Physical Science
The Scientific Revolution

By David Harriman

Notes for Classes 1-31

Course Outline Classes 1-16

I. Background of Greek Science

- Greek ideas in physics
  - Matter (Thales, Anaxagoras, atomism, Aristotle)
  - Motion
  - Forces of electricity (amber) and magnetism (lodestone)
- The crucial discoveries in astronomy
  - Eudoxus, Aristotle, Aristarchus, Hipparchus
- Archimedes
  - The beginning of mathematical physics
- Ptolemy
  - Theory of the solar system
  - Optics

II. Copernican Astronomy

- The heliocentric theory of the solar system
- Evidence for the theory
- Problems with the Copernican theory

III. Triumph of the Heliocentric Astronomy and the Birth of Physics

- Kepler's *physical* astronomy
  - The sun exerts a force on the planets!
  - Discovery of the laws of planetary motion
- Galileo's physics
  - The pendulum
  - Law of free fall
  - Principle of inertia
  - Analysis of motion into components (parabolic trajectories)
- Galileo's discoveries with the telescope

Course Outline Classes 17-31

IV. Newton's Discovery of Universal Laws

- Steps leading to the idea of universal gravitation
  - Circular motion; force and acceleration
  - The sun's force on the planets
  - The falling apple and the acceleration of the moon
- The idea of "mass" and the three laws of motion
- How Newton completed and proved the law of gravitation
  - The evidence: the orbits of planets, comets, and the moon; free fall; the ocean tides; the shape and spin of the Earth
- Other related discoveries
  - The distances from the sun to the planets
  - Determining the gravitational constant

V. Optics and the New Experimental Method

- Snell discovers the law of refraction
- Newton's prism experiments and his theory of colors
- Applications of the theory of colors
  - The reflecting telescope
  - The explanation of rainbows
- Newton's rings and the wave nature of light
- Discovery of the speed of light

VI. Early Discoveries about Gases

- Torricelli's discovery and measurement of air pressure
- Boyle's law of gases
- Fahrenheit's invention of the mercury thermometer
- Charles' law of gases

Notes for Class 1

Introduction

Course covers:

- Ancient Greece through the 17^{th} century scientific revolution.
- Isaac Newton, greatest scientist in history.

Kuba tribe:

Woot the ocean

Woot the digger (made riverbeds and hills)

Woot the flowing (rivers)

Woot who created the woods and savannas

Woot who created the leaves

Woot who created the stones

Woot the sculptor (who made people out of wood)

Woot the inventor of prickly things (fish, thorns, paddles, etc)

Woot the sharpener (edged weapons)

Kuba tribe beliefs: No causality, No logic, No evidence, No mathematics.

Why did science begin in Greece?

Greek ideas in physics

What is matter?

Matter

Thales (ca. 600 B.C.) - Everything is water

Anaxagoras (ca. 450 B.C.) - Everything is different

Atomism (e.g., Democritus ca. 410 B.C.) - Everything as atoms

Aristotle (383–320 B.C.) - Everything as earth, water, air, fire

Motion

Aristotle's Theory of Motion

$$\text{Velocity} \propto \text{Force} / \text{Resistance}$$

Discovery of electricity (amber) and magnetism (lodestone)

Observed effects of rubbed amber

Observed effects of lodestone, which attracts iron

<u>Shape of Earth is Spherical</u>

Evidence cited by Aristotle: ships, stars on horizon, lunar eclipse

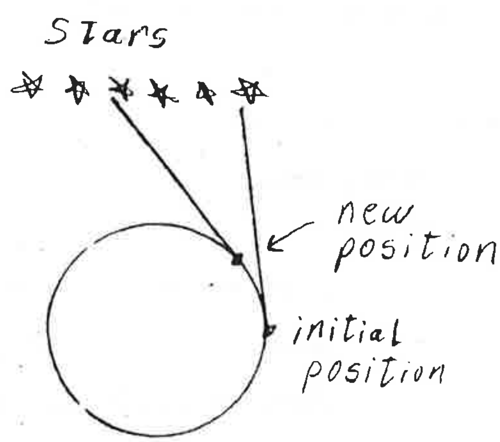


Figure 1.1 – Different stars appear as you travel north.

Notes for Class 2

Review

Early Greek Astronomy

The observed motion of the sun and the change of seasons:

- winter solstice (~ December 22)
- summer solstice (~ June 22)
- length of the night and day are equal (March 21, September 23)

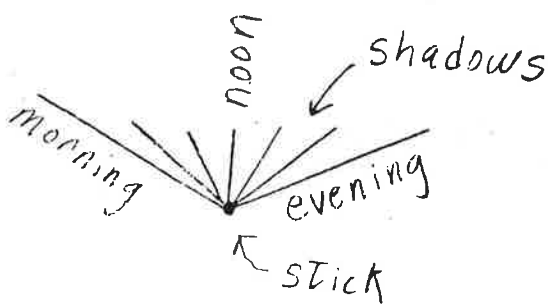


Figure 2.1 - Noon shadow is shortest

The calendar

The observed motion of the stars

- Polaris (or North Star)

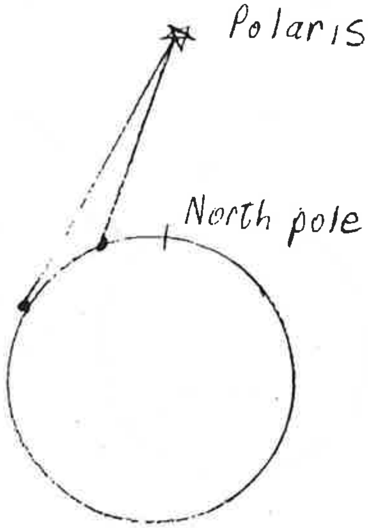


Figure 2.2 - The farther north you travel, the higher in the sky Polaris is

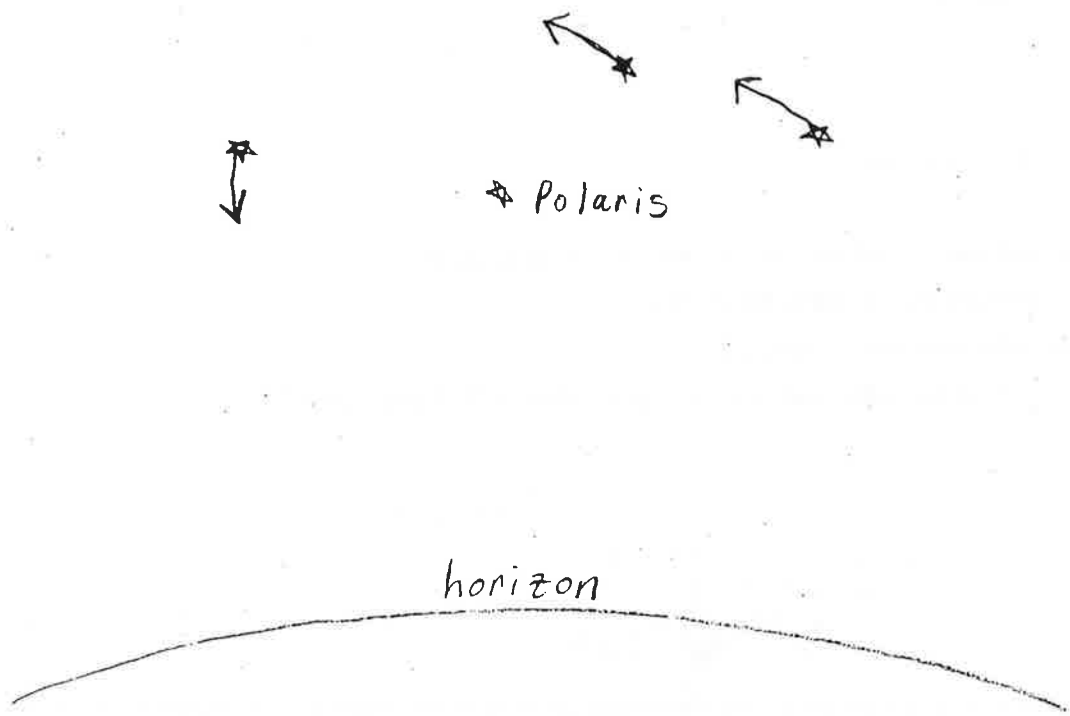


Figure 2.3 - All of the other stars move in circles around Polaris.

The sun's motion relative to the stars

15 degrees per hour, position changes slightly relative to the fixed stars

the ecliptic, tilted 23 degrees with respect to the equator, seasons

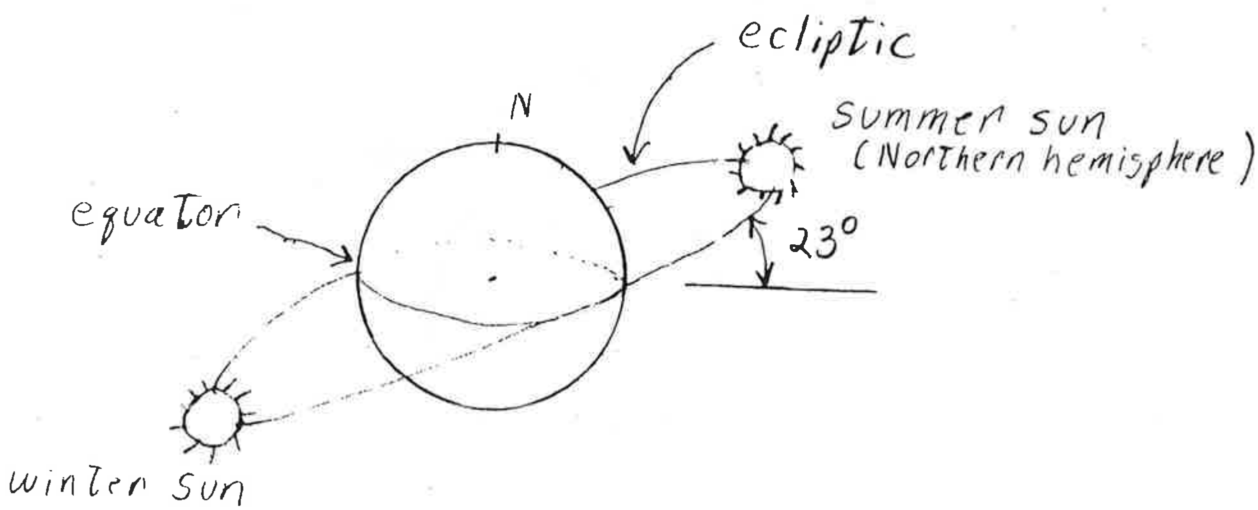


Figure 2.4 – The ecliptic

Motion of the moon and planets:

daily rotation, moon then moves eastward along the ecliptic

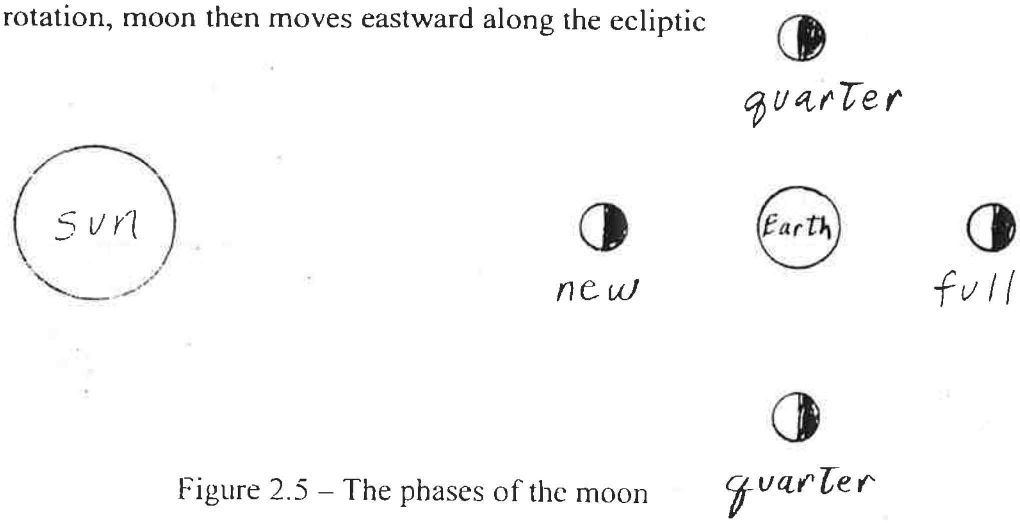


Figure 2.5 – The phases of the moon

The 5 planets known to the Greeks:

Mercury, Venus, Mars, Jupiter, Saturn

The Eudoxan Spheres: A Mathematical Model of the Universe ~350 B.C.

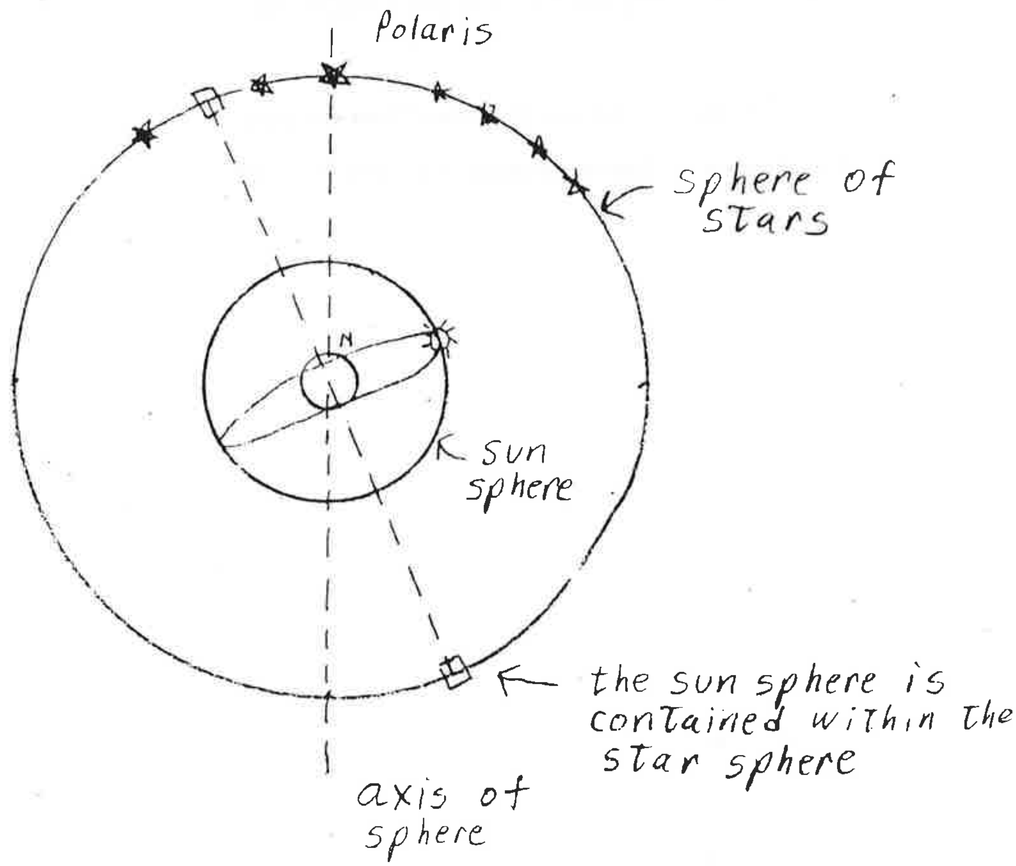


Figure 2.6 - Eudoxian spheres

Distance to the Sun and its Size

The Greeks

Around 280 B.C., Aristarchus

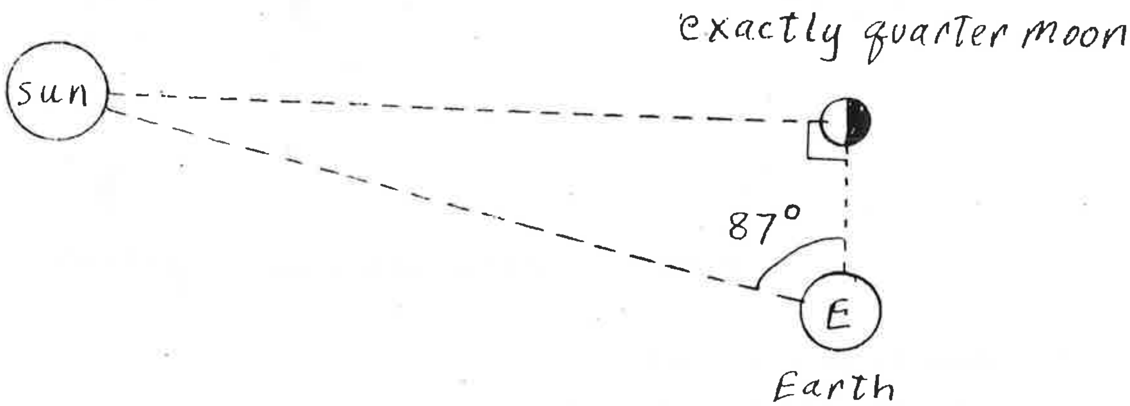


Figure 2.7 - Distance to the sun

Cos 87 = Moon distance / Sun distance

Sun distance / Moon distance = 1 / cos 87 = 19

Notes for Class 3

Clarification 'noon shadows' and sun rotation

Circles: radius, circumference, degrees, radians.

