

• <u>Maximum Range</u> is achieved at a launch angle of 45°.



• <u>Horizontal Motion</u> is constant velocity... easy.
Use $\mathbf{V_x = U_x}$ **and** $\mathbf{S_x = U_x.t}$

• <u>Vertical Motion</u> is constant acceleration at **g= -9.81ms^{-2}**.

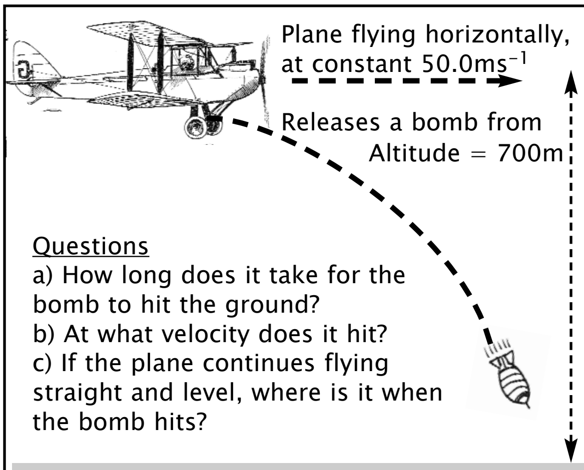
Use $\mathbf{V_y = U_y + g.t}$
to find "**t**" at the max.height (when V_y=0)
or, find $\mathbf{V_y}$ at a known time.

Use $\mathbf{S_y = U_y.t + \frac{1}{2}.g.t^2}$
to find vertical displacement ($\mathbf{S_y}$) at a known time,
or, find the time to fall through a known height
(if U_y=0)

TRY THE WORKSHEET at the end of this section.

Projectiles Launched Horizontally

A common situation with projectile motion is when a projectile is launched horizontally, as in the following example. This involves half the normal trajectory.



<u>Questions</u>
a) How long does it take for the bomb to hit the ground?
b) At what velocity does it hit?
c) If the plane continues flying straight and level, where is it when the bomb hits?

<u>Solution</u>
Because the plane is flying horizontally, the intitial velocity vectors of the bomb are:
Horizontal, U_x= 50.0ms^{-1},
Vertical, U_y= zero

a) Time to hit the ground
We know the vertical distance to fall (-700m (down)), the acceleration rate (g= -9.81ms^{-2}) and that U_y=0.

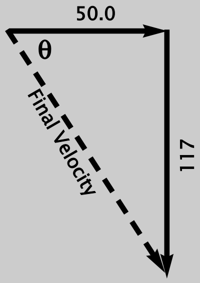
$$\mathbf{S_y = U_y.t + \frac{1}{2}.g.t^2}$$

-700 = 0xt + 0.5 x(-9.81)x t^2
-700 = -4.905xt2
∴ t^2 = -700/-4.905
t = 11.9s

b) Final Velocity at impact

<u>Vertical</u>
$\mathbf{V_y = U_y + g.t}$
= 0 + (-9.81)x11.9
V_y= **-117ms^{-1}**. (down)

<u>Horizontal</u>
$V_x = U_x$
V_x= **50.0ms^{-1}**.



$\mathbf{V^2 = V_y^2 + V_x^2}$
= 117^2 + 50.0^2
∴ V = Sq.Root(16,189)
= **127ms^{-1}**.

Tan θ = 117/50
∴ **θ ≅ 67°**.

Bomb hits the ground at 127ms^{-1}, at angle 67° below horizontal.

c) Where is the Plane?
Since both plane and bomb travel at the same horizontal velocity, it follows that they have both travelled exactly the same horizontal distance when the bomb hits.
i.e. the plane is directly above the bomb at impact.

(In warfare, this is a problem for low-level bombers... the bombs need delayed-action fuses)

Galileo and Projectile Motion

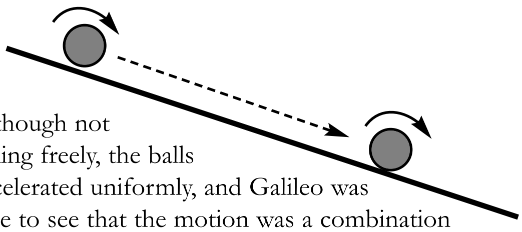
Notice that NONE of the equations used to analyse Projectile Motion ever use the mass of the projectile. This is because all objects, regardless of mass, accelerate with gravity at the same rate (so long as air-resistance is insignificant).

It was **Galileo**, (1564-1642) who you learned about in "The Cosmic Engine", who first discovered this.

Photo: Diana

His famous experiment was to drop objects of the same size and shape, but of different weight, from the leaning tower in Pisa. He found that all objects hit the ground at the same time, thereby proving the point.

He also studied projectile motion. In his day, cannon balls were the ultimate weapon, but trajectories were not understood at all. To slow the motion down for easier study, Galileo rolled balls down an incline:



Although not falling freely, the balls accelerated uniformly, and Galileo was able to see that the motion was a combination of 2 motions:

- horizontal, constant velocity

and

- vertical, constant acceleration

Galileo had discovered the basic principles of Projectile Motion.

Unfortunately, he lacked the mathematical formulas to go any further with his analysis.

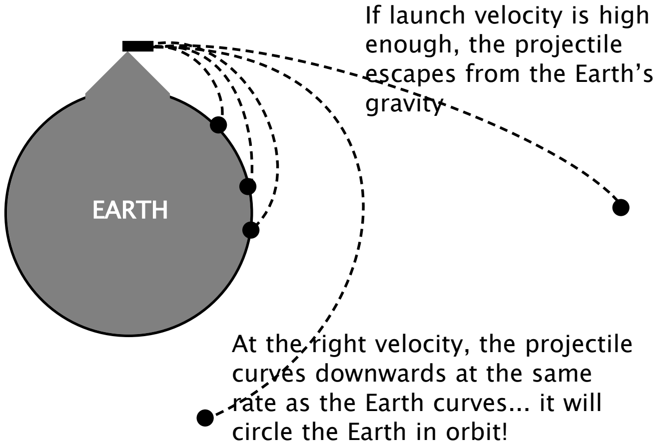
That only became possible after the work of Isaac Newton, and his 3 Laws of Motion, and Theory of Gravitation.

Coincidentally, Newton was born in the same year that Galileo died.

Isaac Newton and Orbiting Satellites

Once Isaac Newton had developed the Maths and discovered the laws of motion and gravity, he too looked at Projectile Motion.

Newton imagined a cannon on a very high mountain, firing projectiles horizontally with ever-increasing launch velocities:



Newton had discovered the concept of a gravitational orbit, and the concept of "escape velocity".

Escape Velocity

is defined as the launch velocity needed for a projectile to escape from the Earth's gravitational field.

Mathematically, it can be shown that

Escape Velocity, $\mathbf{V_e = Sq.Root\ (2GM_E\ /\ R_E)}$

G= Gravitational Constant (see later in topic)
M_E= Mass of the Earth
R_E= Radius of Earth

You are NOT required to learn, nor use, this equation.

What you should learn is that:

- The mass of the projectile is not a factor. Therefore, all projectiles, regardless of mass, need the same velocity to escape from Earth, about 11km per second!
- The Escape Velocity depends only on the mass and radius of the Earth.

It follows that different planets have different escape velocities. Here are a few examples...

PLANET	**ESCAPE VELOCITY** in km/sec	(ms^{-1})
Earth	11.2	1.12×10^4
Moon	2.3	2.3×10^3
Mars	5.0	5.0×10^3
Jupiter	60.0	6.0×10^4

Placing a Satellite in Earth Orbit

In the previous section you saw that a projectile needs an enormous velocity to escape from the Earth's gravitational field... about 11 km per second. Think of a place 11 km away from you, and imagine getting there in 1 second flat!

What about Newton's idea of an orbiting projectile? If it is travelling at the right velocity, a projectile's down-curving trajectory will match the curvature of the Earth, so it keeps falling down, but can never reach the surface. A projectile "in orbit" like this is called a "satellite".

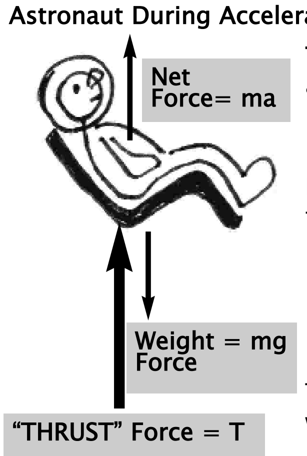
It can be shown that to achieve orbit, the launch velocity required is less than escape velocity, but still very high... about 8 km per second. How is this velocity possible?

In a 19th century novel, author Jules Verne proposed using a huge cannon to fire a space capsule (including human passengers) into space. Let's consider the Physics:

The "g-Forces" in a Space Launch

To accelerate a capsule (and astronauts) upwards to orbital velocity requires a force. The upward "thrust" force must overcome the downward weight force AND provide upward acceleration.

Astronaut During Acceleration to Orbital Velocity



Total Net Force causes acceleration

$\Sigma F = ma$ — Greek letter Sigma (Σ) means total

If up = (+ve), down (-ve) then

$\Sigma F = T - mg = ma$

$\therefore T = ma + mg$

This means the astronaut will "feel" the thrust as an increase in weight.

So, if the Thrust force causes an acceleration of (say) about $10ms^{-2}$, as well as overcoming his weight force, the 80kg astronaut will feel a pushing force of;

$$T = ma + mg$$
$$= 80x10 + 80x10 \quad (g \cong 10ms^{-2})$$
$$= 1{,}600N$$

This is twice his normal weight of 800N... we say the force is "2g".

A fit, trained astronaut can tolerate forces of "5g", but anything above about "10g" is life-threatening. Jules Verne's cannon astronauts would have suffered forces of about 200g... instantly fatal.

Rockets Achieve Orbit

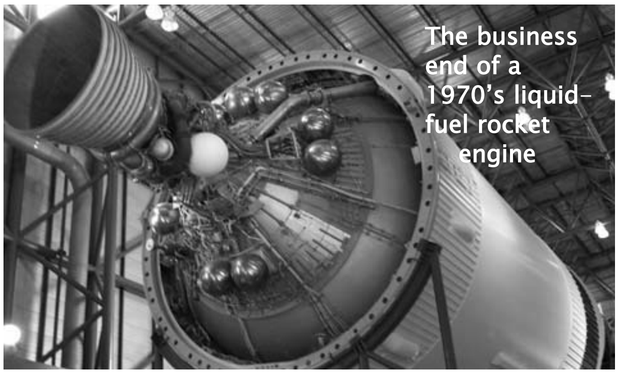
To keep the g-forces low while accelerating to the velocity required for orbit, AND then to operate in the airless conditions of space, the rocket is the only practical technology developed so far.

A Brief History of Rocketry

Simple solid-fuel (e.g. gunpowder) rockets have been used as fireworks and weapons for over 500 years.

About 100 years ago, the Russian **Tsiolkovsky** (1857-1935) was the first to seriously propose rockets as vehicles to reach outer space. He developed the theory of **multi-stage, liquid-fuel rockets** as being the only practical means of achieving space flight.

The American **Robert Goddard** (1882-1945) developed rocketry theory futher, but also carried out practical experiments including the **first liquid-fuel rocket engine**.



The business end of a 1970's liquid-fuel rocket engine

Goddard's experiments were the basis of new weapons research during World War II, especially by Nazi Germany. **Wernher von Braun** (1912-1977) and others developed the liquid-fuel "V2" rocket to deliver explosive warheads at supersonic speeds from hundreds of kilometers away.

At the end of the war many V2's, and the German scientists who developed them, were captured by either the Russians or the Americans. They continued their research in their "new" countries, firstly to develop rockets to carry nuclear weapons (during the "Cold War") and later for space research.

Modern Space Probe, ready for launch

Photo: Michael Diekmann

The Russians achieved the first satellite ("Sputnik" 1957) and the first human in orbit, and the Americans the first manned missions to the Moon (1969).

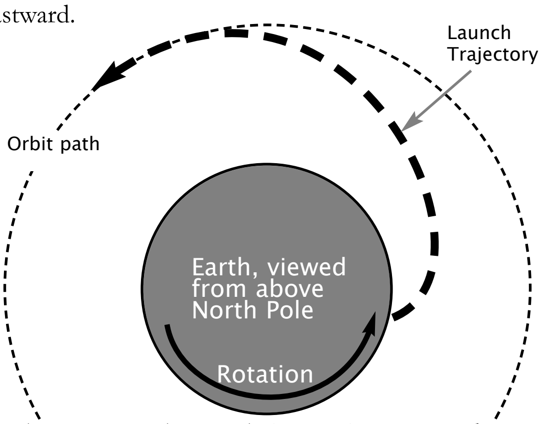
Since then, the use of satellites has become routine and essential to our communications, while (unmanned) probes have visited nearly every other planet in the Solar System.