Circle has 360 degrees

Circumference = $2\pi R$

1 Radian = $360°/2\pi = 57.3°$

$S = \theta R$ where S is arc length, θ is measured in radians

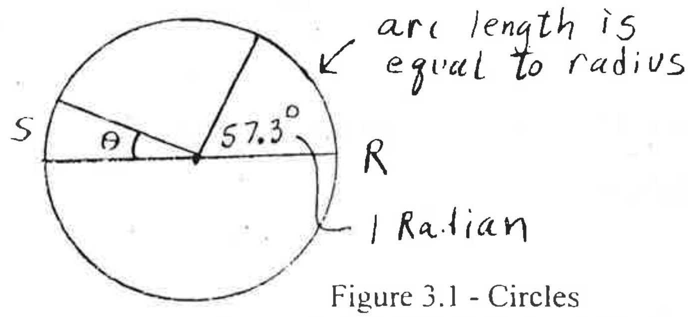


Figure 3.1 - Circles

Right triangles.:

cosine θ = adjacent/hypotenuse

sin θ = opposite/hypotenuse

tan θ = opposite/adjacent

Pythagorean theorem: $c^2 = a^2 + b^2$

A right triangle with sides of length 3, 4 and 5 has the property: $3^2 + 4^2 = 5^2$

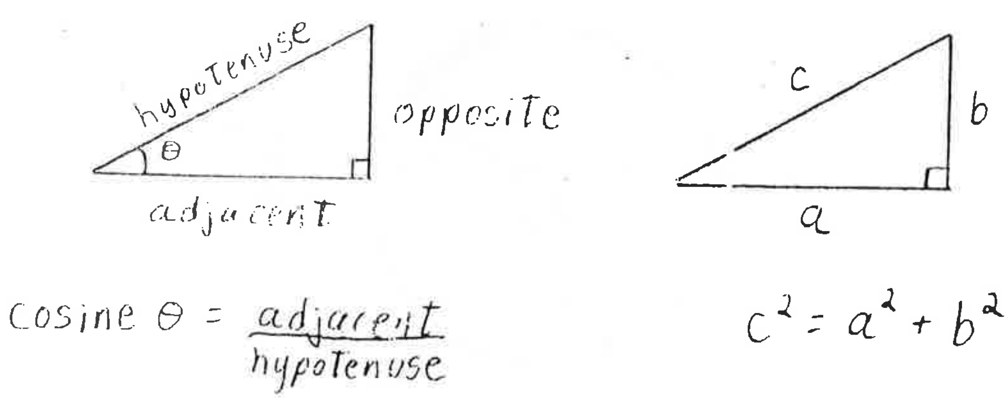


Figure 3.2 - Triangles

Distance to the Sun and its Size

Review

Aristarchus (~280 BC)

See lecture 3, figure 7

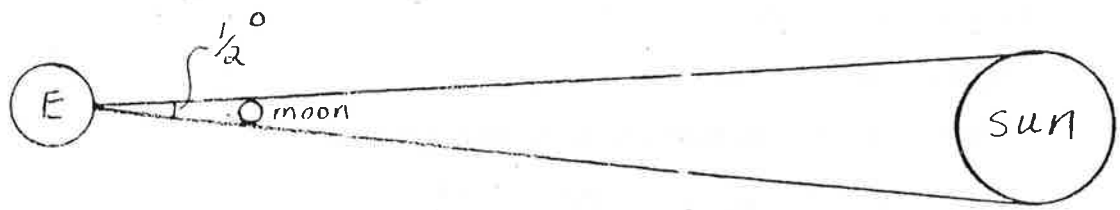


Figure 3.3 – Relative size of sun and moon

Distance to the Moon and its Size

Aristarchus

Step 1: Relating the size of the moon to the distance to the moon.

Key observation: the angular size of the moon is half a degree.

Circumference of moon's orbit = 2 (360) (diameter of moon)

Also: circumference of moon's orbit = 2pi (moon distance)

So: 2pi (moon distance) = 2 (360) (diameter of moon)

moon distance = (360 / pi) (diameter of moon)

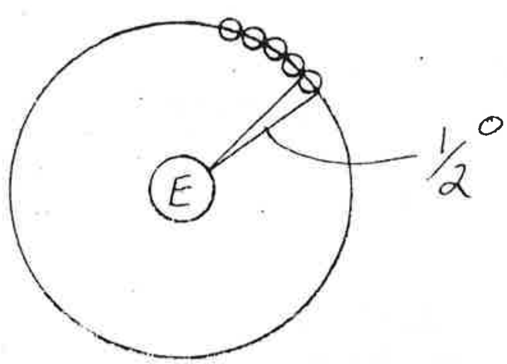


Figure 3.4 – Number of moons in circumference of orbit

<u>Step 2</u>: Relating the size of the moon to the size of the earth.

First key observation: the duration of a lunar eclipse.

Diameter of earth's shadow = 3 (diameter of moon)

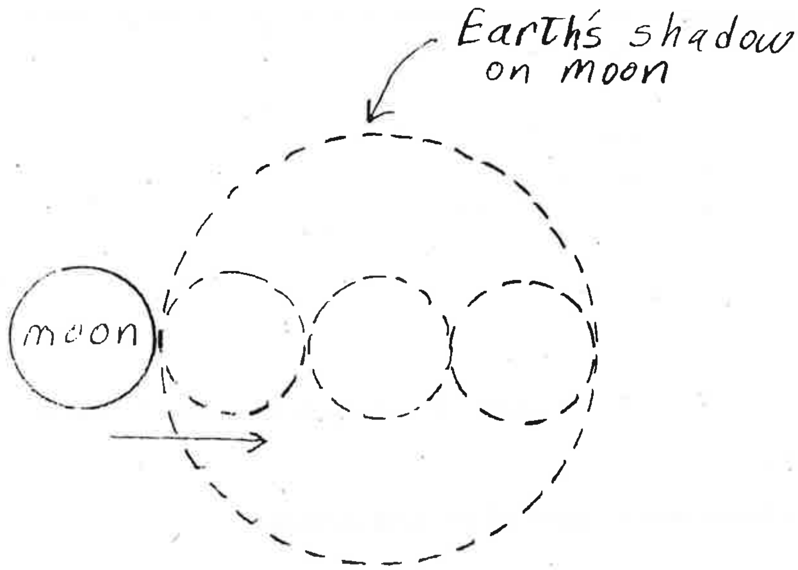


Figure 3.5 – Eclipse of the moon

Second key observation: the moon's shadow on the earth during a solar eclipse.

Earth diameter = earth's shadow diameter + moon diameter

Earth diameter = 4 (moon diameter)

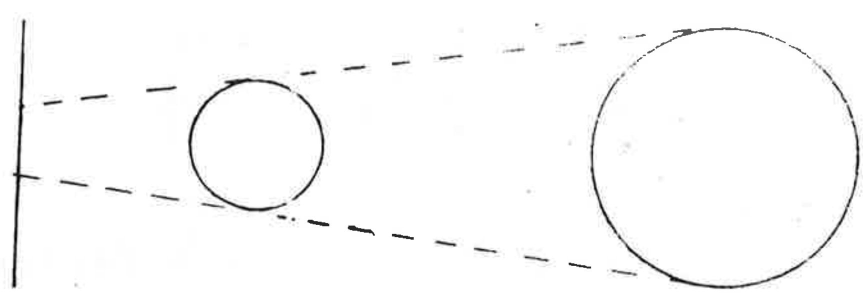


Figure 3.6 – Reduction in shadow diameter

Step 3: Combine step 1 and step 2.

Moon distance = (360 / pi) (earth diameter / 4)

Moon distance = 30 Earth diameters! (Correct!!)

And, according to Aristarchus, the sun is about 600 earth diameters away.

Figure 3.7 – Reduction of moon's shadow

Implications

first heliocentric theory of the solar system

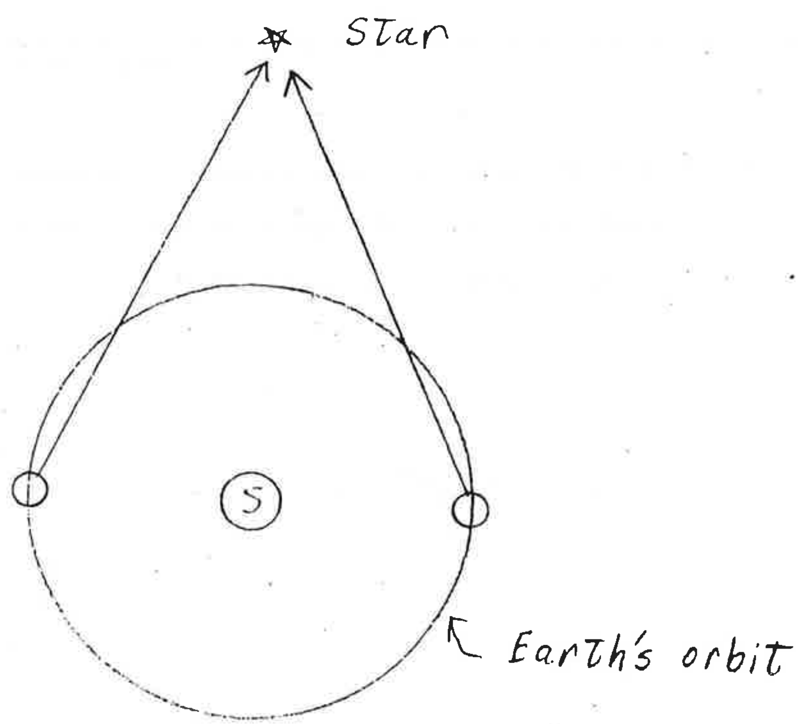


Figure 3.8 – Parallax of the stars

Size of the Earth

calculated accurately by Eratosthenes (~240 B.C)

(Circumference of earth / 500 miles) = (360 / 7.2)

Circumference of earth = 25,000 miles

Since $C/\pi = D$ 25,000/3.14 = 8000 miles

Diameter of earth = 8,000 miles (right answer!)

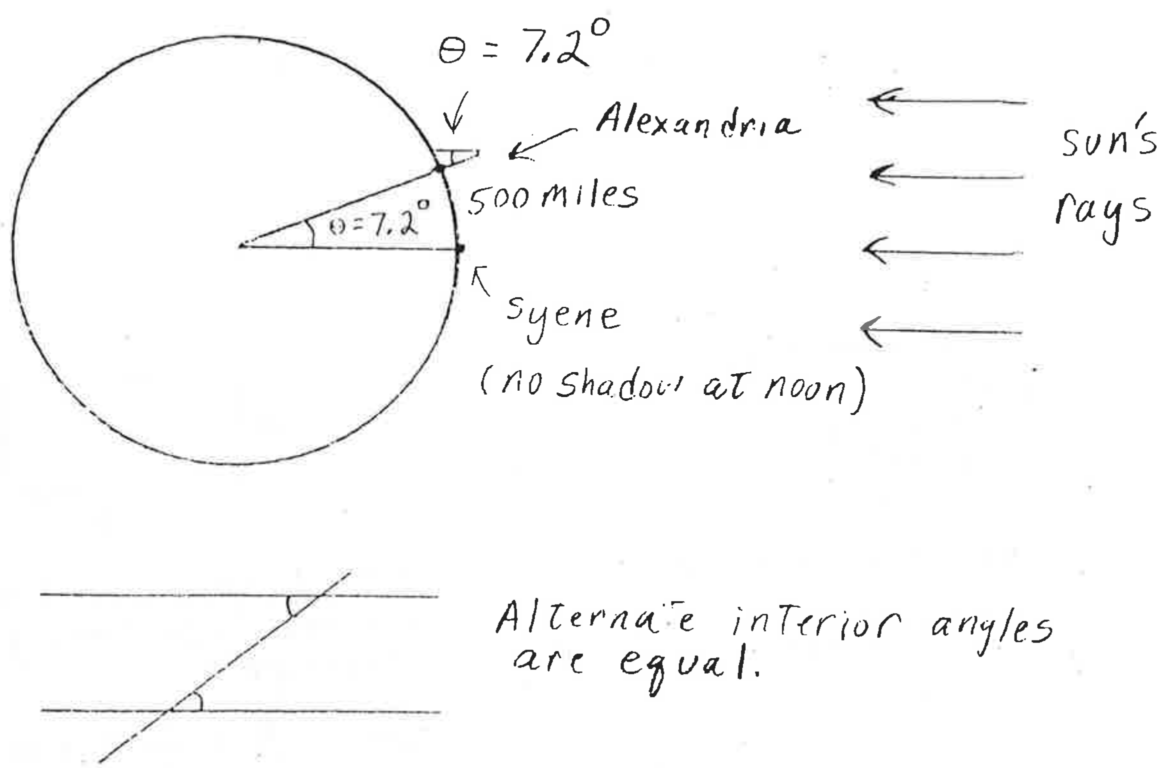


Figure 3.9 – Diameter of the earth

Notes for Class 4

Review

Aristarchus

Eratosthenes - earth diameter is 8000 miles

Moon diameter = 2000 miles (correct)

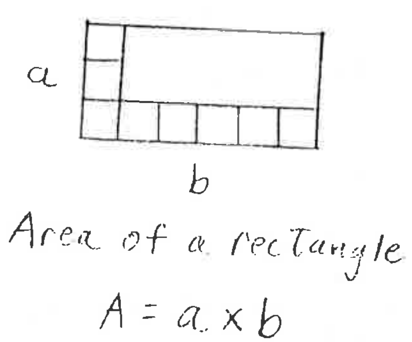
Distance to moon = 240,000 miles (correct)

Sun diameter ~ 40,000 miles

Distance to sun ~ 5,000,000 miles (way too small, but still....)

Archimedes, a great mathematician (~ 287 – 212 BC)

areas and volumes of numerous plane shapes and 3-dimensional solids



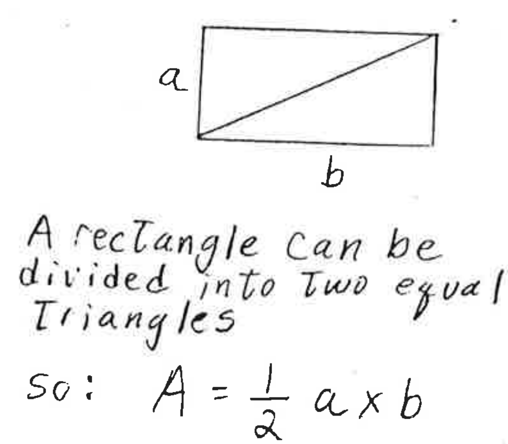
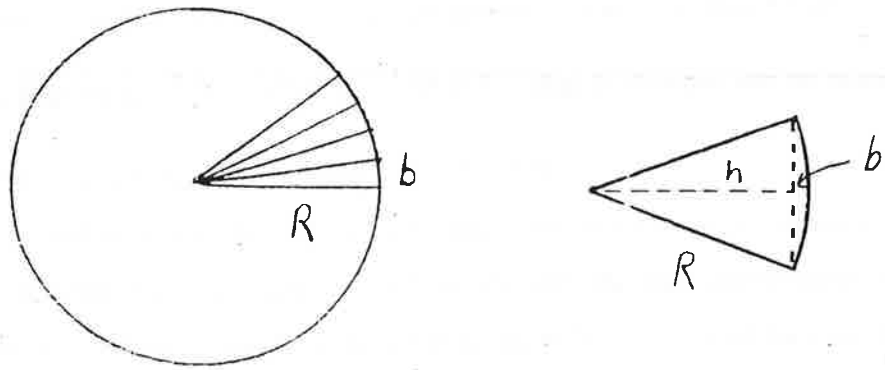


Figure 4.1 – Calculating the area of a triangle

Calculating the area of a circle: Take any triangle formed from the center of a circle out of 2 radii and the tangent connecting them, *b*. The area of that triangle is ½ *Rb*.



For small b: $h \approx R$

So for each Triangle: $A = \frac{1}{2} R b$

Area of circle $\approx \frac{1}{2} R$ (sum of b's)

Area of circle $\approx \frac{1}{2} R$ (circumference)

By definition: $\pi = \frac{C}{D}$ a constant

or: $C = \pi D = 2\pi R$

Substitute in: $A = \frac{1}{2} R (2\pi R)$

$A = \pi R^2$

Figure 4.2 – Area of a circle

Project that one increases the number of triangles by shortening *b* so that the *b* in each case approaches closer and closer to a specific point on the circumference of the circle. The sum of the *b*'s would be the circumference of the circle. The area of the circle would be the area of the countless small triangles ending in the countless small *b*'s., i.e., the area of the circle would be equal to ½ RC (where C is the circumference—the sum of all the individual points, *b*.) Now by definition, $\frac{C}{D}$ is a constant, called π, or C = πD = 2πR. If this is now substituted in the area equation above, one reaches: $A = \pi R^2$ — the formula for the area of any circle. So this formula was reached by the method of continuously diminishing the triangles and then summing up the infinitely small triangles into the area of the circle. He anticipated the idea of taking smaller and smaller increments until one reaches a limit.

Also, Archimedes calculated pi. Making use of the Pythagorean theorem and his method of exhaustion, he divided a circle into 100 triangles. He got:

$$3 + 10/71 < pi < 3 + 1/7$$

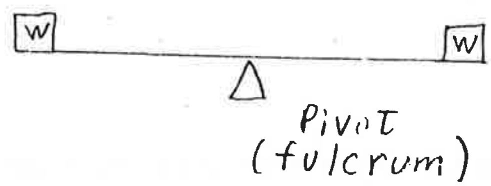
By a similar approach, Archimedes used diminishing wedges to reach the volume of a pyramid; and diminishing pyramids to reach the volume of a sphere.

Applied math to physics and engineering.

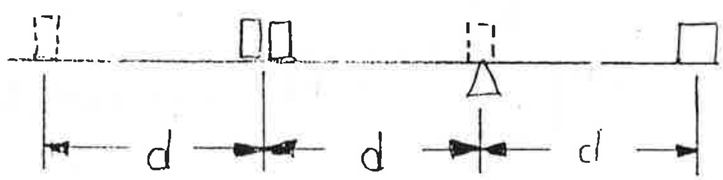
1. The law of levers

$W_1*D_1=W_2*D_2$

With two weights placed equal distances from the center a lever will balance:



Split the left weight into two weights, slightly spaced. Move one closer and one farther away from the fulcrum. Keep spreading the weights until one is over the fulcrum.



So when the lever is in balance: w1 x d1 = w2 x d2

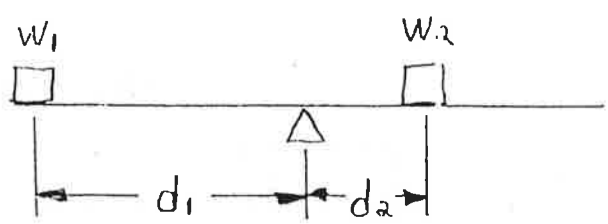


Figure 4.3 – Law of levers

A balance scale works on this principle:

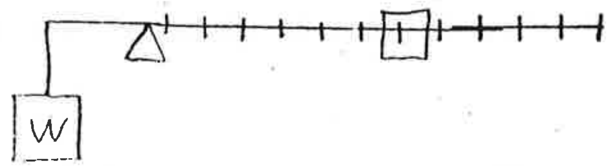


Figure 4.4 – Archimedes' scale: the "steelyard"

2. Archimedes principle of floating bodies. An immersed body is buoyed up by a force equal to the weight of the fluid it displaces.

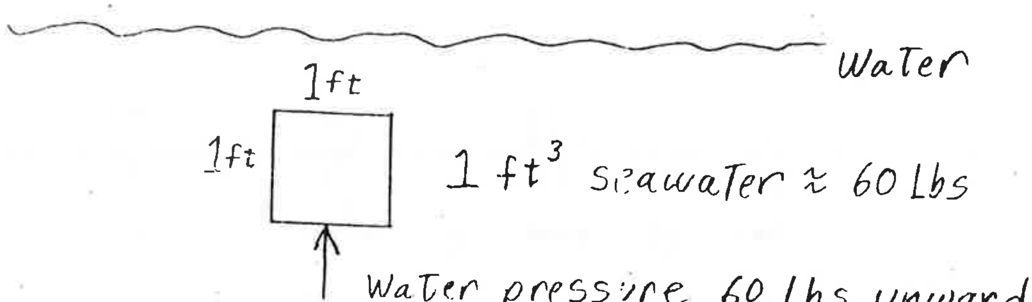


Figure 4.5 – Principle of Buoyancy

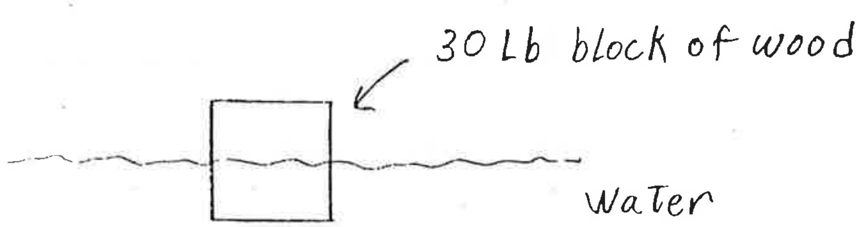


Figure 4.6 – Floating body

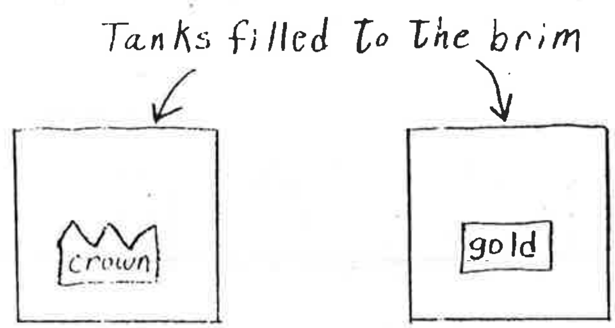


Figure 4.6 – Testing the Crown

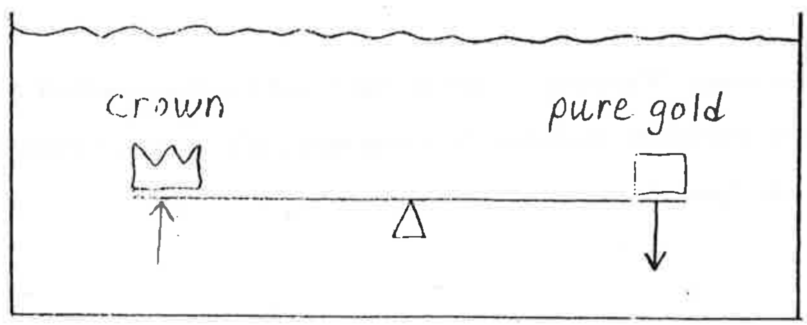


Figure 4.6 – Testing the Crown with a balance

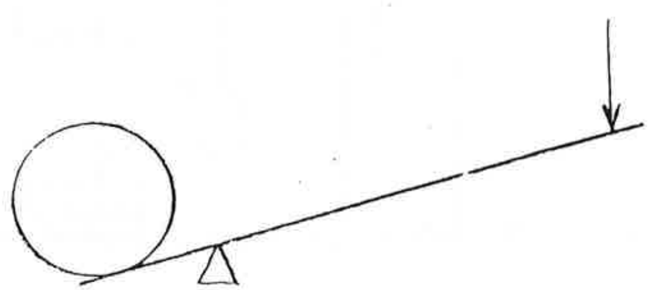


Figure 4.7 – Lifting with a Lever

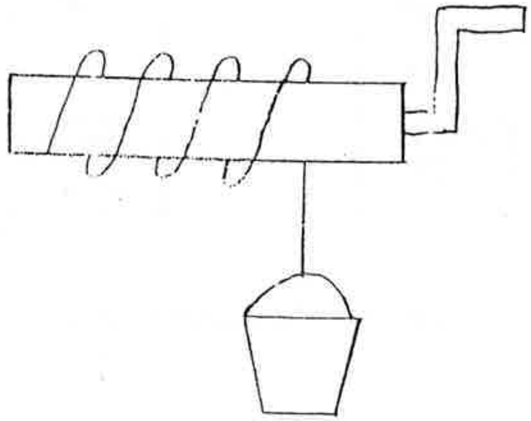


Figure 4.8 – The windlass

His famous statement: "Give me a place to stand, and I will move the Earth."

Archimedes inventions included: the compound pulley, the windlass, the endless screw, and a "steelyard."

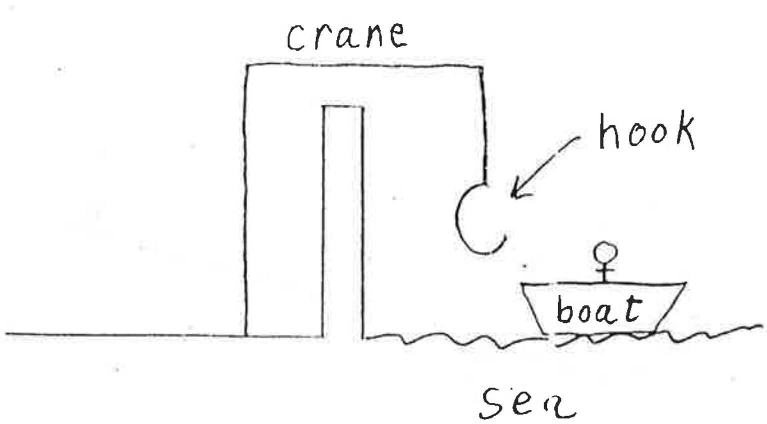
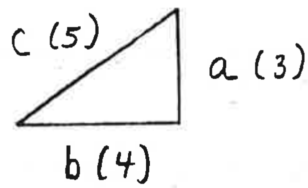
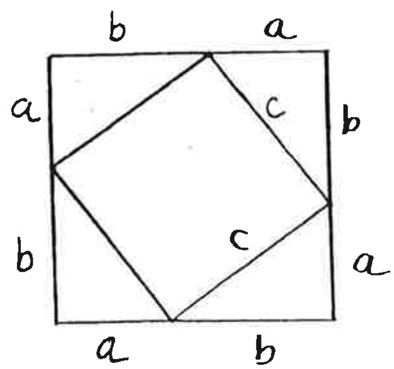


Figure 4.9 – Crane for overturning ships



$$c^2 = a^2 + b^2$$



Area of large square $= (a+b)(a+b)$

Area of 4 triangles $= 4(\frac{1}{2}ab)$

Area of interior square $= c^2$

$$c^2 + 2ab = (a+b)(a+b)$$

$$c^2 + 2ab = a^2 + 2ab + b^2$$

$$c^2 = a^2 + b^2$$

Figure 4.10 – Proof of the Pythagorean Theorem

Notes for Class 5

Review

Archimedes

Aristarchus

Hipparchus, a great astronomer (~ 190 – 120 BC)

- invented new instruments to improve the accuracy of the
- father of trigonometry
- took first steps toward replacing the Eudoxan theory with one more accurate

The Greeks used a protractor to measure the heights of the stars.

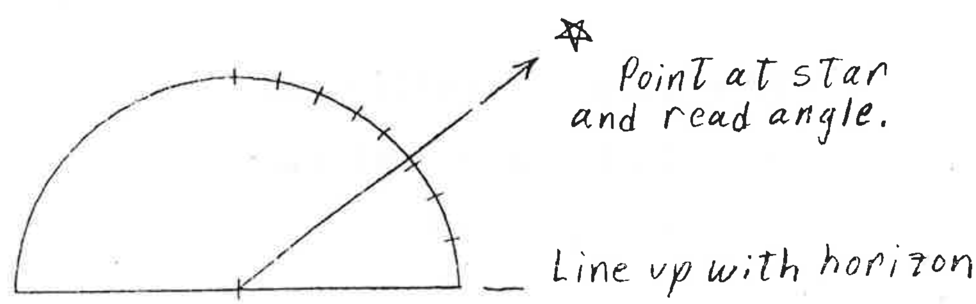
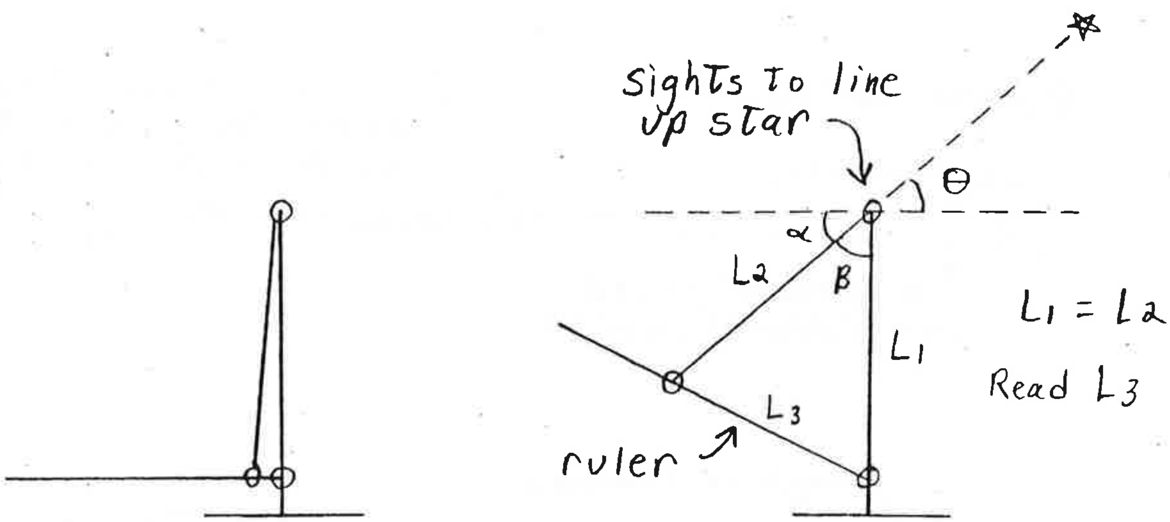
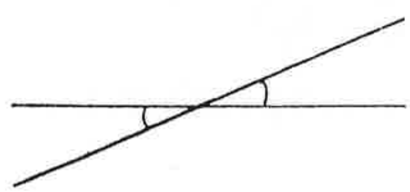


Figure 5.1 Protractor



Looking for θ, angle of star above horizon.

Vertical angles are equal.

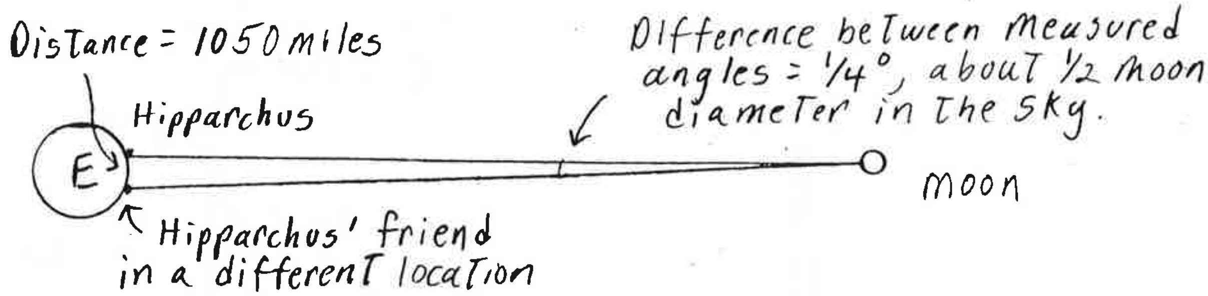


So: $\alpha = \theta$ $\beta = 90^\circ - \alpha$

Figure 5.2 Triquetrum

Hipparchus' achievments

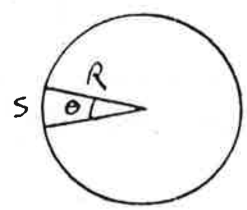
1) Hipparchus used the method of parallax to compute the distance to the moon



angle in radians

$$S = \theta R$$

$$S = \frac{2\pi}{360^\circ}\,\theta^\circ\,R$$



measure: $S = 1050$ miles
$\theta = 1/4^\circ$

Then: $R = 240{,}000$ miles

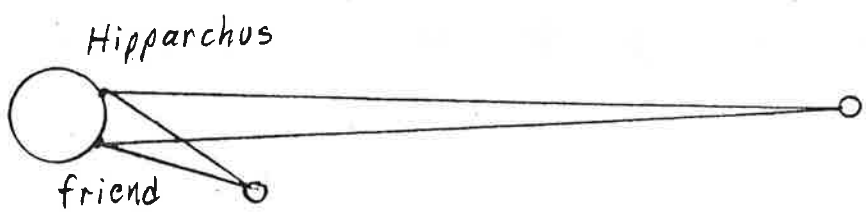


Figure 5.3 Distance to the moon

2) devised more accurate mathematical models for the movements of the sun and moon

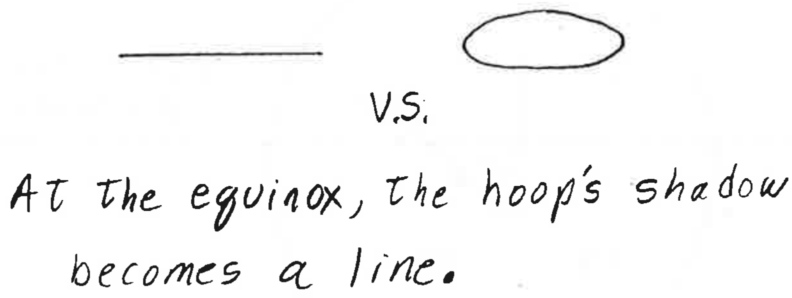
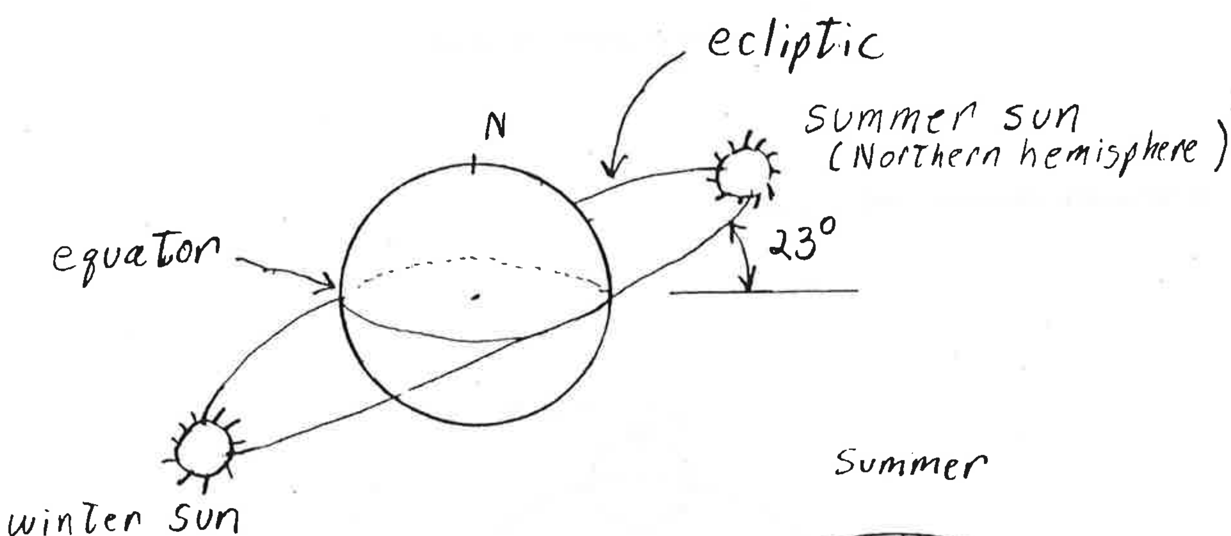


Figure 5.4 Using a ring to find the equinoxes



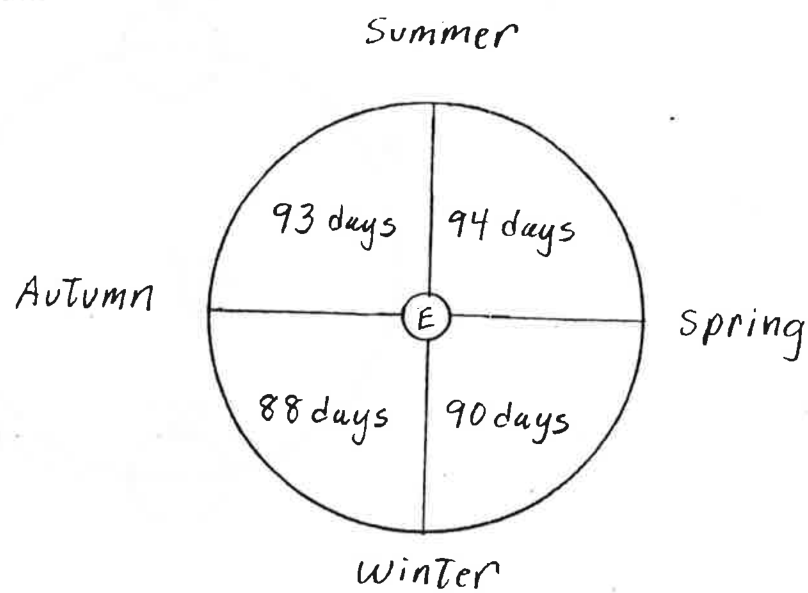


Figure 5.5 Eudoxian model of the seasons

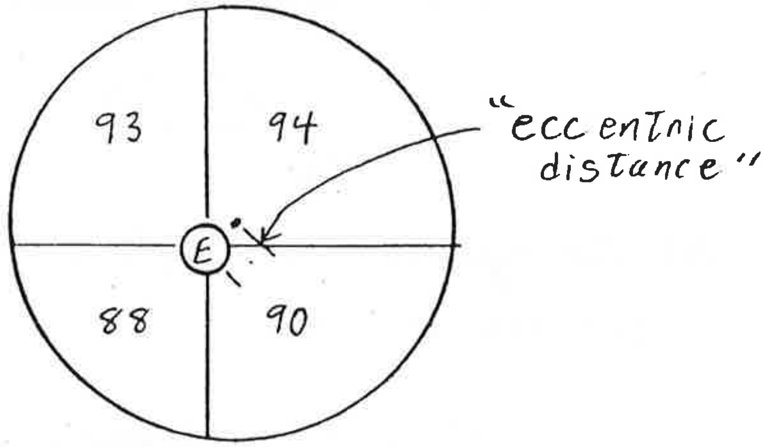


Figure 5.6 eccentric distance

3) "eccentric distance" and epicycle

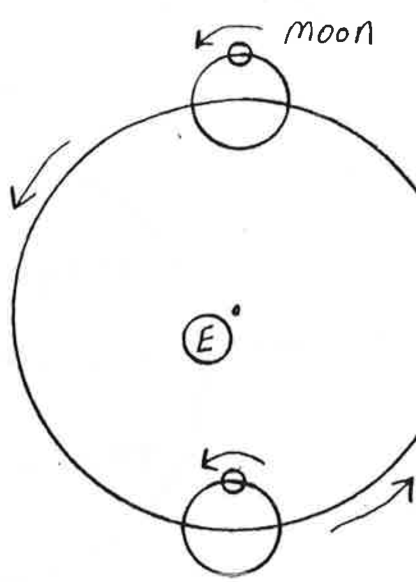


Figure 5.7 Using epicycles for the moon's orbit

4) Hipparchus created the first accurate star map and catalog (with about 1000 stars).