Physics of a Rocket Launch

Direction of Launch

Straight upwards, right?
Wrong!

To reach Earth orbit, rockets are aimed toward the EAST to take advantage of the Earth's rotation. The rocket will climb vertically to clear the launch pad, then be turned eastward.



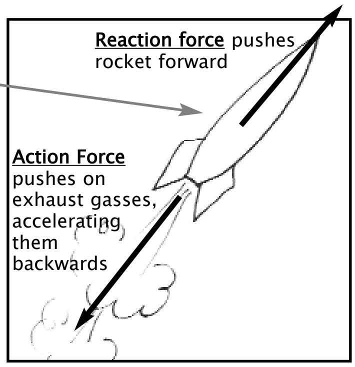
At the equator, the Earth is rotating eastwards at about 1,700km/hr (almost 0.5km/sec) so the rocket already has that much velocity towards its orbital speed.

Rocket launch facilities are always sited as close to the equator as possible, and usually near the east coast of a continent so the launch is outwards over the ocean.

Conservation of Momentum

Why a rocket moves was dealt with in the Preliminary topic "Moving About".

Newton's 3rd Law



Force on Exhaust Gases = Force on Rocket

It can also be shown that

Change of Momentum of Exhaust Gases = Change of Momentum of Rocket

backwards (-ve) ← → forwards (+ve)

(-)Mass x velocity = Mass x velocity

The mass x velocity (per second) of the exhaust gases stays fairly constant during the lift-off.
However, the mass of the rocket decreases as its fuel is burnt.
Therefore, the rocket's velocity must keep increasing in order to maintain the Conservation of Momemtum.

Forces Experienced by Astronauts

If the "Thrust" force from the rocket engine remains constant throughout the "burn", but the total rocket mass decreases due to consumption of the fuel, then the acceleration increases.

The concept of "g-forces" was explained on the previous page.

Thrust Force, $T = ma + mg$

If "T" remains constant, but "m" keeps decreasing, then "a" must keep increasing.
(This assumes "g" is constant... Actually it decreases with altitude, so "a" must increase even more)

Not only does the rocket accelerate upwards, but even the acceleration keeps accelerating!

The astronauts will feel increasing "g-forces". At lift-off, they will experience perhaps only "2g", but over several minutes this will increase to perhaps "5g" as the rocket burns thousands of tonnes of fuel and its mass decreases.

What a relief it must be to reach the weightlessness of orbit!

Photo by Shelley Kiser

Photo: Russian Soyez lift-off, courtesy Ali Cimen, senior reporter, Zaman Daily, Istanbul.

Satellites and Orbits

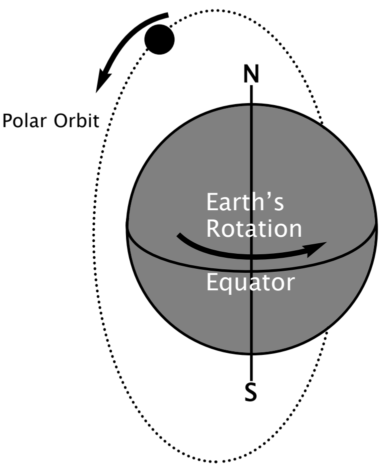
Types of Orbits

There are 2 main types of satellite orbits:

Low-Earth Orbit
As the name suggests, this type of orbit is relatively close to the Earth, generally from about 200km, out to about 1,000km above the surface.

For any satellite, the closer it is, the faster it must travel to stay in orbit. Therefore, in a Low-Earth Orbit a satellite is travelling quickly and will complete an orbit in only a few hours.

A common low orbit is a "**Polar Orbit**" in which the satellite tracks over the north and south poles while the Earth rotates underneath it.



This type of orbit is ideal for taking photos or Radar surveys of Earth.

The satellite only "sees" a narrow north-south strip of the Earth, but as the Earth rotates, each orbit looks at a new strip.

Eventually, the entire Earth can be surveyed.

Being a close orbit, fine details can be seen.

Geo-stationary Orbits
are those where the period of the satellite (time taken for one orbit) is exactly the same as the Earth itself... 1 day.

This means that the satellite is always directly above the same spot on the Earth, and seems to remain motionless in the same position in the sky. It's not really motionless, of course, but orbiting around at the same angular rate as the Earth itself.

Geo-stationary orbits are usually directly above the equator, and have to be about 36,000km above the surface in order to have the correct orbital speed.

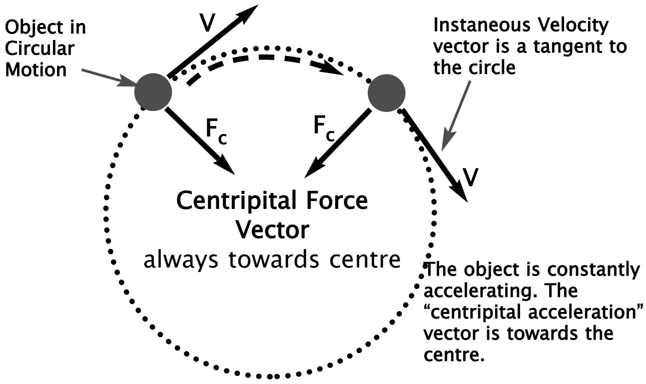
Being so far out, these satellites are not much good for photographs or surveys, but are ideal for communications. They stay in the same relative position in the sky and so radio and microwave dishes can be permanently aimed at the satellite, for continuous TV, telephone and internet relays to almost anywhere on Earth.

Three geo-stationary satellites, spaced evenly around the equator, can cover virtually the whole Earth with their transmissions.

Orbits & Centripital Force

The orbit of a satellite is often an oval-shape, or "ellipse".
However, in this topic we will always assume the orbits are circular... K.I.S.S. Principle.

Circular Motion was introduced in a Preliminary topic.
To maintain motion in a circle an object must be constantly acted upon by "Centripital Force", which acts towards the centre of the circle.



What Causes Centriptal Force?

Example	Centripital Force caused by...
Swinging an object around on a string.	**Tension Force** in the string.
Vehicle turning a circular corner.	**Friction Force** between tyres and road.
Satellite in orbit around Earth.	**Gravitational Force** between satellite mass and Earth's mass.

$$F_c = \frac{mv^2}{R}$$

F_c = Centripital Force, in newtons (N)
m = mass of object in orbit, in kg
v = orbital velocity, in ms^{-1}
R = radius of orbit, in metres (m)

When considering the radius of a satellite orbit, you need to be aware that the orbital distance is often described as the height above the surface. To get the radius, you may need to add the radius of the Earth itself... 6,370km (**6.37×10^6 m**)

Calculating Velocity from Radius & Period
Satellite motion is often described by the radius of the orbit, and the time taken for 1 orbit = the Period (T)

Now, circumference of a circle = $2\pi R$

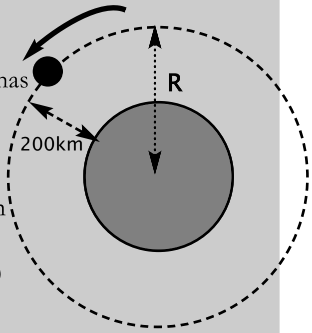
Therefore, the orbital velocity $V = \frac{\overbrace{2\pi R}^{\text{distance traveled}}}{\underbrace{T}_{\text{time taken}}}$

Example Problem next page...

Centripital Force and Satellites

Example Problem

A 250kg satellite in a circular orbit 200km above the Earth, has an orbital period of 1.47hours.



a) What is its orbital velocity?

b) What centripital force acts on the satellite?

(Radius of Earth = $6.37\text{x}10^6$m)

Solution

a) First, find the true radius of the orbit, and get everything into S.I. units:

Radius of orbit = 200,000 + $6.37\text{x}10^6$ = $6.57\text{x}10^6$m

Period = 1.47hr = 1.47 x 60 x 60 = $5.29\text{x}10^3$ seconds

$$V = \frac{2\pi R}{T} = 2 \times \pi \times 6.57\text{x}10^6/5.29\text{x}10^3 = \mathbf{7.80\text{x}10^3 ms^{-1}}.$$

b) $$F_c = \frac{mv^2}{R} = 250\text{x}(7.80\text{x}10^3)^2/6.57\text{x}10^6$$

$$= 2{,}315 = \mathbf{2.32 \times 10^3\ N}.$$

The satellite is travelling at about 8 km/sec, held in orbit by a gravitational force of about 2,300N.

TRY THE WORKSHEET at the end of this section

Kepler's Law of Periods

Example Problem

The satellite in the problem above has a period of 1.47hours, and an orbital radius of 6,570km.

A geo-stationary satellite, by definition, has a period of 24.0hours.

Use Kepler's Law of Periods to find its orbital radius.

Solution

For the satellite above, (units are km & hours) $\frac{R^3}{T^2} = \frac{6{,}570^3}{1.47^2} = 1.31 \times 10^{11}$

According to the law of periods, ALL satellites of Earth must have the same value for R^3/T^2

So, for the geo-stationary satellite:

$$\frac{R^3}{T^2} = 1.31 \times 10^{11}$$

So $R^3 = 1.31\text{x}10^{11}\text{x}(24.0)^2$

$\therefore R = \text{CubeRoot}(7.55\text{x}10^{13})$

$= \mathbf{4.23 \times 10^4\ km}$

This is approx. 42,000km from Earth's centre, or about 36,000km above the surface.

Note: When using Kepler's Law in this way it doesn't matter which units are used, as long as you are consistent. **In this example, km & hrs were used. The same result will occur if metres & seconds are used.**

The Period & Radius Relationship... Kepler's "Law of Periods"

When Johannes Kepler (1571-1630) studied the movement of the planets around the Sun (see Preliminary topic "Cosmic Engine") he discovered that there was always a mathematical relationship between the Period of the orbit and its Radius:

$$R^3 \propto T^2$$

(Greek letter alpha (α) means "proportional to")

This means that

$$\frac{R^3}{T^2} = \text{constant}$$

This means that for every satellite of the Earth, the **(Radius)^3** divided by **(Period)^2** has the same value.

This is a very useful relationship... see Example Problem at bottom left

At this point, the HSC Syllabus is rather vague about whether you need to learn and know the following mathematical development.

You may be safe to ignore it... (K.I.S.S.) but follow it if you can.

Either way, you DO need to be able to use the final equation shown below.

Kepler's Law of Periods was discovered empirically... that is, it was discovered by observing the motion of the planets, but Kepler had no idea WHY it was so.

When Isaac Newon developed his "Law of Universal Gravitation" (next section) he was able to prove the theoretical basis for Kepler's Law, as follows:

The Centripital Force of orbiting is provided by the Gravitational Force between the satellite and the Earth, so

Centripital Force = Gravitational Force

$$F_c = \frac{mv^2}{R} = F_G = \frac{GMm}{R^2}$$

$$\therefore v^2 = \frac{GM}{R} \qquad \text{but } v = \frac{2\pi R}{T}$$

$$\text{So, } \frac{4\pi^2 R^2}{T^2} = \frac{GM}{R}$$

$$\text{re-arranging, } \frac{R^3}{T^2} = \frac{GM}{4\pi^2}$$

Since the right hand side are all constant values, this proves Kepler's Law and establishes the Force of Gravity as the controlling force for all orbiting satellites, including planets around the Sun.

In the above, G=Universal Gravitational Constant

M= mass of the Earth (or body being orbited)

m= mass of satellite... notice that it disappears!

Kepler's Law of Periods (Again!)
On the previous page, the sample problem was able to calculate the orbital radius for a geo-stationary satellite by comparing the ratio of R^3/T^2 for 2 satellites.

With Newton's development of Kepler's Law, we can do it again a different way...
Example Problem
Find the orbital radius of a geo-stationary satellite, given that its period of orbit is 24.0 hours.
(24.0hr = 24.0x60x60 = 8.64×10^4 sec)
Doing this way, you MUST use S.I. units!!

(G= Gravitational Constant = 6.67×10^{-11}
M = Mass of Earth = 5.97×10^{24}kg)

$$\frac{R^3}{T^2} = \frac{GM}{4\pi^2}$$

$$R^3 = \frac{6.67\times10^{-11} \times 5.97\times10^{24} \times (8.64\times10^4)^2}{4\pi^2}$$

$$\therefore R = \text{CubeRoot } (7.5295\times10^{22})$$

$$= \mathbf{4.22 \times 10^7 m}.$$

This is about 42,000km, or about 36,000km above the surface... the same answer as before. (It better be!)

TRY THE WORKSHEET at the end of the section

Decay of Low-Earth Orbits

Where does "Space" begin?
It's generally agreed that by 100km above the surface of the Earth the atmosphere has ended, and you're in outer space. However, although this seems to be a vacuum, there are still a few atoms and molecules of gases extending out many hundreds of kilometres.