5) Hipparchus discovered the "precession of the equinoxes."

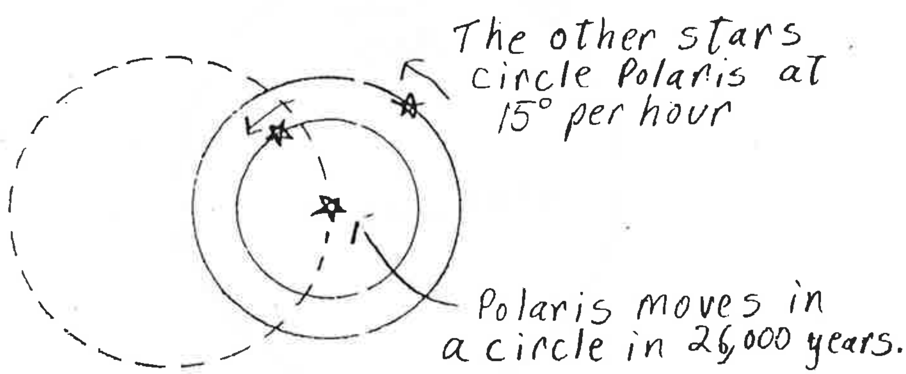


Figure 5.8 precession of the equinoxes

Claudius Ptolemy (100-170 AD)

Epicycles

"equant point"

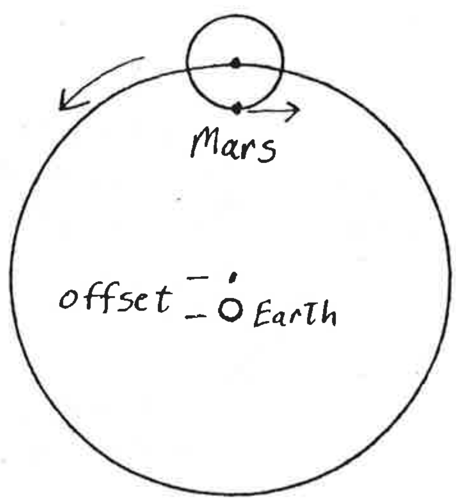


Figure 5.9 Epicycles

Notes for Class 6

Greek astronomy - continued

Review

Hipparchus

Orbit of sun and moon

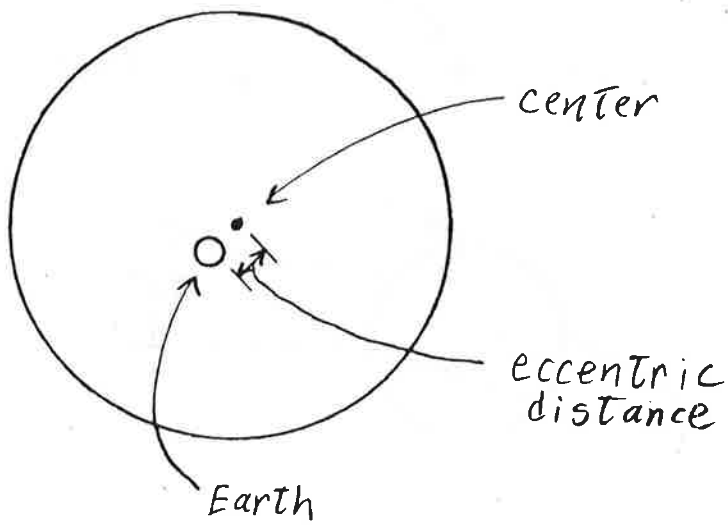


Figure 6.1 eccentric distances

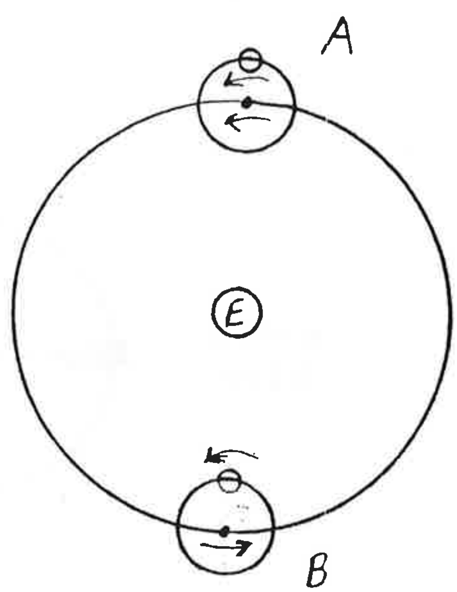


Figure 6.2 Epicycles

Motion of the stars

Eudoxus models the stars

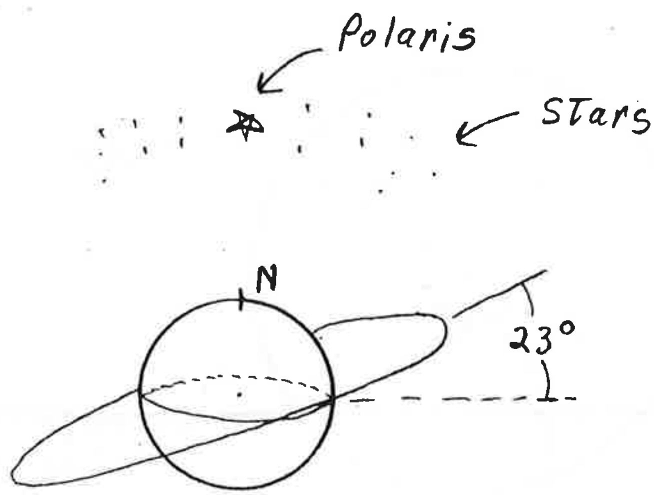


Figure 6.3 Eudoxian model

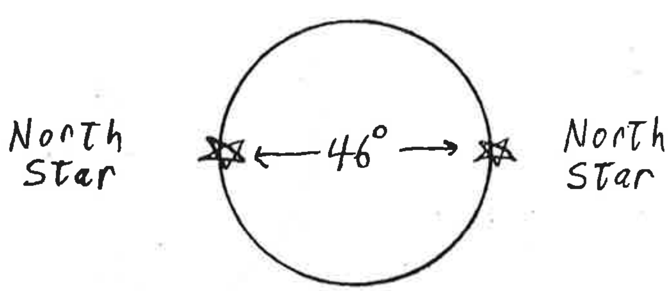


Figure 6.4 precession of the equinoxes

Ptolemy, the last of the great Greek astronomers (~ 100 – 170 A.D.)

devices to fit the observational data: eccentric distances, epicycles, equant points

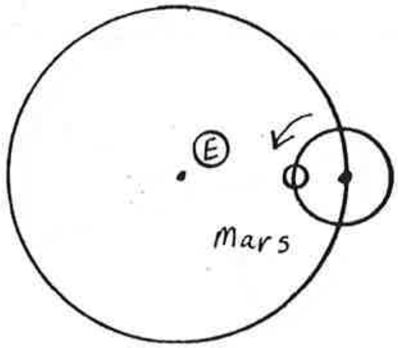


Figure 6.5 Epicycle of Mars

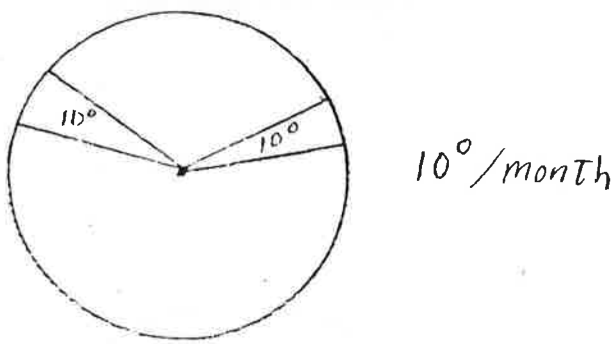


Figure 6.6 Equal angles sweep out equal times

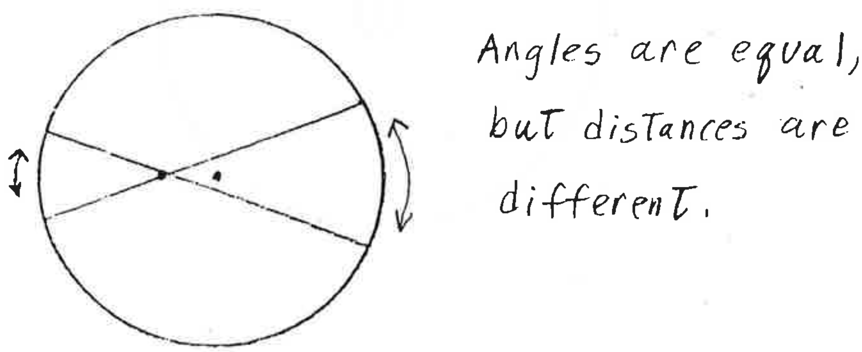


Figure 6.7 Equal angles sweep out different times

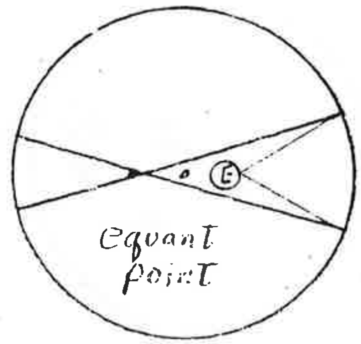


Figure 6.8 Equant point

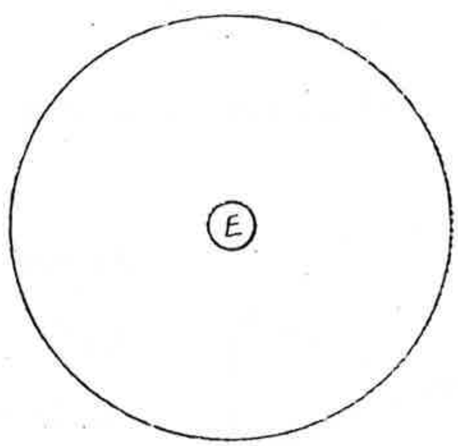


Figure 6.9 Natural circular motion

Summary of Ptolemy's model of the solar system – sun, moon, planets viewed as whole

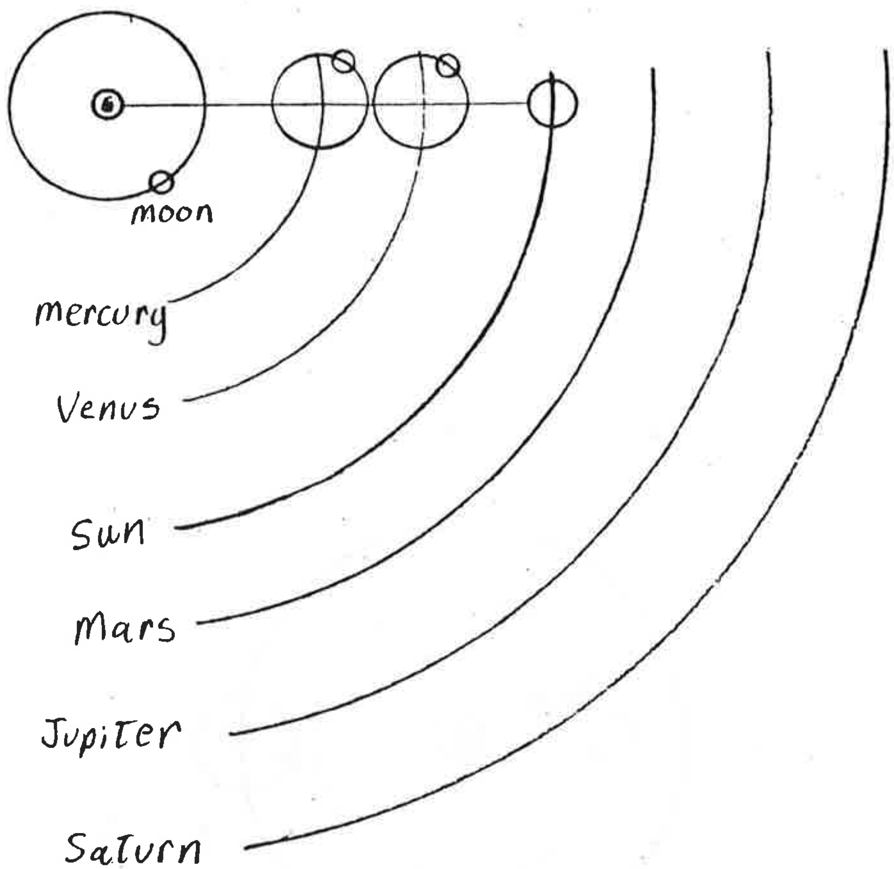


Figure 6.10 Ptolemy's solar system

Criticisms of Ptolemy's theory

Two types of planets

Orbit of Mars

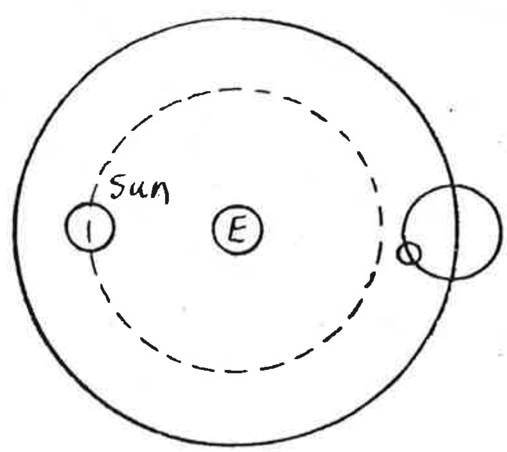


Figure 6.11 Orbit of Mars

Ptolemy's achievement – Optics, study of light

Studied reflection, refraction of light

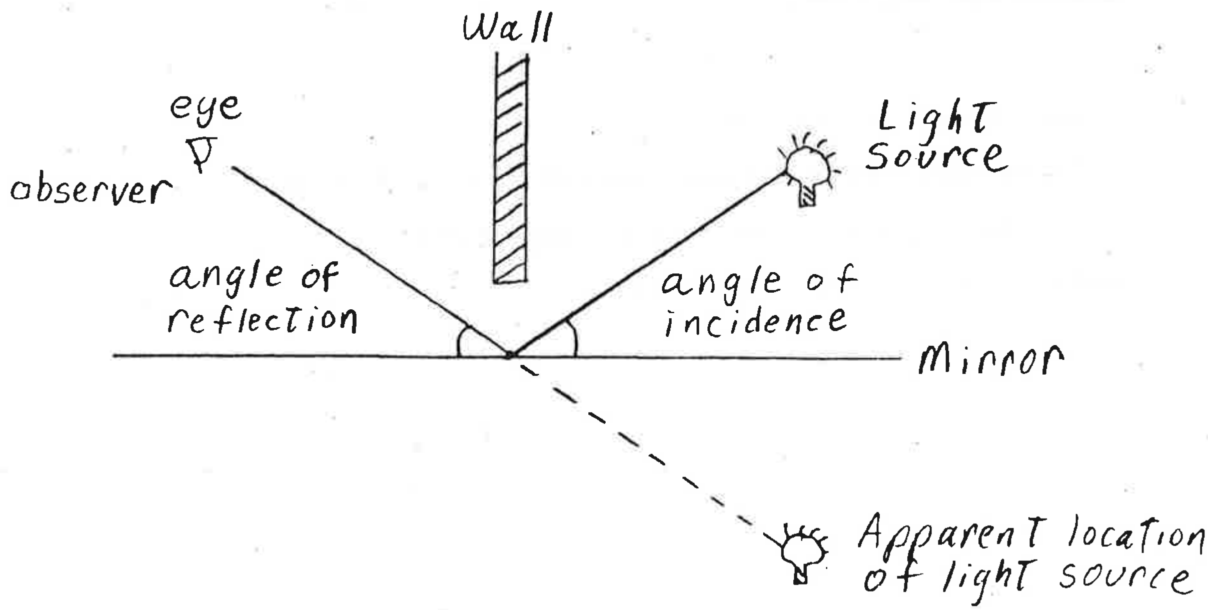


Figure 6.12 Reflection of light

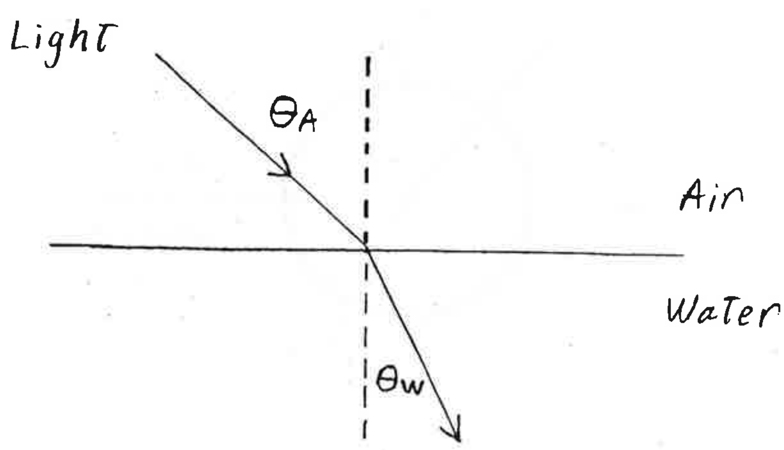


Figure 6.13 Refraction of light

Air to Water: $\theta_A > \theta_W$

Air to Glass: $\theta_A > \theta_G$

Glass to Water: $\theta_G < \theta_W$

Water to Air: $\theta_W < \theta_A$

Experiments with air, water and glass

Refraction experiment with bronze disk with angles marked out

Varied light source and measured angle change

First example of scientific experimentation

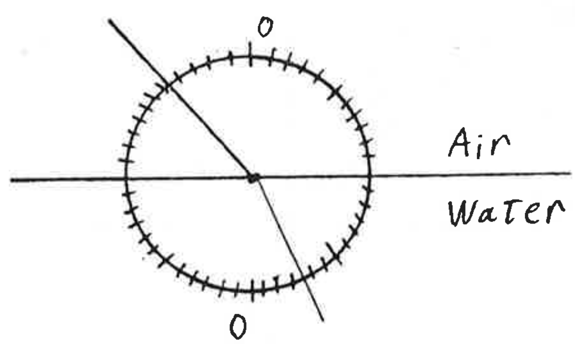


Figure 6.14 Refraction experiment

Notes for Class 7

Ptolemy

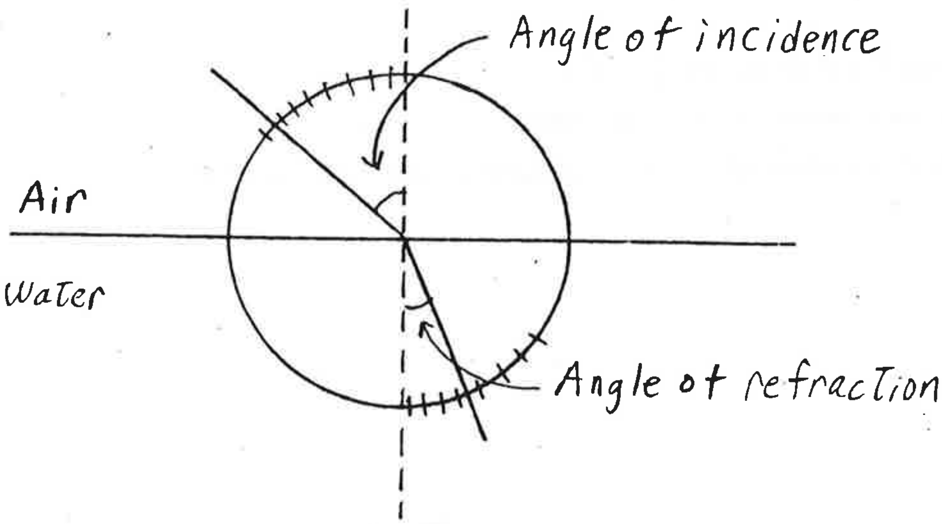


Figure 7.1 Refraction experiment

Figures from Ptolemy's Light Experiments, as light passes from air to water:

Angle of Incidence	10°	20°	30°	40°	50°	60°	70°	80°
Angle of Refraction	8°	15.5°	22.5°	29°	35°	40.5°	45.5°	50°

Differences between the successive angles of refraction: 7.5, 7, 6.5, 6, 5.5, 5, 4.5.

The Descent into the Dark Ages

Saint Augustine (354-430):

Hypatia

The rediscovery of Aristotle

Averroes, the 12th century Aristotelian

The Copernican Theory of the Solar System

Nicholas Copernicus (1473-1543)
heliocentric theory of the solar system
On the Revolutions of the Celestial Spheres (published in 1543)

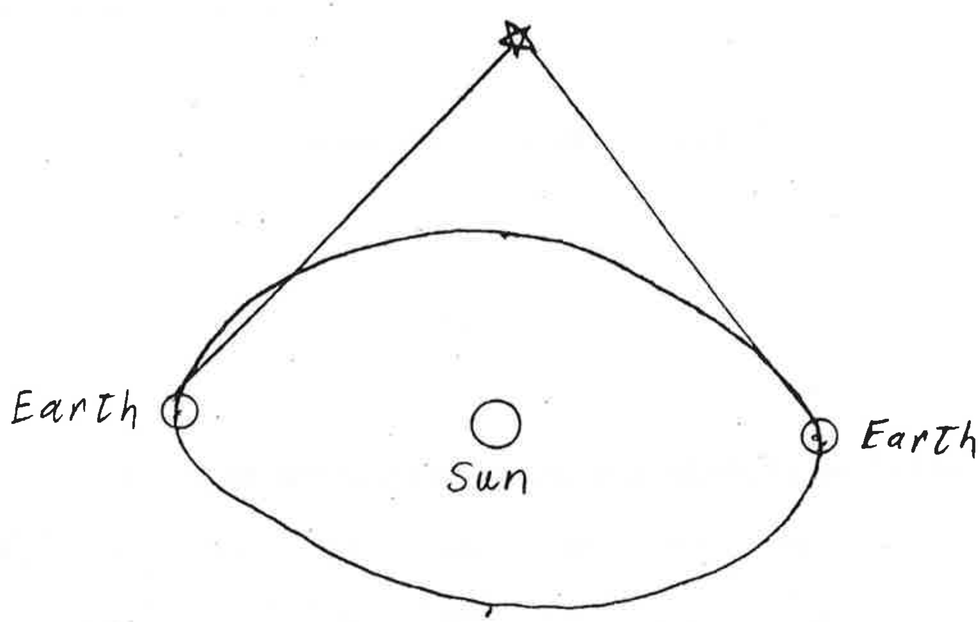


Figure 7.2 Parallax of the stars

Advantages of the heliocentric theory

"Retrograde" motion of the planets is explained.

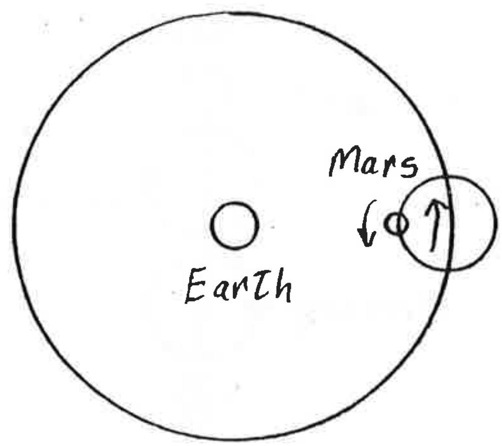


Figure 7.3 Ptolemy's retrograde motion

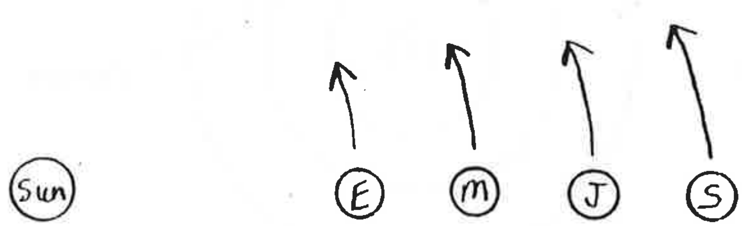


Figure 7.4 Retrograde motion with Copernican theory

The positions of Mercury and Venus, relative to the Sun, are explained.

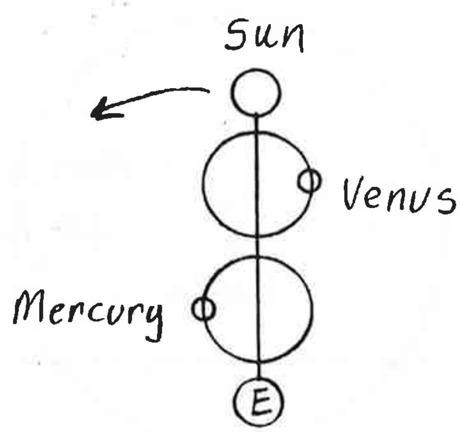


Figure 7.5 Inner planets

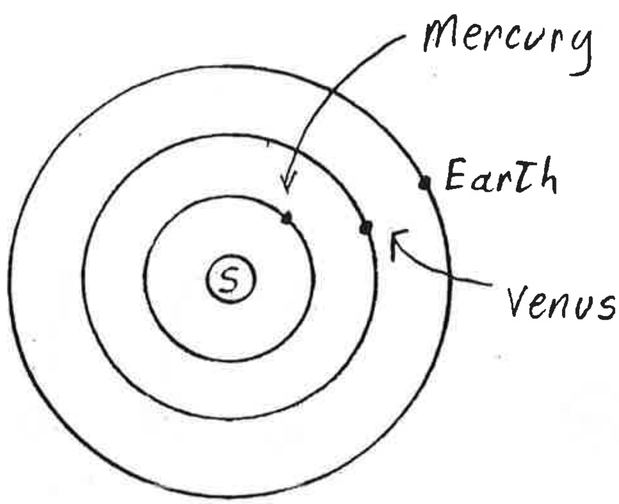


Figure 7.6 Inner planets near the sun

Explains changes in brightness of the planets

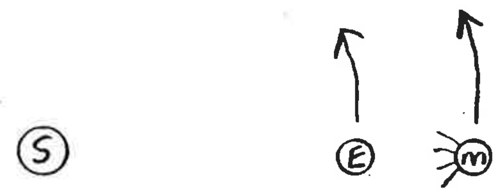


Figure 7.7 Brightness of the planets

Relative distances between solar bodies could be determined

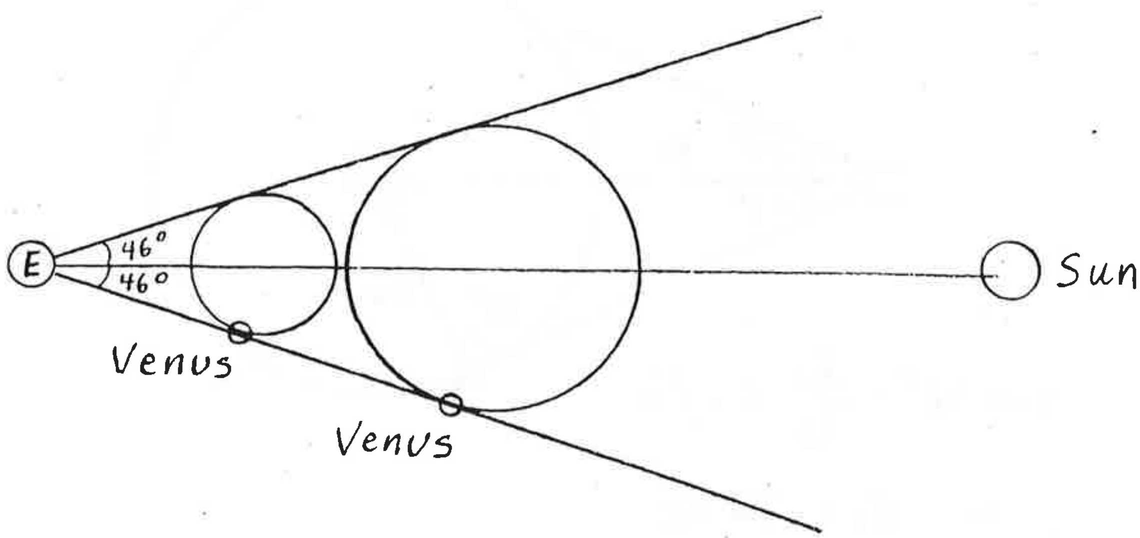
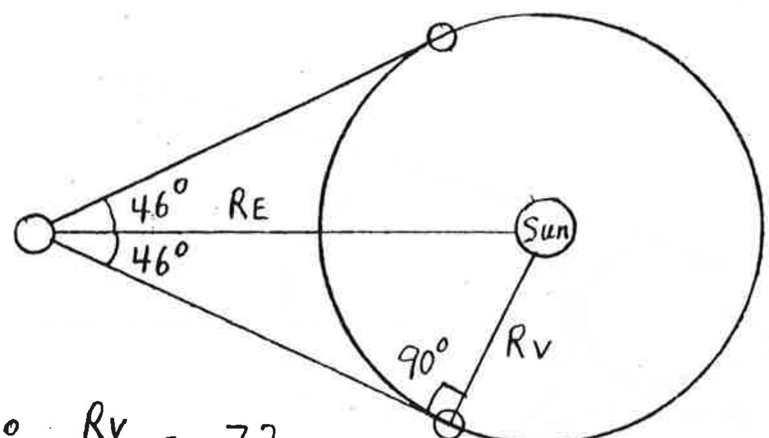


Figure 7.8 Relative size of planetary orbits – Venus

Copernicus was able to calculate the relative distances between the planets and the Sun.



$$\sin 46^\circ = \frac{R_V}{R_E} = .72$$

$$\text{so: } R_V = .72\,R_E$$

Figure 7.9 Relative size of planetary orbit - Venus

Notes for Class 8

Review relative size of planetary orbit – Venus

Hipparchus

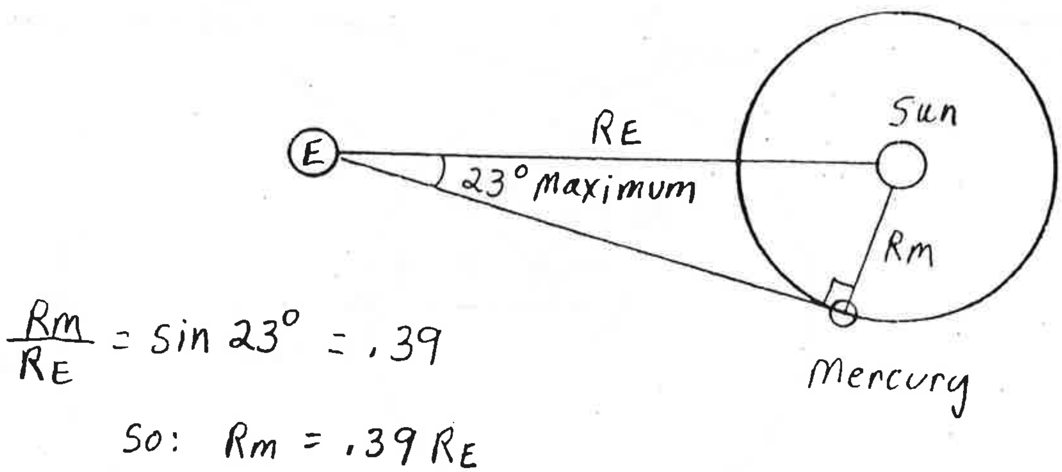


Figure 8.1 Trigonometric ratios

To calculate radius for an outer planet, alternate method required

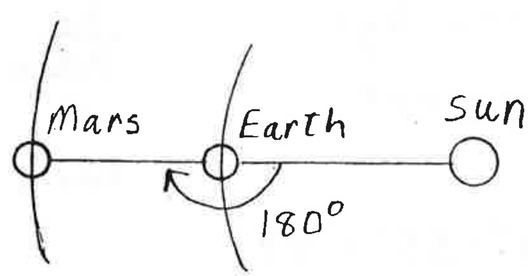
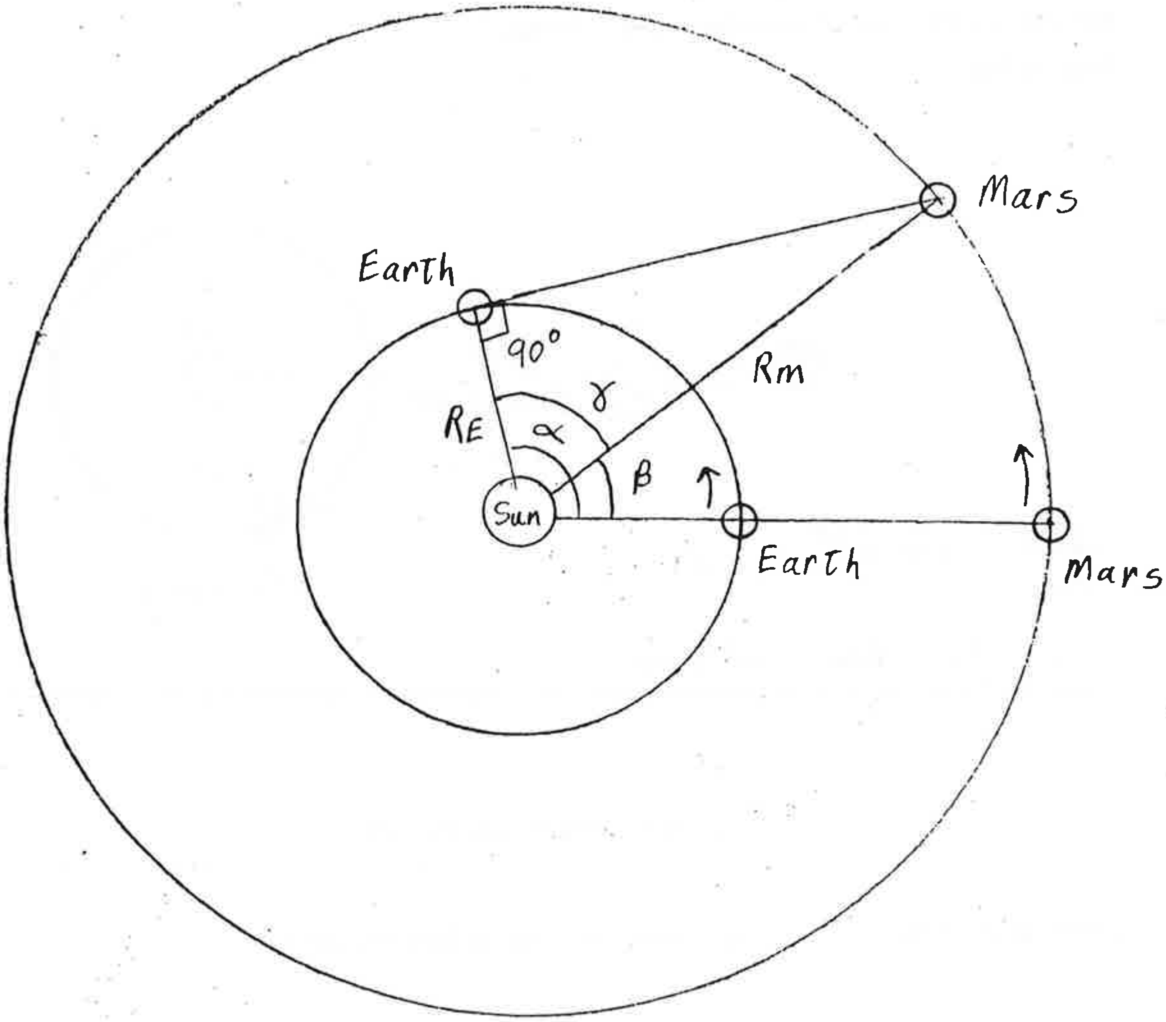