Therefore, any satellite in a low-Earth orbit will be constantly colliding with this extremely thin "outer atmosphere". The friction or air-resistance this causes is extremely small, but over a period of months or years, it gradually slows the satellite down.

As it slows, its orbit "decays". This means it loses a little altitude and gradually spirals downward. As it gets slightly lower it will encounter even more gas molecules, so the decay process speeds up.

Once the satellite reaches about the 100km level the friction becomes powerful enough to cause heating and rapid loss of speed. At this point the satellite will probably "burn up" and be destroyed as it crashes downward.

Modern satellites are designed to reach their low-Earth orbit with enough fuel still available to carry out short rocket engine "burns" as needed to counteract decay and "boost" themselves back up to the correct orbit. This way they can remain in low-Earth orbits for many years.

Re-Entry From Orbit

Getting a spacecraft into orbit is difficult enough, but the most dangerous process is getting it down again in one piece with any astronauts on board alive and well.

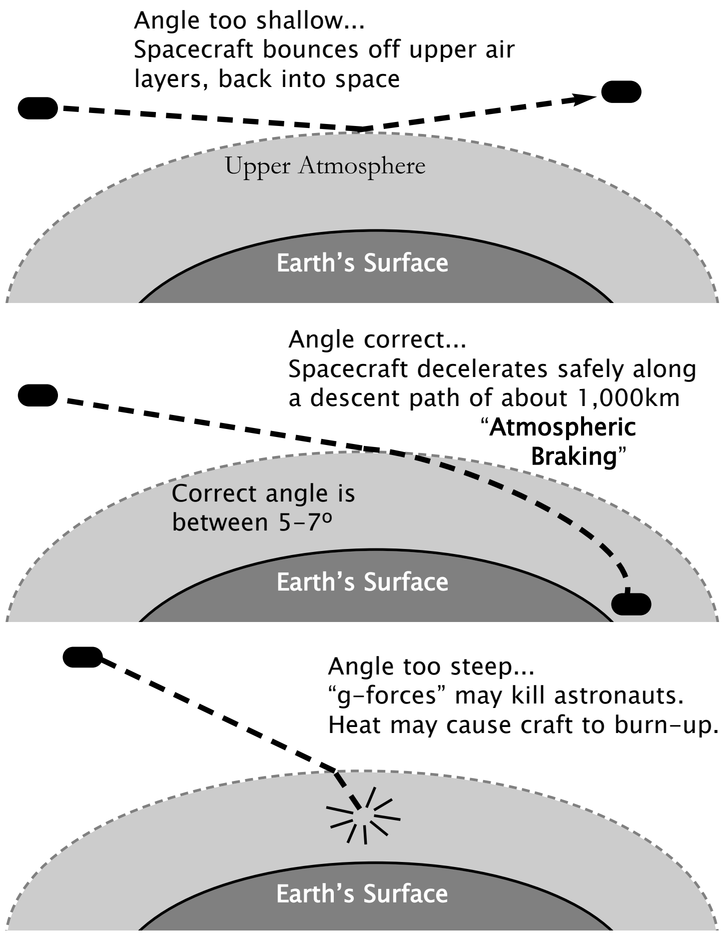
In orbit, the satellite and astronauts have a high velocity (kinetic energy) and a large amount of GPE due to height above the Earth. To get safely back to Earth, the spacecraft must decelerate and shed all that energy.

It is impossible to carry enough fuel to use rocket engines to decelerate downwards in a reverse of the lift-off, riding the rocket back down at the same rate it went up.

Instead, the capsule is slowed by "retro-rockets" just enough to cause it to enter the top of the atmosphere so that friction with the air does 2 things:

- cause deceleration of the capsule at a survivable rate of deceleration not more than (say) "5-g", and
- convert all the E_k and GPE into heat energy.

The trick is to enter the atmosphere at the correct angle:



Early spacecraft used "ablation shields", designed to melt and carry heat away, with the final descent by parachute. The Space Shuttle uses high temperature tiles and high-tech insulation for heat protection, and glides in on its wings for final landing like an aircraft.

Worksheet 2

Part A Fill in the blanks. Check answers at the back.

Projectile Motion

A projectile is any object which is launched, and then moves a).. The path of a projectile is called its b).., and is a curve. Mathematically, the curve is a c).................................

To analyse projectile motion it is essential to treat the motion as 2 separate motions; d)................................... and .... If the launch velocity and the e)........................... of launch are known, you should always start by f).. the initial velocity into horizontal and vertical g).....................................

The horizontal motion is always h).. and the vertical is constant i)....................................... due to j).................................... The usual strategy is to find the k)..................... of flight, by using the fact that at the top of the projectile's arc its vertical velocity is l)........................ Once this is known, it becomes possible to calculate the maximum m)................................. attained, and the n)................................. (total horizontal displacement.). The projectile's position and velocity at any instant can be found by combining the o)... and .... vectors. Maximum range of any projectile occurs when the angle of launch is p)................... degrees upwards.

Historically, it was q).. who first proved that (ignoring air-resistance) all objects accelerate under gravity r)... He also investigated projectile motion and was the first to see that the horizontal motion is constant s)......................... while the t)....................................... is constant acceleration. Later, u).. developed the mathematics of both gravity and motion, which allowed projectile motion to be understood and ananalysed. He also discovered the concept of v)..................... velocity, and of objects being in w)..........................., by imaging what would happen to cannon balls being fired horizontally at increasing velocities from a high mountain.

"Escape Velocity" is defined as the velocity a projectile needs in order to x)..

Satellites & Orbits

If a projectile is travelling horizontally at the correct y).................................., then its down-curving trajectory will match the z)... of the Earth. The projectile will continue to "fall down" but never reach the surface... it is a aa)... which is ab)...................................... around the Earth. To place a satellite in orbit, it must be ac).. up to orbital speeds.

During upward acceleration, an astronaut will experience "ad)................................" which feel like an increase in ae)............................ and can be life-threatening if too high.

The only feasible technology (so far) for achieving the necessary af)..., while keeping the ag)... reasonably low, is the use of ah)................................... One of the important steps in the history of rocketry was achieved by Robert Goddard, who built and tested the first ai)............................-fuelled rocket.

Rockets are always launched towards the aj)......................... to take advantage of the Earth's ak)....................................... Rocket propulsion is a consequence of Newton's al).......... Law. During the launch, momentum is am).......................... The backward momentum gained by the exhaust gases is matched by the an)............................ momentum gained by the ao).. However, the mass of the rocket ap)............................. rapidly as is burns huge amounts of fuel. This means that even with constant thrust, the acceleration rate aq)................................., and the astronauts feel increasing ar).............................

There are basically 2 different types of orbit for a satellite: as).. orbits are when the satellite is at)................................ km from Earth and travelling very au)............................. This is ideal for satellites used for av)... and .... The other type of orbit is called aw)...................................... For this the satellite is positioned so its ax)........................... is exactly 24 hours. This means it orbits at the same relative rate as the Earth's ay).................................., and seems to stay in the az).. This is ideal for ba)... satellites.

Any object undergoing Circular Motion is being acted upon by bb)..................................... force, which is always dircted towards the bc).. For an object twirled on a string, the centripital force is provided by the bd).. For a car turning a corner, it's the force of be).................... between tyres and road. For a satellite, it's the force of bf)....................................

Johannes bg).................................. discovered the "Law of Periods" for satellites. Later, Newton was able to shown that this was a consequence of bh)..................................... attraction between the satellite and whatever it is orbiting.

(Continued...)

COMPLETED WORKSHEETS BECOME SECTION SUMMARIES

Worksheet 2

Part A (cont)

Low-Earth orbits will eventually "bi)............................."
due to the satellite gradually losing speed by collision with bj)..

Re-entry of a spacecraft from orbit is extremely dangerous: bk)....................... from high velocity can cause high g-forces, and friction causes production of bl)........................... energy which can cause the craft to burn-up. The trick is to enter the atmosphere at exactly the correct bm)...........................

Part B Practice Problems

Projectile Motion

1. For each of the following projectiles, resolve the initial launch velocity into horizontal and vertical components.
a) A rugby ball kicked upwards at an angle of 60°, with velocity $20.5ms^{-1}$.
b) A bullet fired horizontally at $250ms^{-1}$.
c) A baseball thrown at $15.0ms^{-1}$, and an up angle of 25°.
d) An artillery shell fired at $350ms^{-1}$, upwards at 70°.
e) An arrow released from the bow at $40.0ms^{-1}$, at 45° up.

2. For the arrow in Q1(e), find
a) the time to reach the highest point of its arc.
b) the maximum height reached.
c) its range (on level ground).

3. The bullet in Q1(b), was fired from a height of 2.00m, across a level field. Calculate:
a) how long it takes to hit the ground.
b) how far from the gun it lands.
c) At the same instant that the bullet left the barrel, the empty bullet cartridge dropped (from rest) from the breech of the gun, 2.00m above the ground.
How long does it take to hit the ground?
Comment on this result, in light of the answer to (a).

4. For the artillery shell in Q1(d), calculate:
a) the time to reach the highest point of its arc.
b) the maximum height reached.
c) its range (on level ground).

5. The rugby ball in Q1(a) was at ground level when kicked.
a) Find its exact position 2.50s after being kicked.
b) What is its instantaneous velocity at this same time?

Orbits and Centripital Force

6. A satellite orbiting 1,000km above the Earth's surface has a period of 1.74 hours. (Radius of Earth=$6.37x10^6$m)
a) Find its orbital velocity, using $V=2\pi R/T$
b) If the satellite has a mass of 600kg, find the centripital force holding it in orbit.

7. A 1,500kg satellite is in a low-Earth orbit travelling at a velocity of 6.13 km/s ($6.13x10^3ms^{-1}$). The Centripital force acting on it is $5.32x10^3$N.
a) What is the radius of its orbit?
b) What is its altitude above the earth's surface?
c) What is the period of its orbit?

8. A satellite is being held in Earth orbit by a centripital force of 2,195N. The orbit is 350km above the Earth, and the satellite's period is 1.52 hours.
a) Find the orbital velocity.
b) What is the satellite's mass?

Kepler's Law of Periods

9. Draw up a table with headings
Radius (m) **Period (s)** **R^3/T^2**

Fill in the table using data for each of the satellites in Q's 6, 7 & 8.
Explain how the data supports Kepler's Law of Periods.

10. Use the <u>average</u> value of R^3/T^2 from the table in Q9 to calculate the following:
a) Find the Radius of an Earth orbit if Period =$1.60x10^3$s.
b) What is the radius of orbit if T=$1.15x10^4$s?
c) Find the period of a satellite if R= $2.56x10^7$m.
d) Find T when the satellite orbit is 2,000km above the Earth's surface.

11.
a) Planet Mars has mass= $6.57x10^{23}$kg.
Calculate the "orbital constant" $GM/4\pi^2$ for Mars.
(G=Gravitational Constant = $6.67x10^{-11}$)
b) Find the orbital Radius of a satellite orbitting Mars, if its Period is $1.60x10^3$s.
c) Find the period of a Mars satellite when R=$2.56x10^7$m.
d) In Q10(c) you calculated the period of an Earth satellite with the same orbital radius.
Compare the answers to Q10(c) and Q11(c). Which satellite travels at the highest orbital velocity?
e) Complete the blanks in this general statement:
At a given orbital radius, a satellite orbiting a smaller planet needs to travel at a .... velocity. The bigger the planet, the .... the velocity would need to be.

Remember that for full marks in calculations, you need to show FORMULA, NUMERICAL SUBSTITUTION, APPROPRIATE PRECISION and UNITS

FULLY WORKED SOLUTIONS IN THE ANSWERS SECTION

3. NEWTON'S LAW OF UNIVERSAL GRAVITATION

Gravitational Fields

The concept of the Gravitational Field was introduced in section 1. Every mass acts as if surrounded by an invisible "force field" which attracts any other mass within the field. Theoretically, the field extends to infinity, and therefore every mass in the universe is exerting some force on every other mass in the universe... that's why it's called Universal Gravitation.

Newton's Gravitation Equation

It was Isaac Newton who showed that the strength of the gravitational force between 2 masses:

- is proportional to the product of the masses, and
- inversely proportional to the square of the distance between them.

$$F_G = \frac{GMm}{d^2}$$

F_G = Gravitational Force, in N.
G = "Universal Gravitational Constant" = 6.67×10^{-11}
M and m = the 2 masses involved, in kg.
d = distance between M & m (centre to centre) in metres.

In the previous section on satellite orbits, you were already using equations derived from this.

Example Calculation 1
Find the gravitational force acting between the Earth and the Moon.
Earth mass = 5.97×10^{24}kg
Moon mass = 6.02×10^{22}kg.
Distance Earth-Moon = 248,000km = 2.48×10^8m.