Figure 8.2 Attempting to calculate radii of outer planets

Two points needed to calculate orbits for outer planets



$$\frac{\alpha}{360^\circ} = \frac{105 \text{ days}}{365 \text{ days}} \qquad \alpha = 104^\circ$$

Mars Year = 687 days

$$\frac{\beta}{360} = \frac{105}{687} \qquad \beta = 55^\circ$$

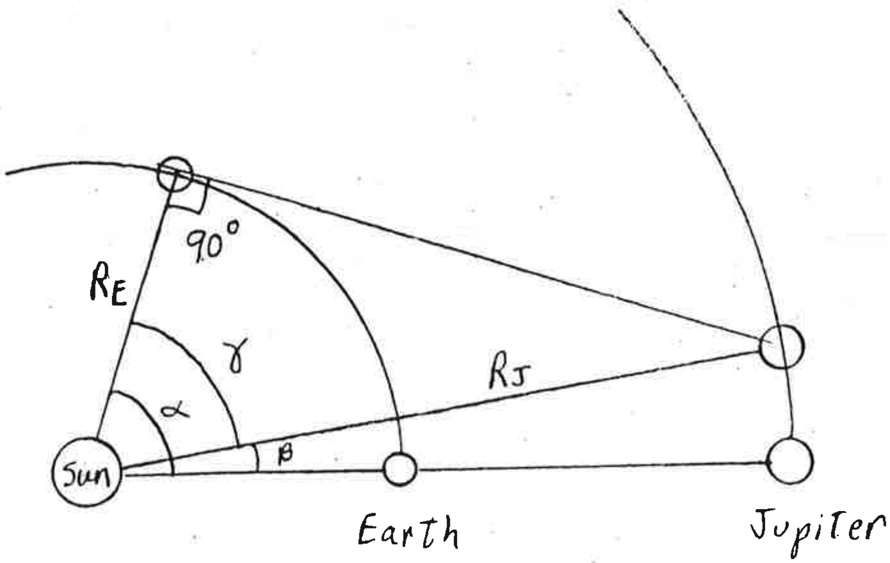
$$\gamma = \alpha - \beta = 104^\circ - 55^\circ = 49^\circ$$

$$\frac{R_E}{R_{Mars}} = \frac{\text{adjacent}}{\text{hypotenuse}} = \cos 49^\circ$$

$$R_{mars} = \frac{R_E}{\cos 49^\circ} = \frac{R_E}{.66}$$

$$R_{mars} = 1.52\, R_E$$

Figure 8.3 Relative size of planetary orbit - Mars



$$\frac{\alpha}{360} = \frac{87 \text{ days}}{365 \text{ days}} \qquad \alpha = 86^\circ$$

$$\frac{\beta}{360} = \frac{87 \text{ days}}{4333 \text{ days}} \text{ (Jupiter year)} \qquad \beta = 7^\circ$$

$$\gamma = \alpha - \beta = 86^\circ - 7^\circ = 79^\circ$$

$$\frac{R_E}{R_J} = \frac{\text{ajacenT}}{\text{hypotenuse}} = \cos 79^\circ$$

$$R_J = \frac{R_E}{\cos 79^\circ} = \frac{R_E}{.19}$$

$$R_J = 5.2\ R_E$$

Figure 8.4 Relative size of planetary orbit – Jupiter

<u>Copernicus' solar system</u>

Planet	Radius of Orbit	Period of Orbit
Mercury	.39R	.24T
Venus	.72R	.62T
Earth	R	T
Mars	1.52R	1.88T
Jupiter	5.2R	11.9T
Saturn	9.5R	29.5T

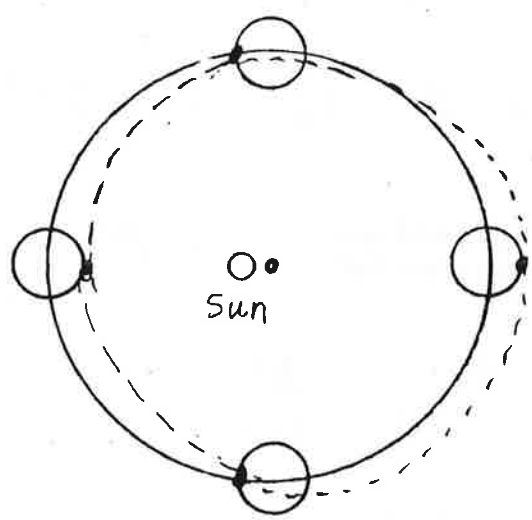


Figure 8.5 Copernicus' epicycles

Notes for Class 9

Copernicus' calculations

Planet	Radius of Orbit	Period of Orbit	Speeds
Mercury	.39R	.24T	1.63V
Venus	.72R	.62T	1.16V
Earth	R	T	$2\pi R/T=V$
Mars	1.52R	1.88T	.81V
Jupiter	5.2R	11.9T	.44V
Saturn	9.5R	29.5T	.32V

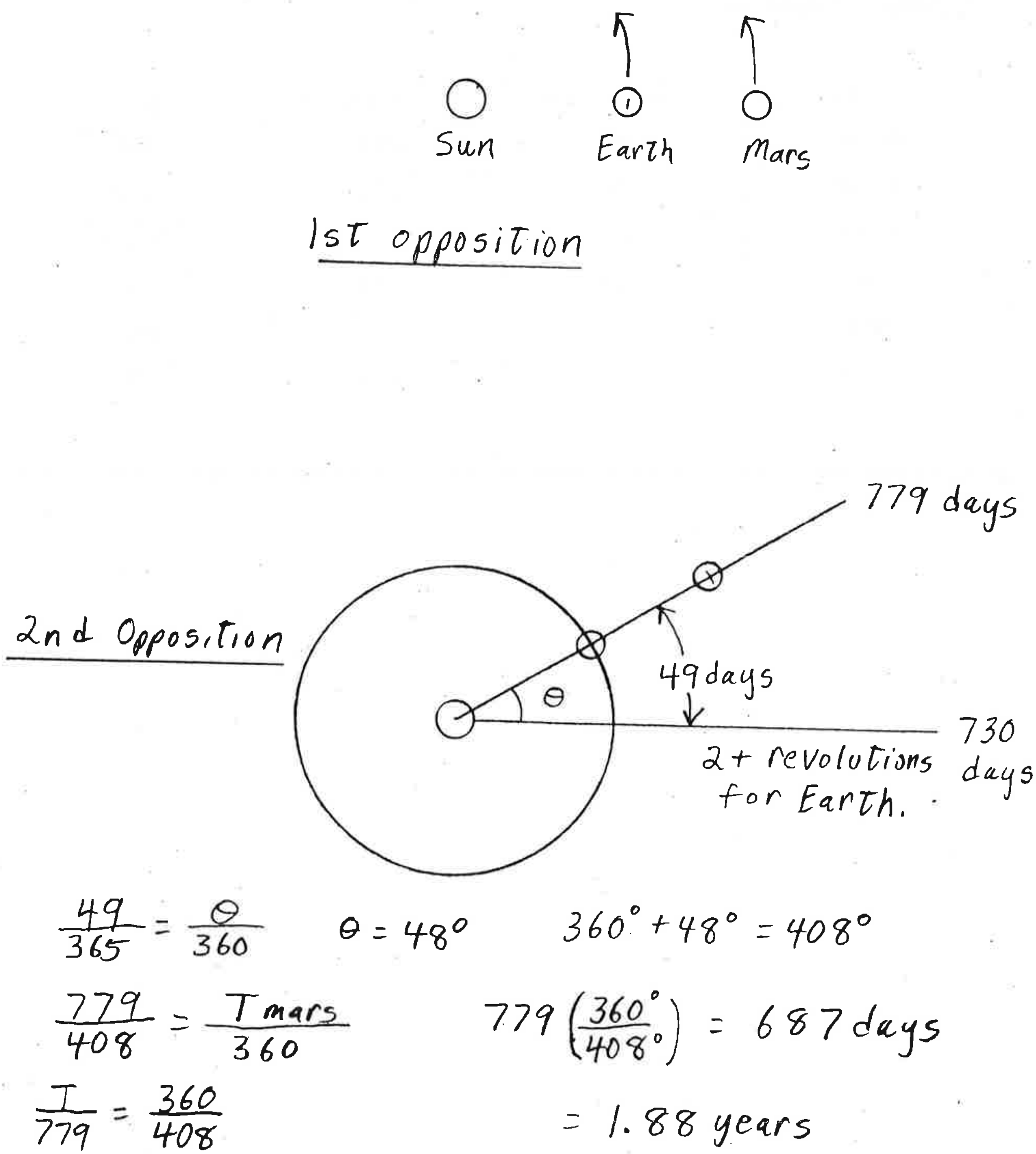
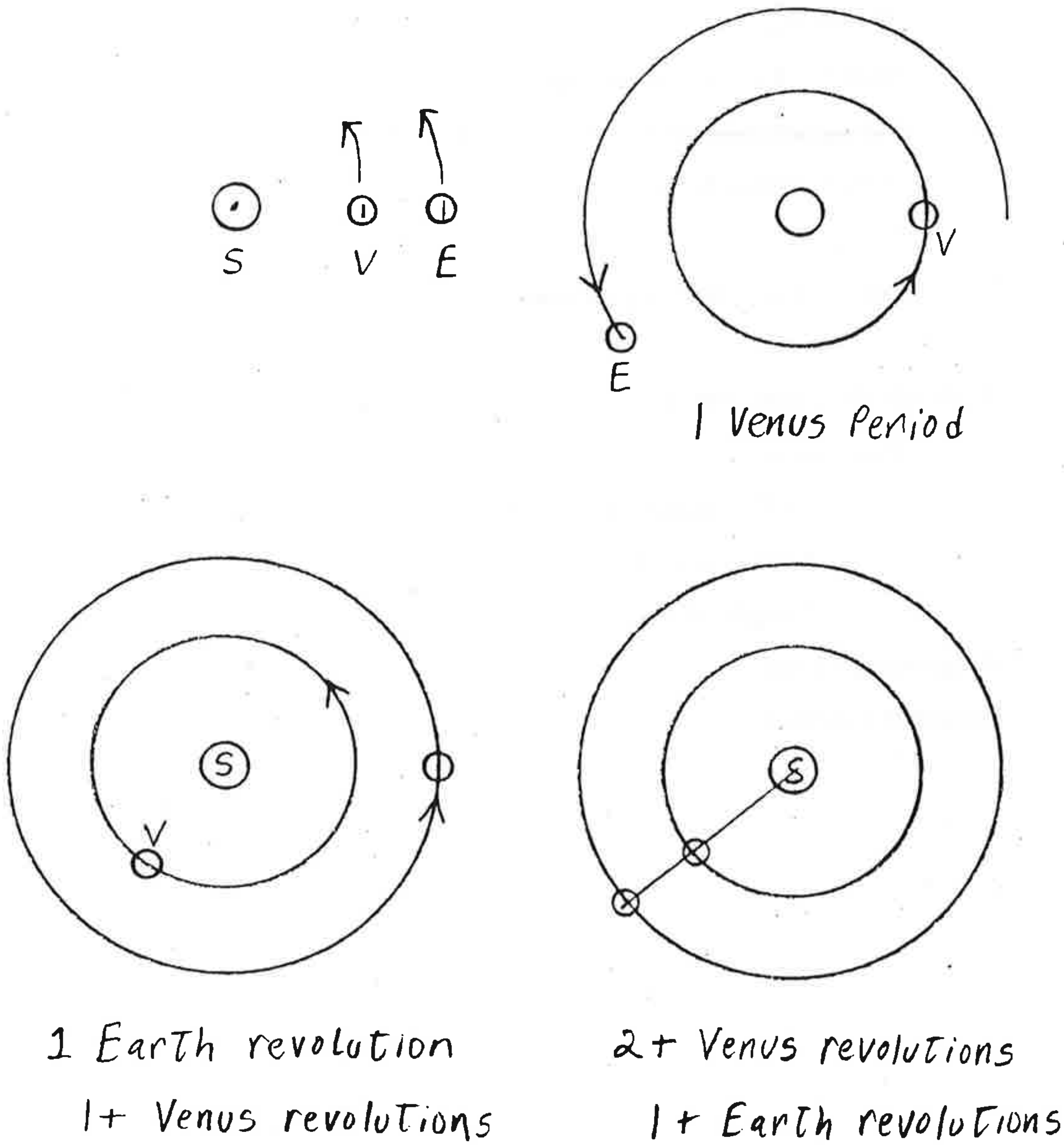


Figure 9.1 Calculation of Mar's period



$$1.6\,T_E = 2.6\,T_V$$

$$T_V = \frac{1.6}{2.6}\,T_E = .62\,T_E$$

Figure 9.2 calculation of Venus' period

Strengths and weaknesses of Copernicus' theory

- Explains retrograde motion
- Inner vs. outer planets
- Brightness
- Motion of earth, not universe
- No equant points
- Speed hard to accept
- Epicycles
- No cause of planetary motion

Tycho Brahe (1546-1601)

- Discoveries
  - 1572 – supernova
  - 1577 – comet
  - Length of year

Gregorian calendar

Protestant England

<u>Notes for Class 10</u>

Astronomy continued
Review Tycho
- 1572 – Supernova
- 1577 – Comet
- Length of Year
- 'Compromise Theory'
- Astronomical data

Johann Kepler (1570-1630)
- Primarily theorist
- Plato
- Kepler and Tycho

Working out orbit of Mars

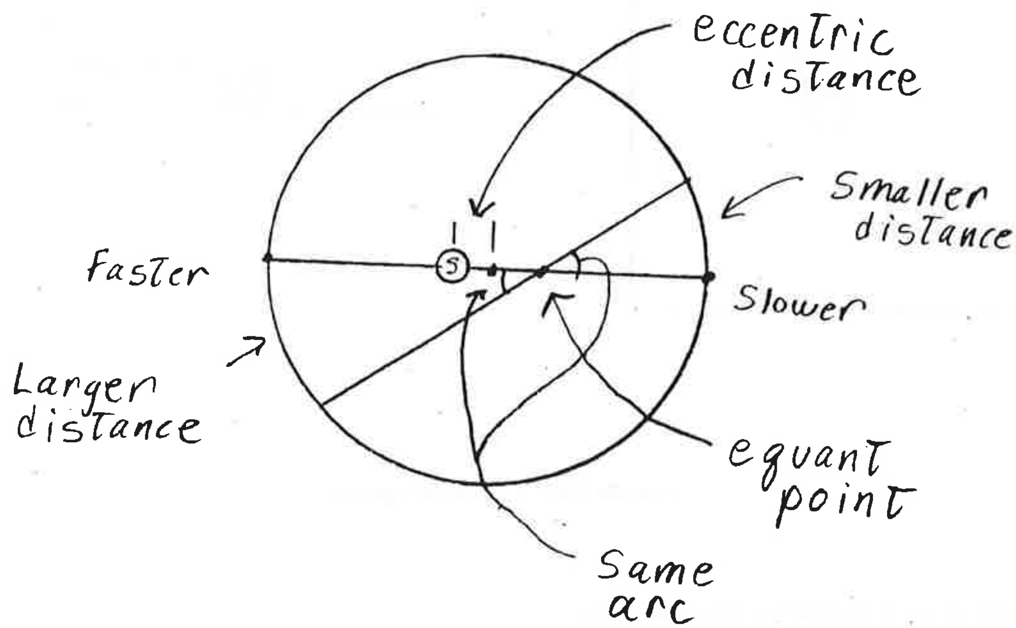


Figure 10.1 Orbit of Mars

Kepler's basic physical idea

Background of ideas influencing Keplers idea

- Magnetism
  - Lodestone
  - Chinese spin game
  - Year 1600 - William Gilbert "Concerning Magnets"