Solution
$$F_G = \frac{GMm}{d^2} = \frac{6.67 \times 10^{-11} \times 5.97 \times 10^{24} \times 6.02 \times 10^{22}}{(2.48 \times 10^8)^2} = \mathbf{3.90 \times 10^{20}N}.$$

Example 2
Find the gravitational force acting between the Earth, and an 80kg person standing on the surface, 6,370km from Earth's centre (d=6.37×10^6m).
Solution
$$F_G = \frac{GMm}{d^2} = \frac{6.67 \times 10^{-11} \times 5.97 \times 10^{24} \times 80}{(6.37 \times 10^6)^2} = \mathbf{785\ N}.$$

This is, of course, the person's weight!... and sure enough
W = mg = 80 x 9.81 = 785N.
Gravitational Force = Weight Force

Effects of Mass and Distance on F_G

How does the Gravitational Force change for different masses, and different distances?

Imagine 2 masses, each 1kg, separated by a distance of 1 metre.

$$F_G = \frac{GMm}{d^2} = \frac{G \times 1 \times 1}{1^2} = G$$

Effect of masses

Now imagine doubling the mass of one object:

$$F_G = \frac{GMm}{d^2} = \frac{G \times 2 \times 1}{1^2} = 2G \quad \text{Twice the force}$$

What if both masses are doubled?

$$F_G = \frac{GMm}{d^2} = \frac{G \times 2 \times 2}{1^2} = 4G \quad \text{Four times the force}$$

Effect of Distance

Go back to the original masses, and double the distance:

$$F_G = \frac{GMm}{d^2} = \frac{G \times 1 \times 1}{2^2} = \frac{G}{4} \quad \text{One quarter the force}$$

Gravitational Force shows the "Inverse Square" relationship... triple the distance = one ninth the force
10 x the distance = 1/100 the force, etc.

Universal Gravitation and Orbiting Satellites

It should be obvious by now that it is F_G which provides the centripital force to hold any satellite in its orbit, (This was developed mathematically on page 14... revise) and is the basis for Kepler's Law of Periods.

Not only does this apply to artificial satellites launched into Earth orbit, but for the orbiting of the Moon around the Earth, and of all the planets around the Sun.

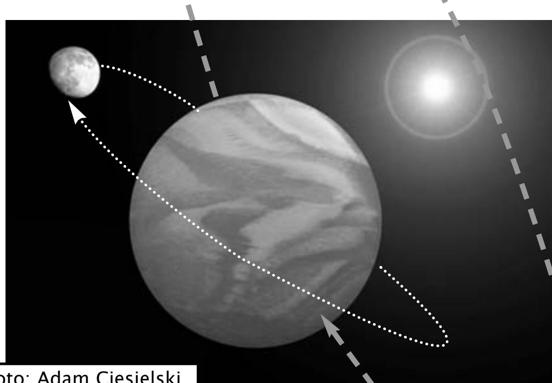


Photo: Adam Ciesielski

Our entire Solar System is orbiting the Galaxy because of gravity, and whole galaxies orbit each other...
...ultimately, gravity holds the entire universe together, and its strength, compared to the expansion of the Big Bang, will determine the final fate of the Universe.

The "Slingshot Effect" for Space Probes

One of the more interesting aspects of gravity and its effects on space exploration is called the "Slingshot Effect".

Here's how the story develops:

• Scientists wish to explore and learn about all the planets, comets, etc, in the Solar System, but...

• It costs billions of dollars to send a space probe to another planet, so...

• It makes sense to send one probe to several planets, rather than a separate spacecraft to each planet, but...

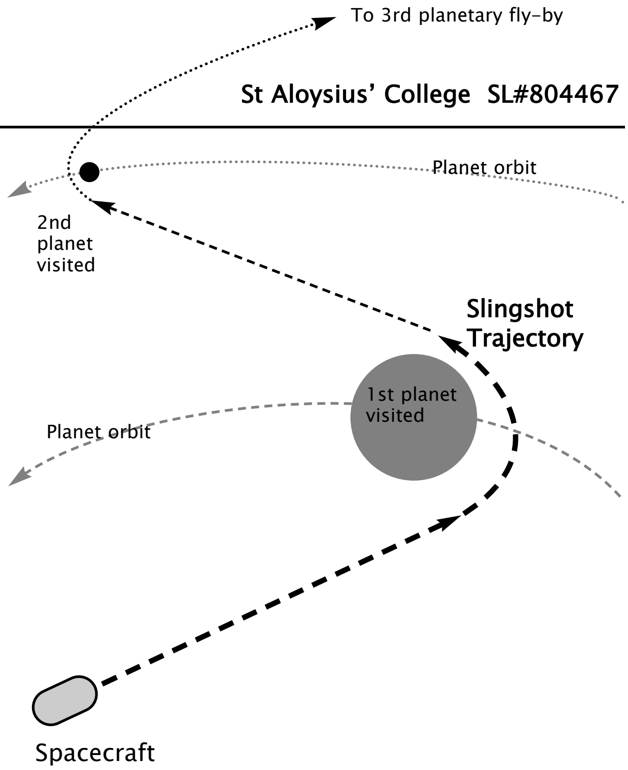
• the distances are enormous. Even at the high speed of an inter-planetary probe (approx 50,000 km/hr) it still takes years to reach some planets.

• Furthermore, having reached and done a "fly-by" to study one planet, the probe may need to change direction and speed to alter course for the next destination, and...

• It may be impossible to carry enough fuel to make the necessary direction changes by using rocket engines alone.

Got all that?

The solution to all these factors is to fly the spacecraft close enough to a planet so that the planet's gravity causes it to swing around into a new direction AND gain velocity (without burning any fuel).



So how can the the spacecraft gain extra velocity (and kinetic energy) from nothing?

The answer is that whatever energy the spacecraft gains, the planet loses. Energy is conserved. The planet's spin will be slowed down slightly by the transfer of energy to the spacecraft.

Of course, the huge mass of a planet means that the energy it loses is so small to be totally insignificant.

Worksheet 3 Universal Gravitation
Fill in the blanks. Check answers at the back.

The strength of the gravitational force of attraction between 2 masses is proportional to a)... and inversely proportional to b)..
So, if one mass is doubled the force will c)............................, but if the distance is doubled, then the force will d)..

The force due to gravity provides the e).. force for all satellites, including the Moon and f)................................... orbiting the Sun. In space exploration, gravity can be used to alter a spacecraft's g)................................ and to gain h).. This is known as the i).. Effect. The spacecraft gains energy, while j)... loses an k)................................ amount.

Part B
Practice Problems

1.
Fred (75kg) and girlfriend Sue (60kg) are very much attracted to each other. How much?
Find the gravitational force attracting them when they are 0.5m apart.

2.
What is the gravitational force of attraction between 2 small asteroids with masses of 6.75×10^{8}kg and 2.48×10^{9}kg separated by 425m?

3.
The mass of the Moon is 6.02×10^{22}kg. A comet with mass 5.67×10^{10}kg is attracted to the Moon by a force of 6.88×10^{10}N. How far apart are the 2 bodies?

4. EINSTEIN'S THEORY OF RELATIVITY

The Aether Theory

The idea of the universal "aether" was a theory developed to explain the transmission of light through empty space (vacuum) and through transparent substances like glass or water.

The basic idea was this:
Sound waves are vibrations in air.
Water waves travel as disturbances in water.
Sounds and shock waves travel through the solid Earth.
It seems that all waves have a "medium" to travel through, so what is the medium for light waves?

From the 17th to 19th centuries, as modern Science developed, it became the general belief that there was a substance called the "aether" which was present throughout the universe as the medium for light waves to be carried in. The aether was invisible, weightless and present everywhere, even inside things like a block of glass, so light could travel through it. The vacuum of space was actually filled by the universal aether.

The Michelson-Morley Experiment

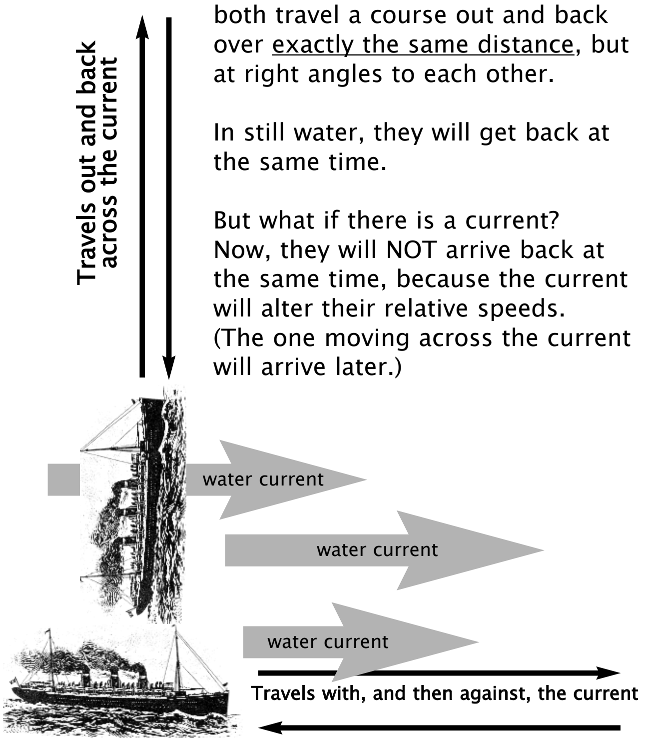
In 1887, American scientists A.A. Michelson and E.W. Morley attempted to detect the aether by observing the way that the movement of the Earth through the aether would affect the transmission of light.

An Analogy to their experiment...

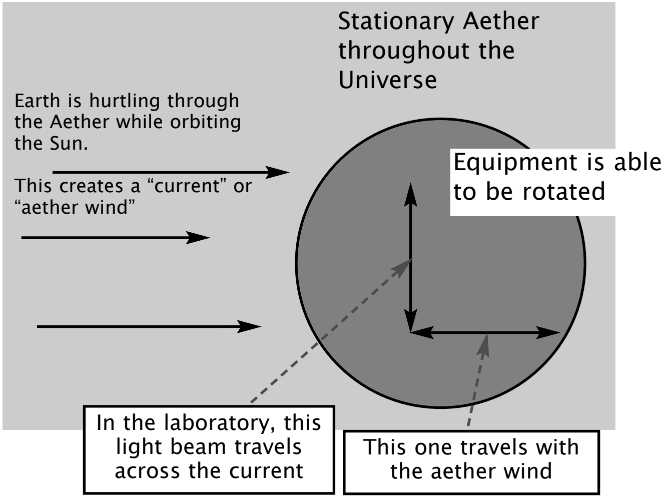
Imagine 2 identical boats, capable of exactly the same speed. They both travel a course out and back over exactly the same distance, but at right angles to each other.

In still water, they will get back at the same time.

But what if there is a current?
Now, they will NOT arrive back at the same time, because the current will alter their relative speeds.
(The one moving across the current will arrive later.)



In Michelson & Morley's experiment the "boats" were beams of light from the same source, split and reflected into 2 right-angled beams sent out to mirrors and reflected back. The "current" was the "aether wind" blowing through the laboratory due to the movement of the Earth orbiting the Sun at 100,000km/hr.



On arrival back at the start, the beams were re-combined in an "interferometer", producing an interference pattern as the light waves re-combined.

The entire apparatus was mounted on a rotating table. Once the apparatus was working, and the interference pattern appeared, the whole thing was rotated 90^o, so that the paths of the light rays in the aether wind were swapped. Theoretically, this should have created a change in the interference pattern, as the difference between the beams was swapped.

The Result...

There was NO CHANGE in the interference pattern.

The experiment was repeated in many other laboratories, with more sensitve interferometers and all sorts of refinements and adjustments.

The result remained negative... no effect of the aether wind could be detected.

Either the experiment has something wrong with it or the theory of the "Aether" is wrong!

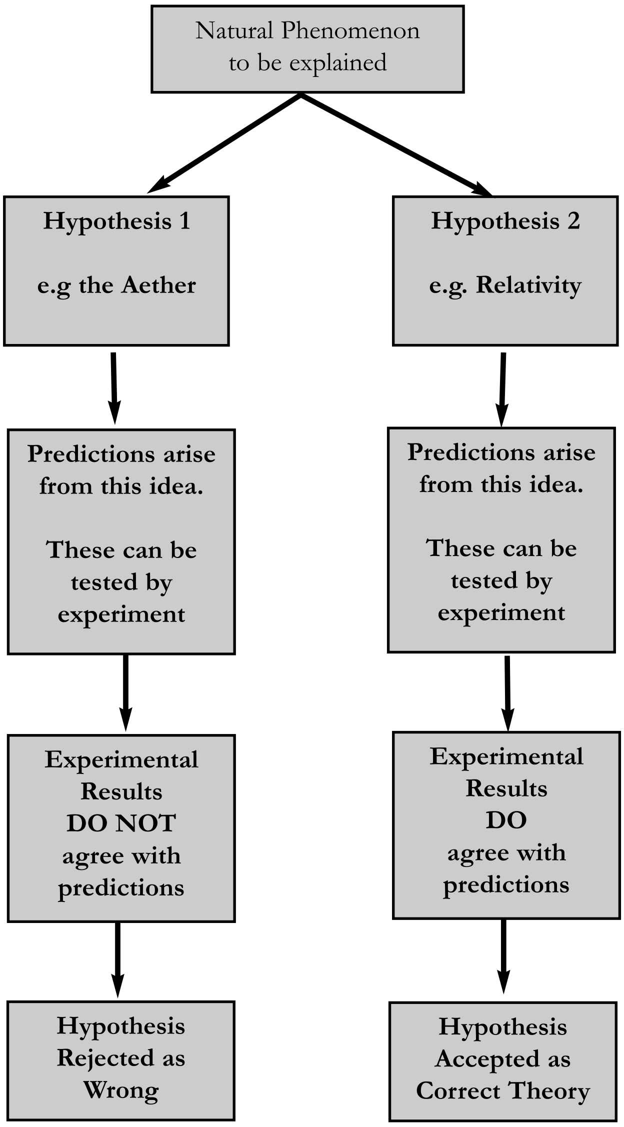
Enter Albert Einstein...

How Science Works

The Michelson-Morley Experiment is probably the most famous "failed experiment" in the history of Science. It's importance is not just historical interest, but a lesson in how Science works.

There is no such thing as a "failed experiment"!

Scientists produce hypotheses in an attempt to explain the universe and its phenomena. There can be 2 or more totally different hypotheses attempting to explain the same thing.



This is exactly what happened. In the 30 years after the Michelson-Morley Experiment, a new Hypothesis was proposed which did not require any "aether". From it arose many predictions which have all been spectacularly confirmed by experiment, so we believe the "Aether Theory" is wrong, and "Relativity Theory" correct.

The Michelson-Morley Experiment was not a failure... it was a vital link in the scientific search for truth.

Relative Motion and Frames of Reference

Ever been sitting in a train at a station looking at another train beside you? Suddenly, the other train begins moving. Or is it your train beginning to move the other way?

The only way to be sure is to look out the other side at the station itself, in order to judge which train is really moving. You are using the railway station as your "<u>Frame of Reference</u>" in order to judge the <u>relative motion</u> of the 2 trains.

We often use the Earth itself (or a railway station attached to it) as our frame of reference. The Earth seems fixed and immovable, so everything else can be judged as moving relative to the fixed Earth... but we also know it's NOT really fixed and unmoving, but orbiting around the Sun.

Astronomers use the background of "fixed stars" as their frame of reference to judge relative planetary movements, but we know that these aren't really fixed either.

In fact, there is no point in the entire Universe that is truly "fixed" that could be used as an "absolute reference" to judge and measure all motion against.

Sir Isaac Newton was aware of this idea, and figured out that it really doesn't matter whether your frame of reference is stationary or moving at a constant velocity. So long as it is not accelerating, the observations, and measurements of motion will come out the same anyway. This raises the idea of an "<u>Inertial Frame of Reference</u>".

An Inertial Frame of Reference is not accelerating

Within any Inertial Frame of Reference all motion experiments (and all "Laws of Physics") will produce the same results

Distinguishing Inertial, and Non-Inertial, Frames of Reference

Imagine you are inside a closed vehicle and cannot see out. How can you tell if your "Frame of Reference" is "Inertial" or not?

A simple indication would be to hang a mass on a string from the ceiling. If it hangs straight down there is no acceleration. If it hangs at an angle, (due to its inertia) then your vehicle is accelerating.

Does it matter whether your vehicle is stationary or moving at constant velocity? Not at all! The mass still hangs straight down, and any Physics experiments will give the same result as any other observer in any other Inertial Frame of Reference.

Albert Einstein's Strange Idea

Albert Einstein (1879-1955) has gone down in the History of Science as one of the "Greats", and just about the only scientist to ever match the achievements of the great Sir Isaac Newton.

Einstein's "Theory of Relativity" is famous as a great achievement, (true!) and as something incredibly complicated that hardly anyone can understand (false! It's a dead-simple idea, but it defies "common sense".)

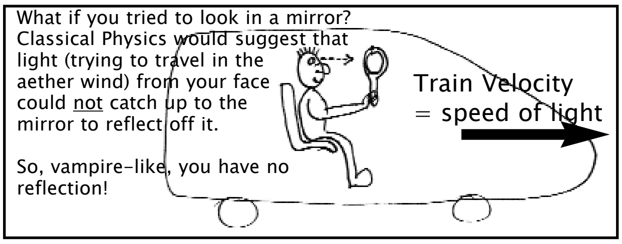
Einstein declared "common sense" = "a deposit of prejudice laid down in the mind prior to the age of 18".
To understand "Einstein's Relativity" you need to ignore "common sense" and have a child-like open-mind to fantasy and the K.I.S.S. Principle...

The Principle of Relativity
was already well known before Einstein, and stated in various forms by Galileo, Newton and many others.

> In an Inertial Frame of Reference
> all measurements and experiments
> give the same results
>
> It is impossible to detect the motion
> of an Inertial Frame of Reference by experiment
> within that frame of reference
>
> The only way to measure the motion
> of your frame of reference
> is by measuring it against
> someone else's frame of reference

These are all statements of the "Principle of Relativity".

Einstein's Gedanken (a "Thought Experiment")
Einstein had, in some ways, a child-like imagination. He wondered what it would be like to travel on a train moving at the speed of light.
(100 years ago a train was the ultimate in high-speed travel).

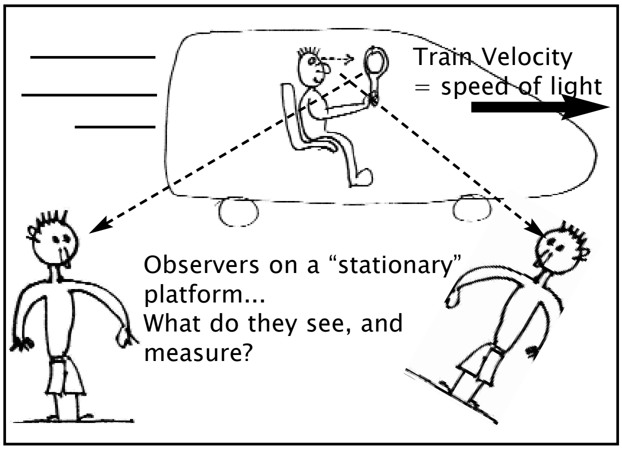


But Einstein remembered Michelson & Morley's failure to measure the "aether wind" and applied the Principle of Relativity...

In a non-accelerating, Inertial Frame of Reference, you would measure the speed of light (and anything else, like reflection) exactly the same as anyone else... you would see your reflection, and everything appears normal.

Implications of Einstein's Relativity Idea

What about a person standing in the train station as you flash (literally!) through at the speed of light? What would they see through the train window as you zap by?

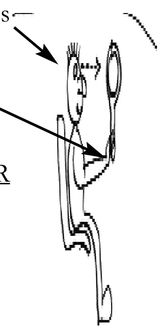


Again, according to the results of the Michelson-Morley experiment, these observers will measure light waves from you as travelling at the same speed of light as you measure inside the train, because everyone is in an Inertial F. of R.

(Naturally, both train and platform are fully equipped with interferometers and high-tech ways to do this)

> But, if you are travelling at the speed of light, how is it possible for you, and the stationary observers on the platform, to both measure the same light wave as having the same velocity?
>
> Well, says Einstein, if THE SPEED OF LIGHT is FIXED, then SPACE and TIME must be RELATIVE.
>
> What does this mean?

The people on the platform see you as compressed in space like this
Furthermore, when they study your watch they see that it is running much slower than their own is.



Seen and measured by them, YOUR LENGTH & TIME HAS CHANGED!
And you see them the same way!

Einstein's conclusion from the Principle of Relativity and the Michelson-Morley experiment is that:

> **The Speed of Light is Always the Same**
> **(for observers in Inertial Frames of Reference)**
> **and therefore,**
> **LENGTH & TIME must change**
> **as measured by another observer**
> **who is in relative motion**

Length Contraction & Time Dilation

If you can ignore "common sense" and accept the fantasy of a train moving at 300,000 km/sec then Einstein's proposal makes sense:

If everyone (in any Inertial F. of R.) measures the speed of light as being the same, then the measurements of SPACE and TIME must be relative, and different as seen by an observer in another F. of R.

It turns out that the measurement of length must get shorter as your velocity increases...
(as seen by an observer in another Inertial F. of R.)

$$L = L_o\sqrt{1 - \frac{v^2}{c^2}}$$

L = Length observed by outside observer
L_o= "rest length" measured within F.of R.
v = relative velocity of observer
c = speed of light = 3.00 x 10^8ms^{-1}

**THIS IS LENGTH CONTRACTION.
IT OCCURS ONLY IN THE DIRECTION OF THE RELATIVE MOTION**

...and time gets longer... it goes slower...

$$t = \frac{t_o}{\sqrt{1 - \frac{v^2}{c^2}}}$$

t = time observed by outside observer
t_o= time measured within F.of R.
v = relative velocity of observer
c = speed of light = 3.00 x 10^8ms^{-1}

THIS IS TIME DILATION

Example Calculation
On board a spacecraft travelling at "0.5c" (i.e. half the speed of light = 1.50x10^8ms^{-1}) relative to the Earth, you measure your craft as being 100 metres long. Carrying out this measurement takes you 100 seconds.

Observers on Earth (with an amazing telescope) are watching you. How much time elapses for them, and what is their measurement of your spacecraft?

Solution
The factor $\sqrt{1 - \frac{v^2}{c^2}}$ = Sq.Root(1- $(1/2)^2/1^2$)
= 0.866
So Length, L=L_ox 0.866 = 100x0.866 = **86.6m**.
Time, t = t_o/ 0.866 = 100/0.866 = **115**s.
They see your craft as being shorter, and your time as going slower!

Relativity and Reality

Do these alterations to time and space really happen?
Yes they do, and they have been measured!

• Extremely accurate "atomic clocks" have been synchronized, then one flown around the world in a high speed aircraft. When brought back together, the clock that travelled was slightly behind the other... while travelling at high speed it's time had slowed down a little, relative to the other.

• Certain unstable sub-atomic particles always "decay" within a precise time. When these particles are travelling at high speeds in a particle accelerator, their decay time is much longer (as measured by the stationary scientists). At high speed the particle's time has slowed down relative to the scientists' time.

It's important for you to realize that, if this particle could think, it would not notice any slow-down in time... its own "feeling" of time and its little digital watch would seem perfectly normal to it. But, from the relative viewpoint of the scientists measuring the particle's decay, its time has slowed down relative to laboratory time.

Mass Changes Too

Not only does length contract, and time stretch, but mass changes too.

$$m = \frac{m_o}{\sqrt{1 - \frac{v^2}{c^2}}}$$

m = mass observed by outside observer
m_o= "rest mass" measured within F.of R.
v = relative velocity of observer
c = speed of light = 3.00 x 10^8ms^{-1}

THIS IS MASS DILATION

Two of the most fundamental laws ever discovered by Science are the "Law of Conservation of Energy" and the "Law of Conservation of Matter". These state that energy and matter (mass) cannot be created nor destroyed.

Einstein found that the only way to avoid breaking these laws under "Relativity" was to combine them. Hence, the most famous equation of all:

$$E = mc^2$$

E = Energy, in joules
m = Mass, in kg
c = speed of light = 3.00 x 10^8ms^{-1}

THIS IS THE EQUIVALENCE OF MASS & ENERGY

Confirmation of Relativity

Einstein published his theory in 2 parts, in 1905 and 1915. At that time there was no way to test the predictions of Relativity to find supporting evidence.

The Michelson-Morley experiment had failed to find supporting evidence for the existence of the "aether", so maybe "Relativity" would fail too, but first scientists had to find testable predictions.

The first test was that, according to Relativity, light from a distant star passing close to the Sun should be bent by a measurable amount, making the star appear to change position in the sky. The only way to test this prediction was during a solar eclipse.

At the next occurrence of an eclipse, the observations were made, and showed results exactly as predicted by Relativity.

In the following years, experiments with nuclear reactions (which led to the development of the "atom bomb", and nuclear power) were able to confirm the conversion of matter into energy according to $E=mc^2$.

Later still came the measurements of time dilation (described on the previous page) and mass dilation has also been measured for high-speed particles in a particle accelerator.

EVERY RELATIVITY PREDICTION THAT CAN BE TESTED HAS SHOWN RESULTS SUPPORTING & CONFIRMING THE THEORY... that's why we believe it to be correct.

How We Define Length & Time

Our S.I. unit of length, the metre, was originally defined by the French as "One ten-millionth of the distance from (a point in) Paris to the Earth's North Pole".