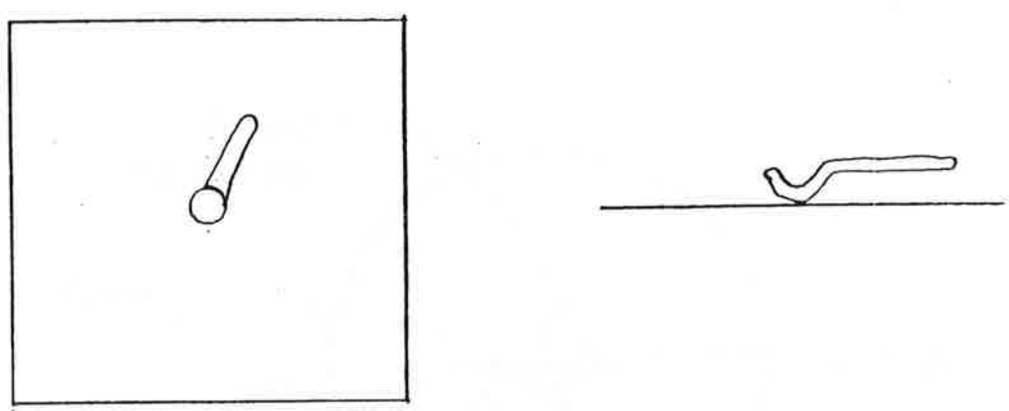


Figure 10.2 Chinese spoon

Consequences of Kepler's physical ideas

- Planetary positions
- Earth speed

Notes for Class 11

Review and continue Kepler

Consequences of Kepler's physical idea

- Planetary positions
- Earth's speed varies in its orbit

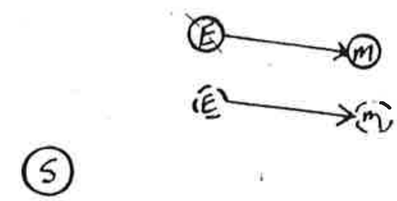


Figure 11.1 Relative position of Mars

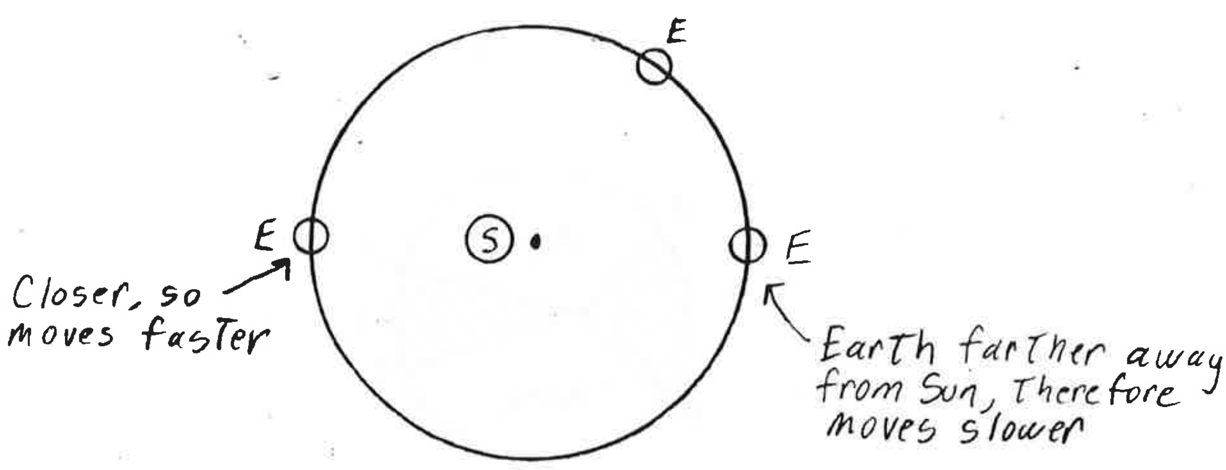


Figure 11.2 Relative position of Earth

Kepler's model of the Earth's orbit

$V \propto 1/R$ larger distance, smaller speed

Kepler's 2nd Law

Planet's speed inversely proportional to its distance to the sun

The line from the sun to the planet sweeps out equal areas in equal times

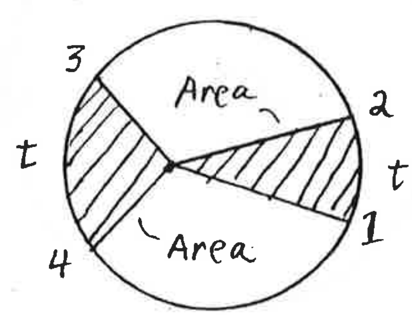


Figure 11.3 Kepler's second law

Back to Mars

Kepler's ideas about the solar force, assumes it's magnetic

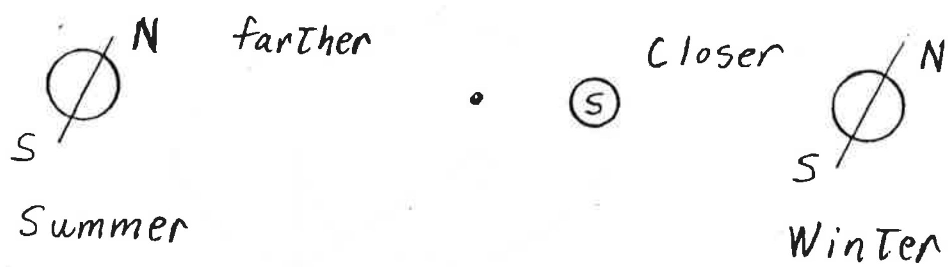


Figure 11.4 Magnetic solar force

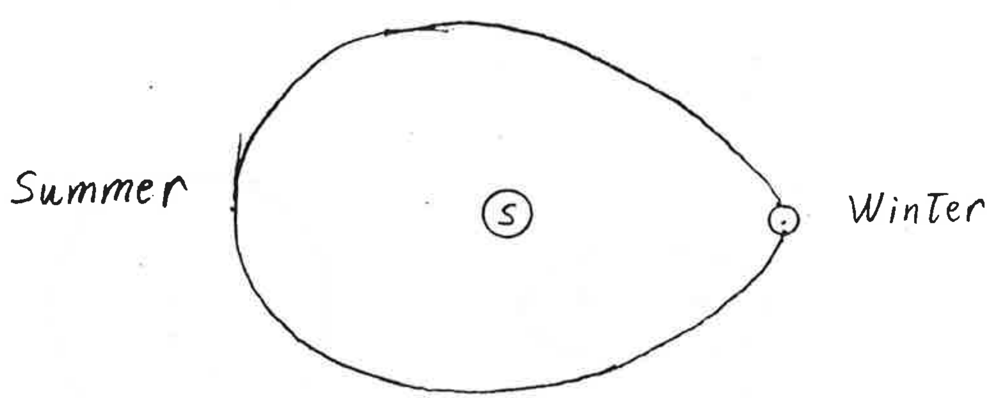


Figure 11.5 Oval orbit of Mars

Kepler realizes that an elliptical orbit fits the data better

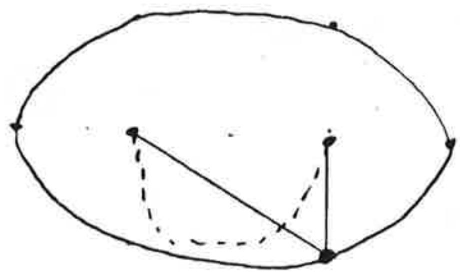


Figure 11.6 Making an ellipse

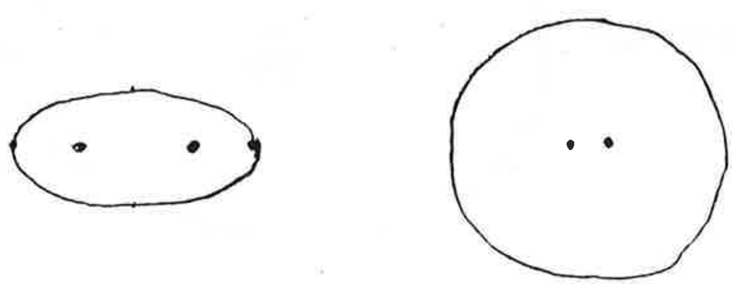


Figure 11.7 Flat and round ellipses

Background on ellipses

Greeks

Apollonius (3rd century BC)

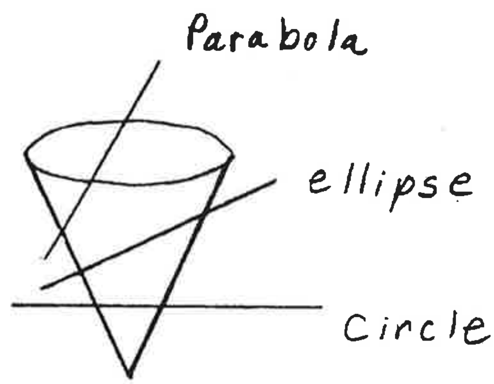
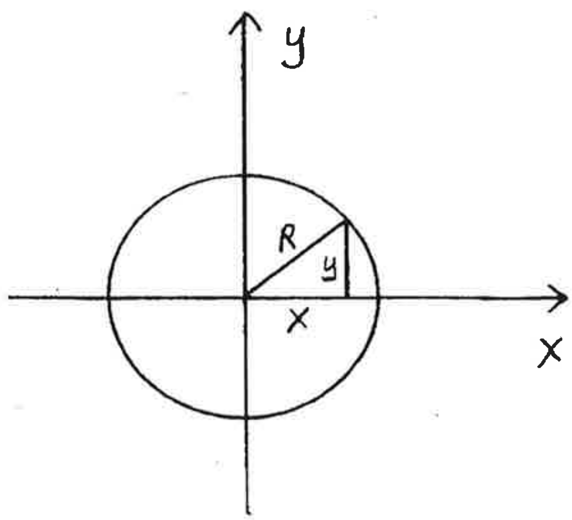


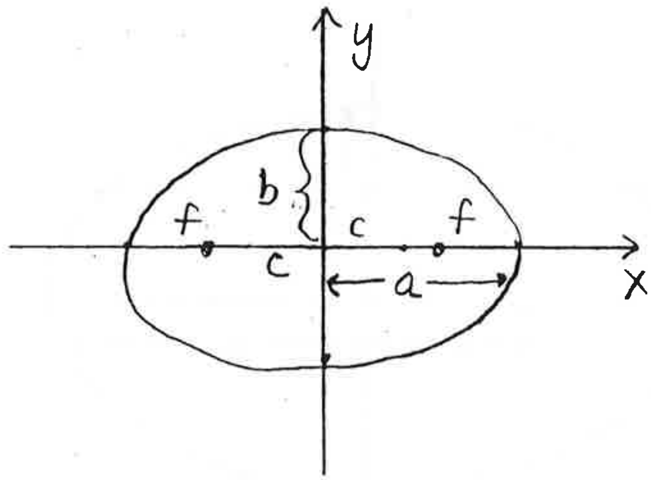
Figure 11.8 Conic sections



$$x^2 + y^2 = R^2$$

Divide both sides by R^2: $\frac{x^2}{R^2} + \frac{y^2}{R^2} = 1$

Figure 11.9 Graphing a circle

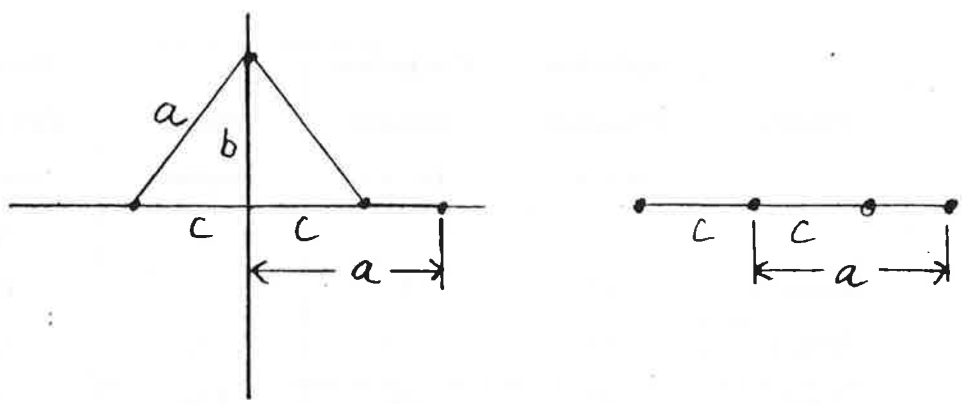


$a > b \qquad \frac{x^2}{a^2} + \frac{y^2}{b^2} = 1$

if $y = 0$ then $x^2 = a^2$

if $x = 0$ then $y^2 = b^2$

Foci:

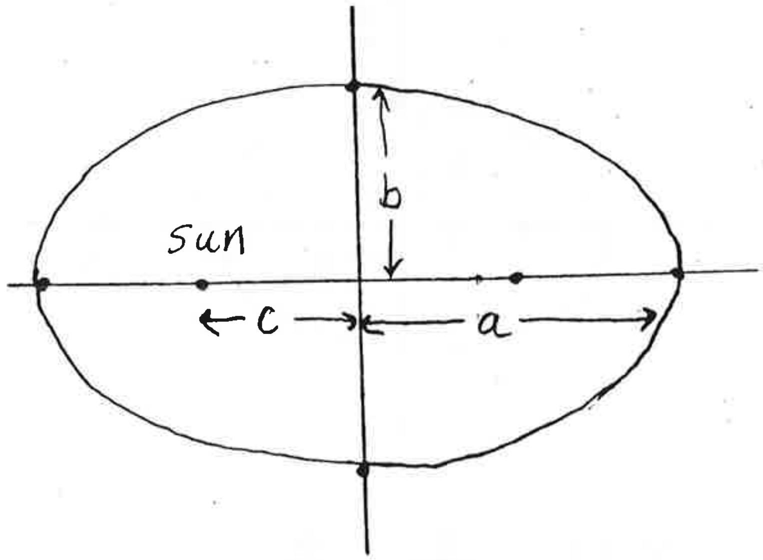


$a^2 = b^2 + c^2 \qquad (a+c) + (a-c) = 2a$

Figure 11.10 Graphing an ellipse

<u>Notes for Class 12</u>

Kepler
Elliptical orbits



a = semi-major radius

b = semi-minor radius

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

Figure 12.1 Elliptical orbits

Planet	**Aphelion Distance (a + c)**	**Perihelion distance (a - c)**	**Mean radius a**	**How far sun is off center c**	**c/a**
Mercury	.47	.31	.39	.08	.21
Venus	.73	.72	.72	.01	.01
Earth	1.02	.98	1.00	.02	.02
Mars	1.67	1.38	1.52	.15	.10
Jupiter	5.45	4.95	5.2	.25	.05
Saturn	10.1	8.97	9.5	.54	.06

1st Law – a planet's speed is proportional inversely with its distance from the sun

$V \propto 1/R$

2nd Law – Ellipses – applies to a particular planet

Planet	Mean radius a	T	a^3/T^2	V (a/T)	aV^2
Mercury	.387	.241	1.0	1.61	1.0
Venus	.723	.615	1.0	1.18	1.0
Earth	1.000	1.000	1.0	1.0	1.0
Mars	1.52	1.88	1.0	.81	1.0
Jupiter	5.2	11.9	1.0	.44	1.0
Saturn	9.5	29.5	1.0	.33	1.0

Kepler's 3rd law a^3/T^2 can be rewritten:

V = Distance/Time

$V \propto a/T$

$a^3/T^2 = a(a/T)^2$

$a^3/T^2 \propto aV^2$

Approximate because speed of planets is not constant

Kepler's lack of influence

Poor writer

Valid discoveries mixed with other notions

Kepler explains ocean tides

Kepler discovers orbits are elliptical, Galileo finds 4 moons circling Jupiter

Planet	**# moons**
Earth	1
Mars	(must have 2)
Jupiter	4
Saturn	(must have 8)

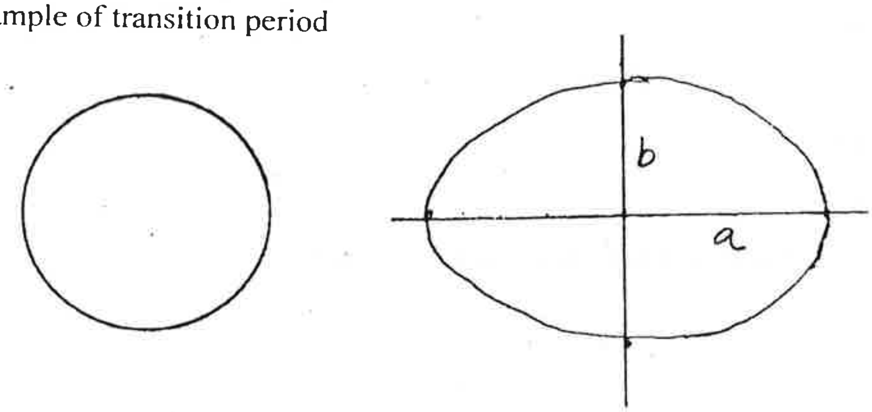
Kepler's book: 'Harmony of the World" 1619

3rd Law: The cube of the major radius divided by the square of the orbital period is the same for each planet

Comets

Solar system

Kepler as example of transition period



$A = \pi r^2$ $\qquad$ $A = \pi a b$

when $a = b$ an ellipse is a circle

Figure 12.2 Area of an ellipse

Notes for Class 13

Astronomy most developed in ancient times
Back to Physics

Galileo Galilei (1564-1642)
One of the most important scientists in history

Connection between astronomy and physics
Bridge between old and modern era of science