Based on this, a special metal bar was carefully made to be used as the "standard" metre from which all other measuring devices were made.

As our technology improved, so did our ability to measure time and distance. Today we define the metre as "the distance travelled by light during a time interval of 1/299,792,458th of a second."

Our defintion of length is actually based on the measurement of time! (What's even more amazing is that we actually have ways to measure such a fraction of a second!)

So how do we define "a second" of time?
The modern definition involves a multiple of the time it takes for a certain type of atom to undergo an atomic "vibration", which is believed to be particularly regular and is, of course, measurable.

Some Implications of Relativity

Several of the Relativity equations contain the factor: $\sqrt{1 - \frac{v^2}{c^2}}$

This is known as the "Lorentz-FitzGerald Contraction". In the following explanations it will be referred to as the "**LFC**".

Consider firstly, what happens to the value of the LFC at different relative velocities:

If V=zero: LFC = Sq.Root(1-0) = 1

This means that if you (in your spacecraft) and the observer watching you have zero relative velocity (i.e. you are travelling at the same relative speed) then both of you will measure the same length, time and mass... no relativistic effects occur.

As V increases, the value of the LFC decreases:

Relative Velocity (as fraction of c)	Value of LFC
0.1c	0.995
0.5c	0.886
0.9c	0.436
0.99c	0.141
0.999c	0.045

Approaching c ↓ Approaching zero ↓

If V = c: LFC = Sq.Root(1 - 1) = zero

This all means that as your spacecraft accelerates and approaches the speed of light, your faithful observer sees your length approach zero, your time slowing down and approaching being totally stopped, and your mass increasing to approach infinity.

At the speed of light, the calculations for time and mass dilation become mathematically "undefined"... this is generally taken to mean that **no object can ever be accelerated up to the speed of light**.

Another way to reach this conclusion is that as you speed up, your mass increases. To accelerate more, greater force is needed because your increased mass resists acceleration. As your mass approaches infinity, an infinite amount of force is needed to accelerate you more...it's impossible to reach c.

All the energy put into trying to accelerate goes into increasing your mass, according to $E=mc^2$.

Simultaneous Events
Another consequence of Relativity is that you, and your observer, will not agree on simultaneous events. You may see 2 things occur at the same instant, but the relativistic observer will see the 2 events occurring at different times.

Worksheet 4 Relativity
Part A Fill in the blanks

The theory of the "aether" was invented to explain a).. because it was thought that all waves needed a b).. to travel through. The aether was invisible and c)..., and was present throughout the d)..

The American scientists e).............................& .... attempted to detect the aether by experiment. Their apparatus used 2 f)..., travelling at right angles. When brought together by mirrors, the beams produced an g).. pattern. The idea was that the pattern should change when the apparatus was h)..., because one beam should be travelling with the "aether wind" and the othet i)................................... it. This "aether wind" would be caused by j)...................... .... through space. The result was that k)..

An "l)................................. Frame of Reference" is one which is not m)... Within such a place, all measurements and experiments will give the n)............... .... This idea is known as the "Principle of o)...". Albert Einstein applied this principle to the Michelson-Morley result. He concluded that all observers will always measure the speed of light as being p).. For this to happen, then q)............................... and .... must be relative. This means that the measurements of length and time as seen by r).. .... will be different.

Relativity Theory predicts that Length will s).............................. while time will t)................................ Also, mass will u)..........................., thereby making it impossible to actually v)... Relativity also predicts that mass can be converted into w)................................... and vice-versa.

COMPLETED WORKSHEETS BECOME SECTION SUMMARIES

Although it defies common sense, many aspects of Relativity have been confirmed by x)...................................... For example, synchronized clocks have been found to disagree if one of them is y)... .... The conversion of mass into energy has been observed (many times) during z)........................... reactions.

Part B Practice Problems

1.
A spacecraft is travelling at 95% of the speed of light relative to an observer on Earth. On board is a fluorescent light tube which is 0.95m long and is switched on for 1 hour ship-time.

a) How long is the fluoro tube as seen be the Earth observer?
b) The Earth observer measures the time for which the light was on. What time does he measure?

2.
A sub-atomic particle has a "rest mass" of 5.95×10^{-29}kg. The particle was accelerated by a particle accelerator up to a velocity of 0.99c. (99% of "c")

a) What relativistic mass will the particle now have, if measured by the scientists in the laboratory?
b) What relativistic mass will it have if accelerated up to 0.9999c? (99.99% of "c")

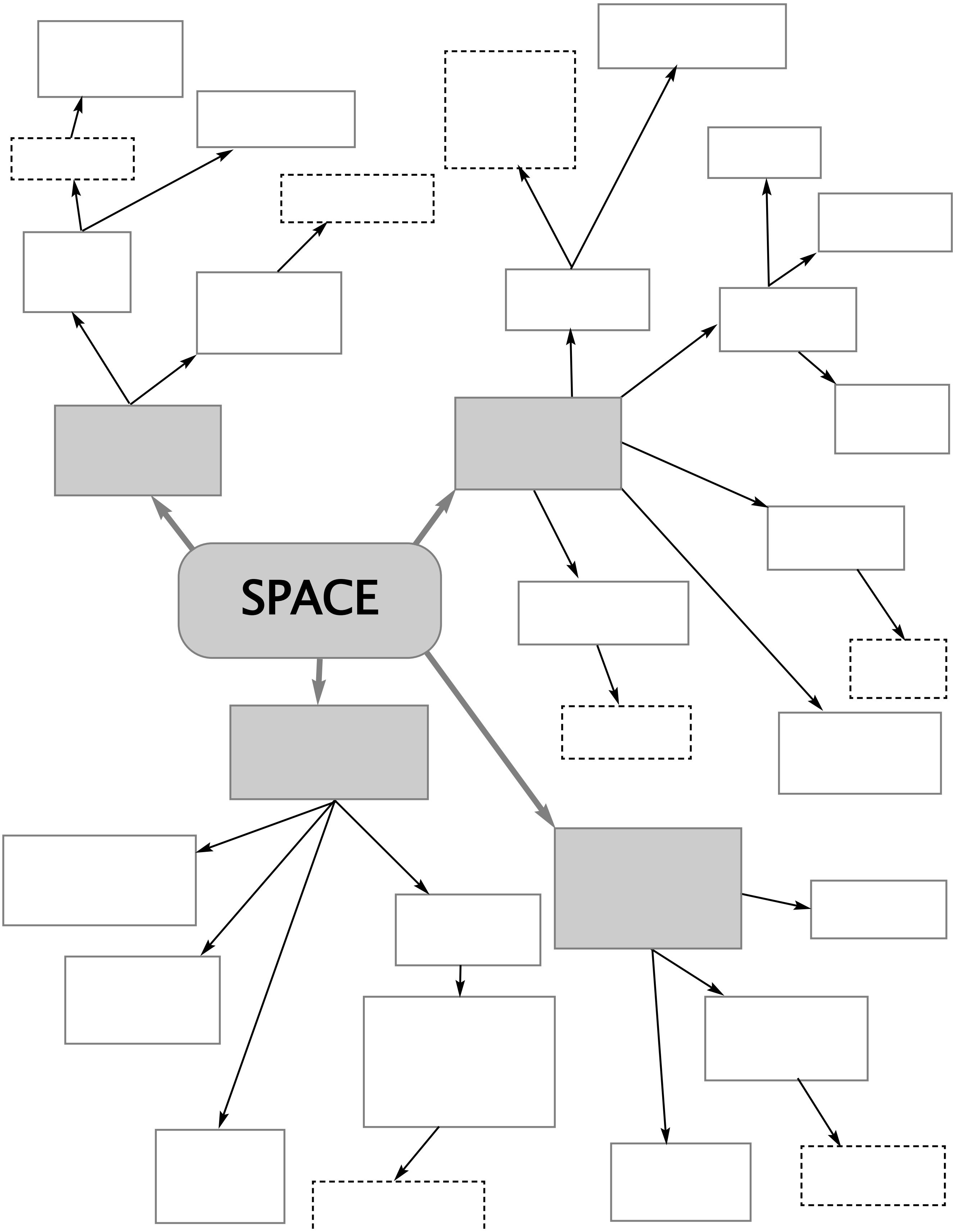
3.
In a nuclear reactor, over a period of time, a total of 2.35kg of "mass deficit" occurs. This mass has "disappeared" during the nuclear reactions. Calculate the amount of energy this has released.

4.
According to the "Big Bang" Theory, in the first moments of the Universe there was nothing but energy. Later, matter formed by conversion from the energy.

Calculate how much energy was needed to produce enough matter to form the Earth (mass= 5.97×10^{24}kg).

CONCEPT DIAGRAM ("Mind Map") OF TOPIC

Some students find that memorizing the OUTLINE of a topic helps them learn and remember the concepts and important facts. Practise on this blank version.



Practice Questions

These are not intended to be "HSC style" questions, but to challenge your basic knowledge and understanding of the topic, and remind you of what you NEED to know at the K.I.S.S. principle level.

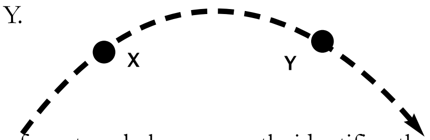
When you have confidently mastered this level, it is strongly recommended you work on questions from past exam papers.

Part A Multiple Choice

1. According to the formal definition of "Gravitational Potential Energy" (GPE)
A. There is zero GPE on the surface of the Earth.
B. GPE depends on mass, height and velocity.
C. There is zero GPE at an infinite distance from Earth.
D. GPE depends only on the weigh of the object.

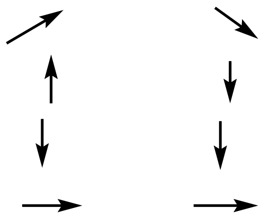
2. On Earth g≅$10ms^{-2}$ while on Mars g≅$4ms^{-2}$. A 100kg object transported to Mars would have mass and weight (respectively) of:
A. 100kg and 400N.
B. 400kg and 1,000N.
C. 100kg and 1,000N.
D. 400kg and 400N.

3. The diagram shows the trajectory of a projectile, and 2 points X & Y.



Which pair of vectors below correctly identifies the total acceleration vector of the projectile at points X and Y?

Point X **Point Y**



A.
B.
C.
D.

4. To analyse projectile motion mathematically, usually the first thing to do is to:
A. find the time of flight.
B. calculate the range.
C. calculate the maximum height reached.
D. resolve the initial velocity into vertical & horizontal components.

5. Ignoring air-resistance, the maximum range for any projectile (for the same launch velocity) will occur when:
A. it is launched horizontally.
B. it is launched at 45^o upwards.
C. it is launched to achieve a greater height.
D. its vertical acceleration is increased.

6. It is known that the value of "escape velocity" for any planet is
• proportional to the mass of the planet, and
• inversely proportional to the planet's radius.
Therefore, the planet which would definitely have a lower escape velocity than Earth would have (compared to Earth)
A. more mass, smaller radius.
B. less mass, larger radius.
C. more mass, larger radius.
D. less mass, smaller radius.

7. During a launch, the acceleration of a rocket:
A. increases, because mass decreases.
B. increases, because kinetic energy increases.
C. decreases, because momentum increases.
D. remains constant, because of constant thrust force.

8. To get maximum advantage from the rotation of the Earth, a space launch is always directed toward the
A. north
B. south
C. east
D. west

9. The chief of the C.I.A. has asked you to plan the deployment of a spy-satellite in an orbit suitable for taking photos of suspected terrorist bases, in many locations, world-wide. You would be best to plan for the satellite to be in a:
A. Low-Earth Orbit, around the Equator.
B. Geo-stationary Orbit, above the Equator.
C. Geo-stationary orbit, allowing full earth coverage.
D. Low-Earth, Polar Orbit.

10. Once the Space Shuttle reaches its orbital velocity the engines are turned off, and the craft orbits in free-falling circular motion. This motion is characterized by:
A. constant acceleration directed at a tangent to the circle.
B. constant velocity, with no forces acting.
C. constant centrifugal force, pushing things outwards.
D. constant acceleration directed at the centre of the circle.

11. The data below relates to 3 of the moons of Jupiter and one of the moons of Mars. The units of measurement are arbitrary. Which moon (A,B,C or D) belongs to Mars?

Moon	Orbital Radius	Orbital Period
A.	9.2	12.5
B.	8.5	10.0
C.	13.3	19.6
D.	10.0	12.8

12. All Low-Earth orbits are prone to "decay" because of:
A. the satellite running out of fuel to maintain forward speed.
B. friction with the few gas molecules in its orbital path.
C. Earth's gravity gradually pulling it downwards.
D. magnetic effects of a Polar orbit.

13.
The gravitational force between 2 masses is "F" units when they are distance "d" apart.
If these masses were brought closer, to a distance "0.25d", then the force between them would be:
A. 0.25 F
B. 4F
C. F/16
D. 16F

14.
The "Aether" was an idea
A. for a new anaesthetic.
B. used to explain the Principle of Relativity.
C. to explain how light could travel in a vacuum.
D. to explain the interference of light waves.

15.
In an "Inertial Frame of Reference" a mass hanging from the ceiling by a string would probably.
A. swing back and forth.
B. hang straight down.
C. hang at an angle from the vertical.
D. undergo mass dilation due to relativistic effects.

16.
Two cosmonauts in separate spacecraft travelling at different relativistic velocities are able to make a series of observations and measurements of their own spacecraft, and of each other's spacecraft. The one thing they would agree with each other about is:
A. the simultaneity of 2 events occurring together.
B. the value of the velocity of light.
C. the passage of time in each other's spacecraft.
D. the length of each other's spacecraft.

17.
The first experimental confirmation of Einstein's Theory of Relativity was:
A. the change in the apparent position of a star due to the gravity of the Sun.
B. the result of the Michelson-Morley Experiment.
C. the release of energy from the first atom bomb.
D. measurements made with a mirror on a high speed train.

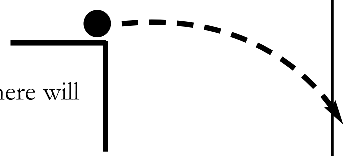
18.
From the Earth, you are able to observe and measure several features of an alien spacecraft as it flies by at 90% of the speed of light. Compared to the measurements made by the alien on board, your measurements would show:

	Craft mass	Craft length	Craft time
A.	less	shorter	faster
B.	more	longer	slower
C.	more	shorter	slower
D.	less	longer	faster

Longer Response Questions
Mark values shown are suggestions only, and are to give you an idea of how detailed an answer is appropriate.

19. (3 marks)
An alien creature weighs 7.25×10^3N on its home planet. On Earth, the creature weighs 5.84×10^3N.
a) What is the creature's mass?
b) What is the value of "g" on the creature's home planet?

20. (4 marks)
A ball was rolled along a horizontal table at $5.45ms^{-1}$.
If the table is 1.20m high, where will the ball hit the ground?



21. (8 marks)
An arrow was released from the bow at an upward angle of 60^o and an initial velocity of $42.0ms^{-1}$. It hits its target at the same horizontal level from which it was released.
a) Find the time of flight.
b) Find the maximum height reached.
c) Calculate the distance from bow to target.

22. (6 marks)
These military bombs are designed to be dropped from the aircraft at an altitude of 15,000m when the plane is in level flight at a velocity of $300ms^{-1}$.

Photo: Arian Kulp

a) Ignoring air-resistance, how far in front of the target must the bombs be released?
b) How fast will they be going (magnitude only) when they hit the ground?

23. (3 marks)
It was Isaac Newton who discovered the concept of "orbiting" the Earth by thinking about projectiles.
Outline Newton's scenario for how a projectile could end up in orbit.

24. (4 marks)
Author Jules Verne wrote a novel in which a space ship was launched by firing it from a cannon, on a journey to the Moon. The required velocity would be $1.05 \times 10^4ms^{-1}$.
With the cannon barrel 200m long, it would be reasonable for the time of launch (i.e. duration of acceleration) to be 7.50s.

a) Calculate the acceleration rate of the capsule.
b) What is the value (in terms of "g") of the "g-force" that the passengers would experience?
c) Comment on the feasibility of such a launch.

25. (3 marks)
Give a brief outline of the contributions of <u>one</u> of these men to the science of rocketry.
Tsiolkovsky, Goddard or von Braun

26. (4 marks)
The early space rocket engines produced a constant "thrust force" throughout their "burn". One of the advantages of the Space Shuttle engine is that it has a throttle control. During launch, the engine is gradually throttled back and thrust reduced during the ascent into orbit.
Explain how this contributes to the safety and comfort of the astronauts on board.

27. (6 marks)
a) Use the relationship $R^3/T^2 = GM/4\pi^2$ to find the radius of orbit of an Earth satellite with a period of 2.00hours.
b) Calculate the orbital velocity of this satellite.
c) Find the strength of the force holding it in orbit, given that the satellite has a mass of 2,650kg.

28. (5 marks)
Discuss the problems of recovering a spacecraft from orbit and outline the process of "atmospheric braking", with reference to the importance of the angle of descent.

29. (5 marks)
An astronaut with mass (including spacesuit) 120kg is standing on the surface of the planet Mercury. The planet has a mass of 2.99×10^{23}kg and radius 2.42×10^{6}m.
a) Calculate the gravitational force acting on the astronaut.
b) From your answer to (a) calculate the value of "g" on the surface of Mercury.

30. (5 marks)
a) Explain what is meant by the "Slingshot Effect".
b) Why is it useful in space exploration.
c) State how energy is conserved in the process.

31. (7 marks)
Give a brief description of the famous Michelson-Morley experiment, including:
a) their aim or purpose in doing the experiment.
b) an outline of the method used.
c) the results.

32. (3 marks)
What did Albert Einstein conclude about the measurement of space and time, taking into account the results of the Michelson-Morley experiment?

33. (8 marks)
A sub-atomic particle, at rest in the laboratory, has the following characteristics:
Mass = 3.22×10^{-27}kg. Diameter= 7.38×10^{-16}m.
Half-Life (Time to "decay")= 2.58×10^{-2}s.

The particle is now accelerated up to a velocity of 0.999c (i.e. 99.9% of the speed of light) in a particle accelerator.
Calculate:
a) its relativistic
i) diameter
ii) half-life
iii) mass
as measured by the scientists in the laboratory.
b) While travelling at 0.999c, the particle undergoes a nuclear reaction which results in its total annihilation by conversion to energy. What energy release is measured by the scientists? (The scientists observe the conversion of its relativistic mass, not rest-mass)

Remember that for full marks in calculations, you need to show FORMULA, NUMERICAL SUBSTITUTION, APPROPRIATE PRECISION and UNITS

Answer Section

Worksheet 1 Part A

a) force
b) gravity
c) accelerate
d) 10 (9.81)
e) period
f) gradient
g) force field
h) attracts
i) repel
j) gravitational field
k) mass
l) work done
m) infinity
n) negative
o) 9.81
p) weight
q) mass

Part B Practice Problems - Mass & Weight

1.

a) i) **575kg** ii) **575kg** iii) **575kg**.

b) i) W=mg = 575x9.81 = 5,641 = **$5.64x10^3$N**.

ii) In free-fall orbit everything is weightless. W = **zero**.

iii) W=mg = 575x1.6 = 920 = **$9.2x10^2$N**.

iv) W=mg = 575x25.8 = 14,835 = **$1.48x10^4$N**.

2.

a) On Mars; W=mg, so m=W/g = 250/2.8 = 65.8kg

On Earth; W=mg = 65.8x9.81 = 645 = **$6.5x10^2$N**.

b) On Neptune; W=mg = 65.8x10.4= 684 = **$6.8x10^2$N**.

c) On Moon; W=mg = 65.8x1.6 = 105 = **$1.1x10^2$N**.

3.

a) On Neptune; W=83.0 = mg, so m= 83.0/10.4 = **7.98kg**.

b) On Earth; W=mg = 7.98x9.81 = **78.3N**.

c) W=206=mg, so g=206/7.98 = 25.8ms^{-2}. **matches Jupiter**

Worksheet 2 Part A

a) only under gravity
b) trajectory
c) parabola
d) horizontal & vertical
e) angle
f) resolving
g) components
h) constant velocity
i) acceleration
j) gravity
k) time
l) zero
m) height
n) range
o) horizontal & vertical
p) 45
q) Galileo
r) at the same rate
s) velocity
t) vertical
u) Newton
v) escape
w) orbit
x) escape from the Earth's gravitational field
y) velocity
z) curvature
aa) satellite
ab) in orbit
ac) accelerated
ad) g-forces
ae) weight
af) velocity
ag) g-forces
ah) rockets
ai) liquid
aj) east
ak) rotation
al) 3rd
am) conserved
an) forward
ao) rocket
ap) decreases
aq) increases
ar) g-forces
as) low-Earth
at) 200-1,000
au) quickly/fast
av) photos & surveys
aw) geo-stationary
ax) period
ay) rotation
az) same position in the sky
ba) communication
bb) centripital
bc) centre of the circle
bd) tension in the string
be) friction
bf) gravity
bg) Kepler
bh) gravitational
bi) decay
bj) gas molecules/upper atmosph.
bk) deceleration
bl) heat
bm) angle

Worksheet 2

Part B Practice Problems

Projectile Motion

1.

U_y = U.Sinθ U_x = U.Cosθ

a) = 20.5xSin60 =20.5xCos60

= **17.8ms^{-1}**. = **10.3ms^{-1}**.

b)vertical = **zero** horizontal = **250ms^{-1}**.

c) U_y = 15.0xSin25 U_x = 15.0xCos25

= **6.34ms^{-1}.** = **13.6ms^{-1}**.

d) = 350xSin70 = 350xCos70

= **329ms^{-1}.** = **120ms^{-1}**.

e) = 40.0xSin45 = 40.0xCos45

= **28.3ms^{-1}.** = **28.3ms^{-1}**.

2.

a) At highest point, V_y=0, and $\mathbf{V_y = U_y + g.t}$

0 = 28.3 + (-9.81x t)

t = -28.3/-9.81

= **2.88s**.

b) $S_y = U_y.t + \frac{1}{2}.g.t^2$

= 28.3x2.88 + (0.5x (-9.81) x 2.88^2)

= 81.5 + (-40.7) = **40.8m**.

c) $S_x = V_x.t$ = 28.3 x (2.88x2) (twice the time to reach max.ht.)

= **163m**.

3.

a) It is fired from max height, so S_y = -2.00 (down, so -ve)

$S_y = U_y.t + \frac{1}{2}.g.t^2$

-2.00 = 0xt +(0.5x(-9.81)x t^2)

-2.00 = 0 - 4.905 x t^2

t^2 = -2.00/-4.905

t = **0.639s**.

b) $S_x = V_x.t$ = 250x0.639 = **160m**.

c) see working for (a).

Empty cartridge takes 0.639s to hit the ground. It falls down at exactly the same rate as the bullet. The difference is where each lands horizontally.

4.

a) At highest point, V_y=0, and $\mathbf{V_y = U_y + g.t}$

0 = 329 + (-9.81)x t

t = -329/-9.81

= **33.5s**.

b) $S_y = U_y.t + \frac{1}{2}.g.t^2$

= 329x33.5 + (0.5x(-9.81)x33.5^2)

= 11,022 - 5,505

= 5,517 = **$5.52x10^3$m**.

c) $S_x = V_x.t$ = 120x(33.5x2) (twice the time to reach max.ht.)

= 8,040 = **$8.04x10^3$m**.

5.

a) Vertical displacement

$S_y = U_y.t + \frac{1}{2}.g.t^2$

= 17.8x2.50 + (0.5x(-9.81)x2.50^2)

= 44.5 + (-30.65)

=13.4m (+ve, therefore up)

Horizontal Displ.

$S_x = V_x.t$

= 10.3 x 2.50

= 25.8m

Ball is 25.8 metres down-field and 13.4 m high.

b) Vertical velocity

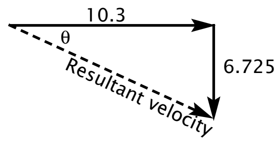
$V_y = U_y + g.t$

= 17.8 + (-9.81)x2.50

= -6.725ms^{-1} (downwards)

Horizontal velocity

$V_x = U_x$ = 10.3 ms^{-1}



$V^2 = V_y^2 + V_x^2 = 10.3^2 + 6.725^2$

∴ V = sq.Root(151.32) = **12.3ms^{-1}**.

Tan θ = 6.725/10.3, ∴ **θ ≅ 33° below horizontal**

Worksheet 2 Part B (cont.)

Orbits & Centripital Force

6.

a) T=1.74 hours = 1.74x60x60= 6,264s

R= 1,000 km (=10^6m) + $6.37x10^6$ = $7.37x10^6$m

V = $2\pi R/T$

= $2x\pi x7.37x10^6/6,264$

= 7,393 = **$7.39x10^3 ms^{-1}$**.

b) $F_c = mv^2/R = 600x(7.39x10^3)^2/7.37x10^6$

= **$4.45x10^3$N**.

7.

a) $F_c=mv^2/R$, so $R = mv^2/F = 1,500x(6.13x10^3)^2/5.32x10^3$

= **$1.06x10^7$m**.

b) Altitude = $1.06x10^7 - 6.37x10^6$ = **$4.23x10^6$m (4,230km)**

c) $V=2\pi R/T$, so $T = 2\pi R/V = 2x\pi x1.06x10^7/6.13x10^3$

= **$1.09x10^4$s. (3.02 hours)**

8.

R = 350km + $6.37x10^6$m = $6.72x10^6$m

T= 1.52 hrs = 1.52x60x60 = $5.47x10^3$s.

a) $V=2\pi R/T = 2x\pi x6.72x10^6/5.47x10^3$

= **$7.72x10^3 ms^{-1}$**.

b) $F_c=mv^2/R$, so $m = F.R/v^2 = 2,195x6.72x10^6/(7.72x10^3)^2$

= **247kg**.

Kepler's Law of Periods

9.

Question	Radius(m)	Period(s)	R^3/T^2
6	$7.37x10^6$	$6.26x10^3$	$1.02x10^{13}$
7	$1.06x10^7$	$1.09x10^4$	$1.00x10^{13}$
8	$6.72x10^6$	$5.47x10^3$	$1.01x10^{13}$

The ratio R^3/T^2 is the same for all 3 satellites.
(slight differences are due to rounding-off errors in calculations)
Keplers Law states that this ratio should be the same for the satellites of any planet.

10.

Average value from table = $1.01x10^{13}$= constant

a) R^3 = constant x T^2

R=Cube.Root($1.01x10^{13}x(1.60x10^3)^2$) = **$2.96x10^6$m**.

b) R=Cube.Root($1.01x10^{13}x(1.15x10^4)^2$) = **$1.10x10^7$m**.

c) $T^2 = R^3$/constant

T =Sq.Root($(2.56x10^7)^3/1.01x10^{13}$) = **$4.08x10^4$s**.

d) R = 2,000km + $6.37x10^6$m = $8.37x10^6$m.

T =Sq.Root($(8.37x10^6)^3/1.01x10^{13}$) = **$7.62x10^3$s**.

11.

a) constant = $GM/4\pi^2 = 6.67x10^{-11}x6.57x10^{23}/4x\pi^2$

= **$1.11x10^{12}$**

b) R^3/T^2 = constant, so R=Cube.Root(constant x T^2)

= Cube.root($1.11x10^{12}x(1.60x10^3)^2$)

= **$1.42x10^6$m**.

c) T =sq.Root(R^3/constant) = $(2.56x10^7)^3/1.11x10^{12}$

= **$1.23x10^5$s**.

d) Earth satellite, T = $4.08x10^4$s.

Mars satellite, T = $1.23x10^5$s.

Earth satellite's period is shorter, therefore it travels faster.

e) At a given orbital radius, a satellite orbiting a smaller planet needs to travel at a ....**lower**.....velocity. The bigger the planet, the ....**faster (higher)**.... the velocity would need to be.

Worksheet 3 Universal Gravitation

Part A

a) the product of the masses
b) the square of the distance between them
c) double
d) decrease by a factor of 4.
e) centripital
f) the planets
g) direction/trajectory
h) speed
i) Slingshot
j) planet
k) equal

Part B Practice Problems

1.

$F_G = GMm/d^2 = 6.67x10^{-11}x75x60/0.5^2$

= **$1.20x10^{-6}$N**. (about 1 millionth of a newton)

2.

$F_G = GMm/d^2 = 6.67x10^{-11}x6.75x10^8x2.48x10^9/425$

= **$2.63x10^5$N**.

3.

d =Sq.Root(GMm/F)

= Sq.root($6.67x10^{-11}x6.02x10^{22}x5.67x10^{10}/6.88x10^{10}$)

= **$1.82x10^6$m**.

(Since this equals 1,820km, and the radius of the Moon is 1,738km, then the comet is just 82km from the surface... DEEP IMPACT about to happen!)

Worksheet 4 Relativity

Part A

a) transmission of light in vacuum
b) medium
c) massless / weightless
d) Universe
e) Michelson & Morley
f) beams of light
g) interference
h) rotated 90 degrees
i) across
j) the Earth's motion
k) no change to the interference pattern-no aether wind detected.
l) Inertial
m) accelerating
n) same results
o) Relativity
p) the same
q) space & time
r) an observer travelling at a different relative velocity
s) shorten
t) lengthen / slow down
u) increase
v) accelerate to the speed of light
w) energy
x) observation/experiment
y) transported at high speed
z) nuclear

Part B Practice Problems

4. Using the abbreviation "**LFC**"= $\sqrt{1 - \frac{v^2}{c^2}}$
(see page 24)

a) At 0.95c, LFC = Sq.root(1 - $(0.95^2/1^2)$)

= 0.31

$L = L_0$ x LFC = 0.95 x 0.31 = **0.29m**.

b) $t = t_0$ /LFC = 1/0.31 = **3.2 hours**.

5.

a) At 0.99c, LFC = Sq.root(1 - $(0.99^2/1^2)$)

= 0.14

$m = m_0$ / LFC = $5.95x10^{-29}/0.14$ = **$4.25x10^{-28}$kg**.

b) At 0.9999c, LFC = Sq.root(1 - $(0.9999^2/1^2)$)= 0.01414

$m = m_0$ / LFC = $5.95x10^{-29}/0.01414$ = **$4.21x10^{-27}$kg**.

6.

$E=mc^2 = 2.35x(3.00x10^8)^2$ = **$2.12x10^{17}$J**.

7.

$E=mc^2 = 5.97x10^{24}x(3.00x10^8)^2$ = **$5.37x10^{41}$J**.

Practice Questions

Part A Multiple Choice

1. C	**5. B**	**9. D**	**13. D**	**17. A**
2. A	**6. B**	**10. D**	**14. C**	**18. C**
3. C	**7. A**	**11. A**	**15. B**	
4. D	**8. C**	**12. D**	**16. B**	

Part B Longer Response Questions

In some cases there may be more than one correct answer. The following "model" answers are correct but not necessarily perfect.

19.

a) On Earth: W=mg, so m=W/g = $5.84 \times 10^3/9.81$ = **595kg**.

b) On home planet: W=mg, so g=W/m = $7.25 \times 10^3/595$ = **12.2ms⁻²**.

20.

$U_y=0$, $U_x=5.45ms^{-1}$, S_y = -1.20m (down (-ve))

Time of flight: $S_y = U_y.t + 0.5.g.t^2$

$-1.20 = 0xt + (0.5x(-9.81)xt^2)$

t = sq.root(-1.20/-4.905)

= 0.495s.

Horizontal distance: $S_x = U_x.t$ = 5.45x0.495 = **2.95m**.

The ball lands 2.95m from the base of the table.

21.

$U_y = U.Sin\theta$ = 42.0xSin60 = $36.4ms^{-1}$

$U_x = U.Cos\theta$ = 42.0xCos60 = $21.0ms^{-1}$.

a) At max.height, Vy = 0, and $V_y = U_y + g.t$

0 = 36.4 x (-9.81)x t

t = -36.4/-9.81

= 3.71s (to highest point)

Time of flight = 3.71x2 = **7.42s**.

b) $S_y = U_y.t + 0.5.g.t^2$ (use time to highest point)

$= 36.4x3.71 + (0.5x(-9.81)x3.71^2)$

= 135 + (-67.5) = **67.5m**.

c) Range: $S_x = U_x.t$ = 21.0x7.42 (Time for entire flight)

= **156m**.

22.

a) $U_y=0$, $U_x=300ms^{-1}$, S_y = -15,000m (down (-ve))

Time of flight: $S_y = U_y.t + 0.5.g.t^2$

$-15,000 = 0xt + (0.5x(-9.81)xt^2)$

t = sq.root(-15,000/-4.905)

= 55.3s.

Horizontal distance: $S_x = U_x.t$ = 300x55.3 = 16,590m

= **1.66×10^4m**.

Bombs must be released over 16km before the target.

b) $V_y = U_y + g.t$ $U_x=300ms^{-1}$.

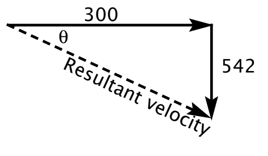
= 0 + (-9.81)x55.3

= $542ms^{-1}$.

$V^2 = V_y{}^2 + V_x{}^2 = 542^2 + 300^2$

∴ V = sq.Root(383,764) = **$619ms^{-1}$**.

(almost twice the speed of sound!)



23.

He imagined a cannon firing projectiles horizontally from a very high mountain. As the launch velocity is increased, the shot travels further before reaching the ground. At a high-enough velocity, the downward curve of its trajectory could match the curvature of the Earth. This projectile would travel right around the Earth, constantly falling towards it, but never getting any closer.

24.

a) a = (v-u)/t = $(1.05 \times 10^4 - 0)/7.50$

= **1,400 (1.40×10^3) ms^{-2}**.

b) multiple of "g": 1,400/9.81 =**143 times "g"**

Passengers experience g-force equivalent of 143 times their normal weight.

c) This amount of g-force would be instantly fatal.

This is not a feasible method for human space launch.

25.

(example) For 3 marks, try to make 3 points.

Robert Goddard built and tested the first liquid-fuel rocket engine, an essential step for practical rocketry. His experiments in the 1920's-1930's were the basis for later research during World War II which led to the first long-range rockets. Goddard also advanced the theory of multi-stage rockets as the way to reach outer space.

26.

Although a rocket may produce constant thrust, the mass decreases rapidly as the fuel is burned. This means that the rate of acceleration increases during the ascent. This means that the g-forces keep increasing.

By being able to throttle back the engines, the Space Shuttle can reduce this effect and maintain more constant g-forces during the acent. This is much safer and more comfortable for the astronauts.

27.

a) period, T= 2.00hr = 2.00x60x60 = 7,200s.

$R^3/T^2 = GM/4\pi^2$

R = Cube.Root($GMT^2/4\pi^2$)

= Cube.Root($6.67 \times 10^{-11} \times 5.97 \times 10^{24} \times (7,200)^2/4\pi^2$)

= **8.06×10^6m**.

b) V = $2\pi R/T$ = $2 \times \pi \times 8.06 \times 10^6/7,200$

= **$7.03 \times 10^3 ms^{-1}$**.

c) $F_c=mv^2/R$ = $2,650 \times (7.03 \times 10^3)^2/8.06 \times 10^6$

= **1.62×10^4N**.

28.

It is impossible for a spacecraft to carry enough fuel to use its rocket engines for the complete deceleration and descent from the high speed of orbit. So atmospheric braking is used instead. If the capsule enters the atmosphere at just the right angle, friction can slow it down gradually, with the energy being converted to heat.

If the re-entry angle is too steep, the g-forces will be too high, and the craft may burn up. If the angle is too shallow, the craft may bounce off the atmosphere and go into an un-recoverable orbit.

29.

a)$F_G=GMm/d^2 = 6.67 \times 10^{-11} \times 2.99 \times 10^{23} \times 120/(2.42 \times 10^6)^2$

= **409N**.

b) This gravitational force is the astronaut's weight, and

W= mg, so g=W/m = 409/120 = **$3.41ms^{-2}$**.

30.

a) The Slingshot Effect is the technique of flying a spacecraft near a planet so that the planet's gravity accelerates the craft and alters its trajectory onto a new, desired heading.

b) It is useful for enabling a craft to visit several planets on one flight, gaining speed and a new direction without the need for large amounts of fuel.

c) The gain of energy by the spacecraft is exactly equal to the loss of energy by the planet (which loses an insignificant amount of rotational energy).

31.

a) The M-M experiment was designed to detect the "universal aether" which had been hypothesized as a medium for transmission of light waves.

b) The method involved a beam of light, split into 2 beams which travelled at right angles. Mirrors then recombined the beams in an interferometer to produce an interference pattern. The apparatus could then be rotated 90 degrees. Since one beam traveled along the "aether wind" (caused by the Earth's movement) and the other across it, there should have been a change in the interference pattern when the apparatus was rotated.

c) The result was negative. No change in the interference pattern occurred.

32.

Einstein concluded that the speed of light is constant for all observers in any Inertial Frame of Reference (IFR), regardless of relative motion. This why the M-M experiment failed to detect a difference between the speed of light in 2 different directions.

However, this requires that the measurements of space and time must be different relative to an observer's IFR. This means that measurements of length and time taken in one IFR, will be different to what a relativistic observer sees.

33.

a) At 0.999c, the "LFC" factor $\sqrt{1 - \frac{v^2}{c^2}}$ = Sq.Root(1 - $\frac{0.999^2}{1^2}$)

= 0.0447

i) $L = L_0$ x LFC

= $7.38 \times 10^{-16} \times 0.0447$ = **3.30×10^{-17}m**. (observed diameter)

ii) $t = t_0$ /LFC

= 2.58×10^{-2} / 0.0447 = **5.77×10^{-1}s** (observed half-life)

iii) $m = m_0$ / LFC

= 3.22×10^{-27}/ 0.0447 = **7.20×10^{-26}kg** (observed mass)

b) $E = mc^2 = 7.20 \times 10^{-26} \times (3.00 \times 10^8)^2$ = **6.48×10^{-9}J**.

NOTICE ANY ERRORS?

Our material is carefully proof-read but we're only human

If you notice any errors, please let us know

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