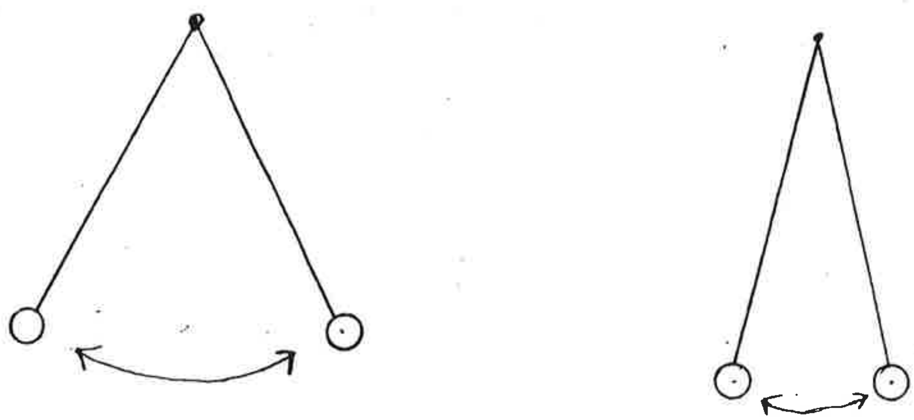


Figure 13.1 Pendulum

Figure 13.2 Amplitude of a pendulum

L (ft)	50T (sec)	T	L/T^2
1	56	1.12	.8
2	79	1.58	.8
3	97	1.94	.8
4	111	2.22	.8

So: $L = .8T^2$

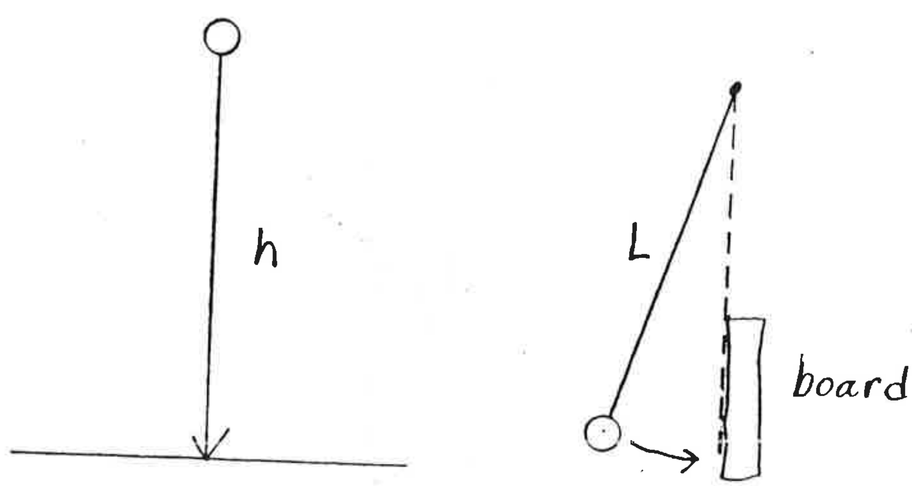


Figure 13.3 Pendulum vs. free fall

L (ft)	2	4	6	8
h (ft)	2.5	5	10	15

Constant ratio between L & h

$L = .8\ T^2$

$\tau = ¼ * T$ Time is ¼ the pendulum period

$\tau_f = T/4$ Time of fall is period divided by 4

$L = 4/5 * h$ (from chart)

Substitute $4/5 * h = .8\ (4\tau_f)^2$

$h = 16\ \tau_f^2$

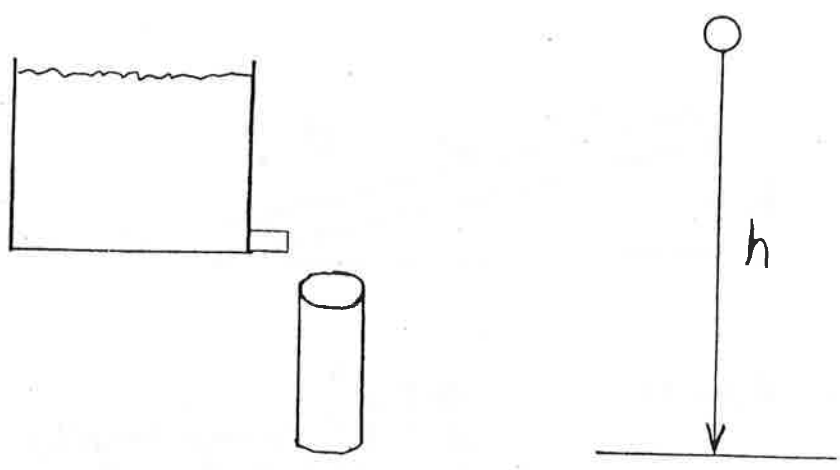


Figure 13.4 Water clock

Example of freefall data:

h(ft)	4	16	32	64	144
T(sec)	.5	1	1.5	2.0	3.0

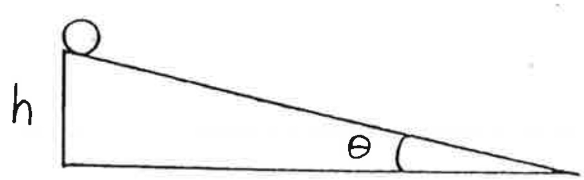


Figure 13.5 Ramp

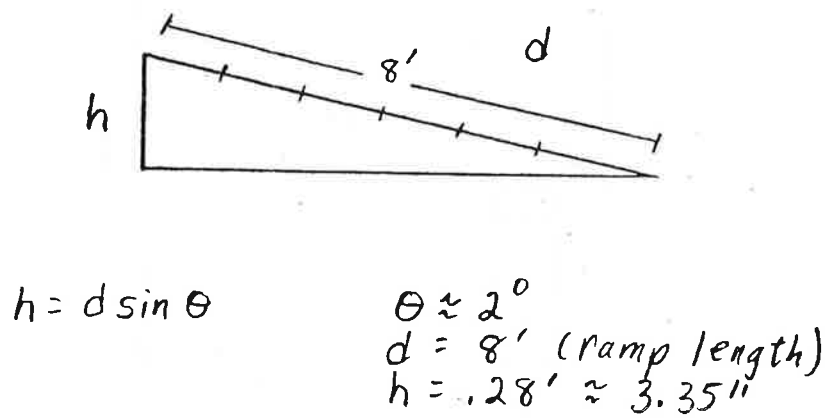
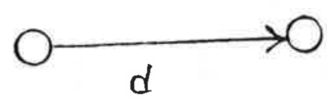


Figure 13.6 Ramp with threads

t	d	
.5	1.5”	6” in
1.0	6”	1^{st} second
1.5	1’2”	1’6” in
2.0	2’	2^{nd} second
2.5	3’2”	2’6” in
3.0	4’6”	3^{rd} second
3.5	6’2”	3’6” in
4.0	8’	4^{th} second



Average speed is $\frac{d}{t}$

or: $V_{avg} = \frac{d}{t}$

Figure 13.7 Average speed

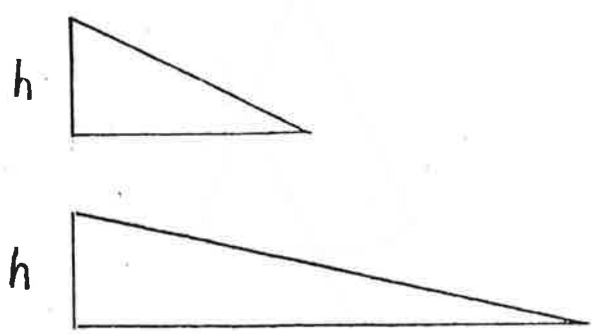


Figure 13.8 Ramps with same height but different angles

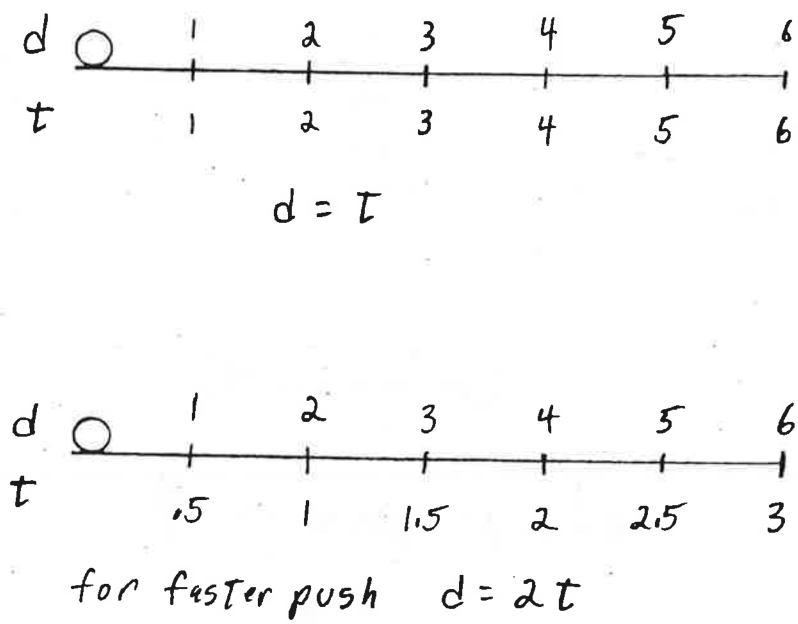


Figure 13.9 Horizontal motion

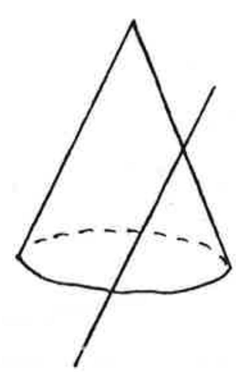


Figure 13.10 Parabola is a conic section

Notes for Class 14

Galileo

Pendulum law $L = .8T^2$

Free Fall law $h = 16\,t^2$

Mixed motion

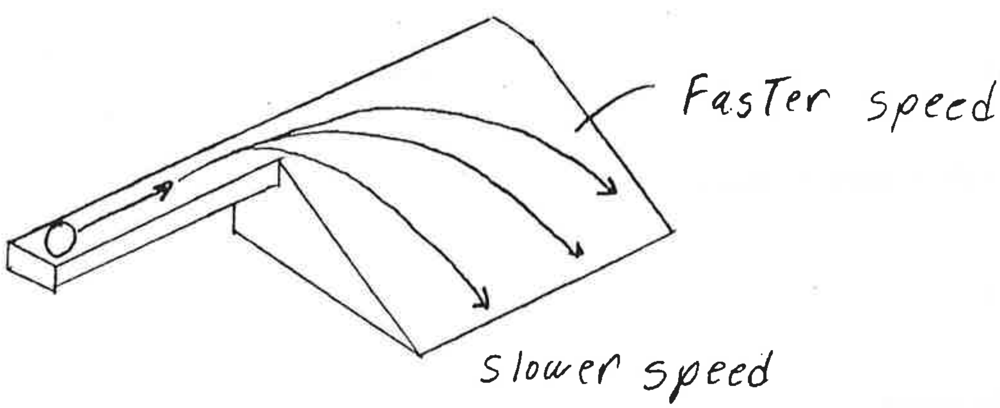


Figure 14.1 Mixed motion ramp

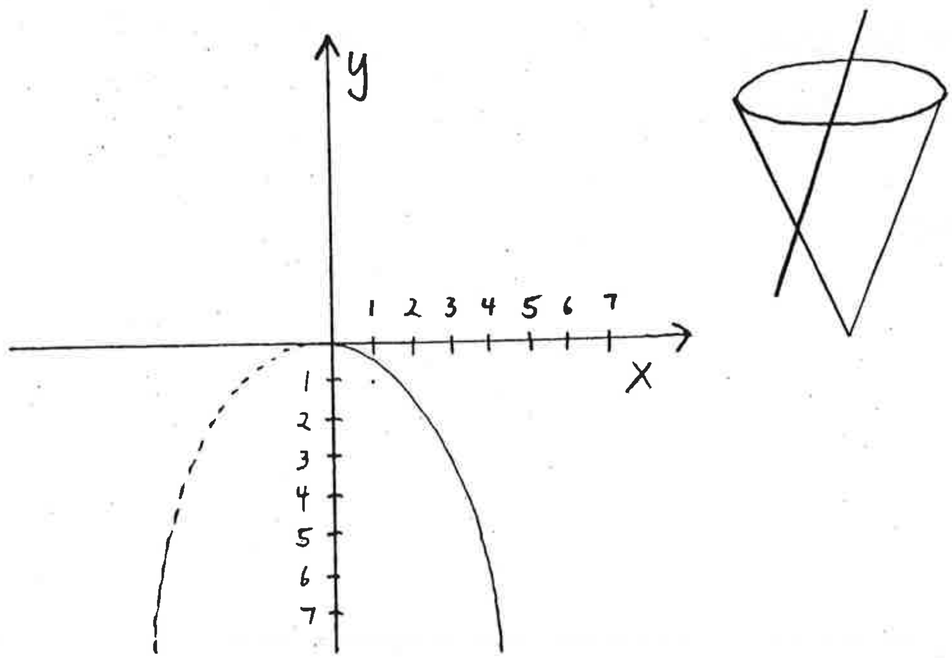


Figure 14.2 Parabola is a conic section

$y = (\text{constant})\ X^2$

$y = c_1\ t^2$

$x = V\ t$ (V = speed, t= time)

So:

$x/V = t$

By substitution:

$y = c_1\ (x/V)^2 = (c_1 / V^2)\ x^2$

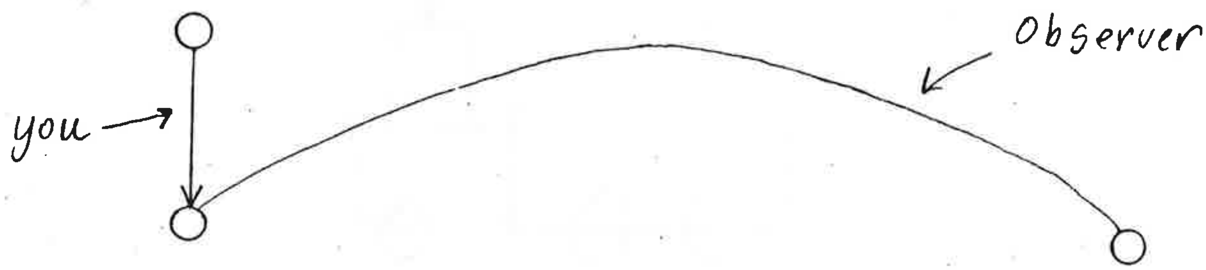


Figure 14.3 Path of a ball

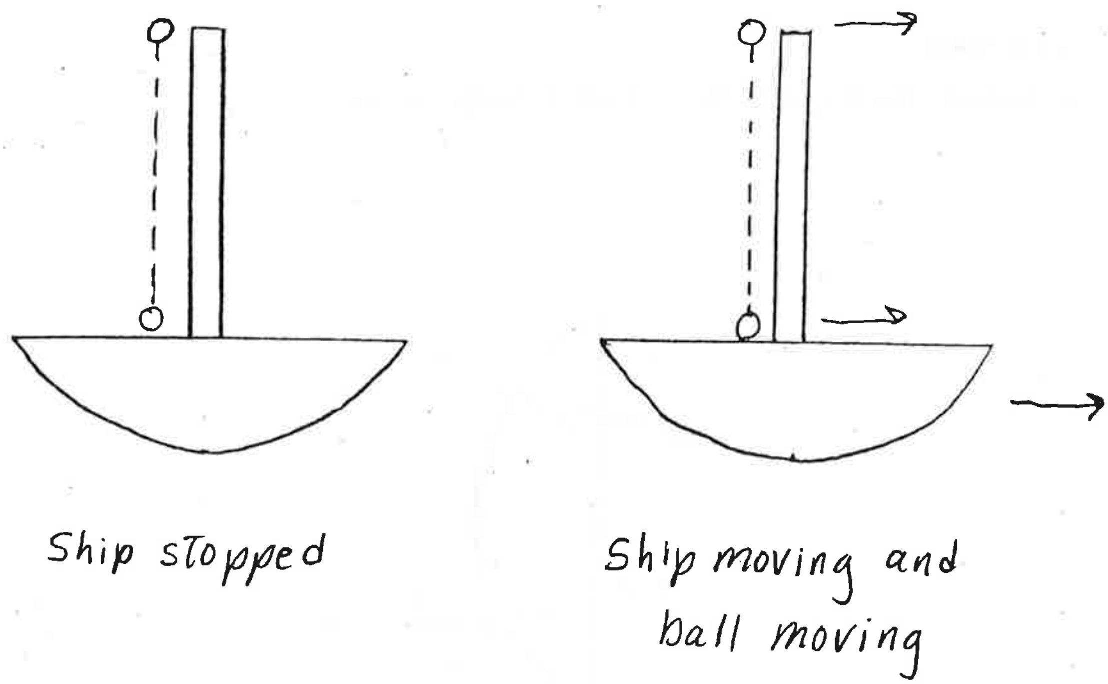


Figure 14.4 dropping an object from the mast of a ship

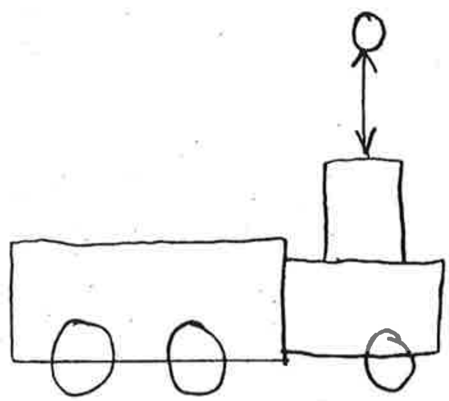


Figure 14.5 Toy train with a cannon

Telescope

Background

Refraction – the way light bends when it changes media

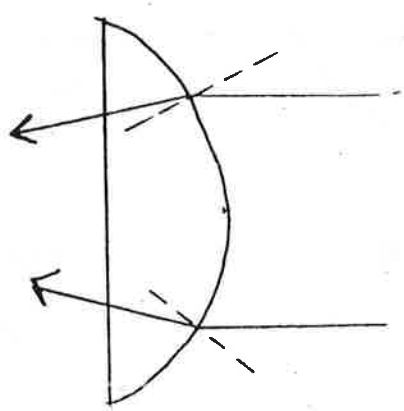


Figure 14.6 Convex lens

Convex – bulges out

Concave – sinks in

Convex lens converges the light.

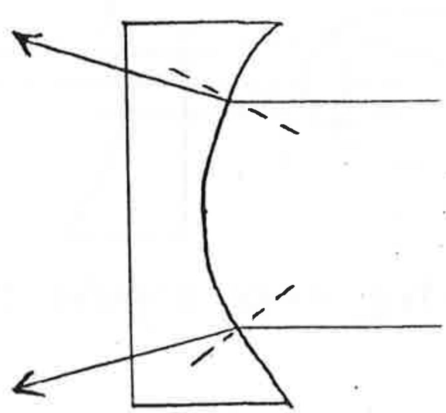


Figure 14.7 Concave lens

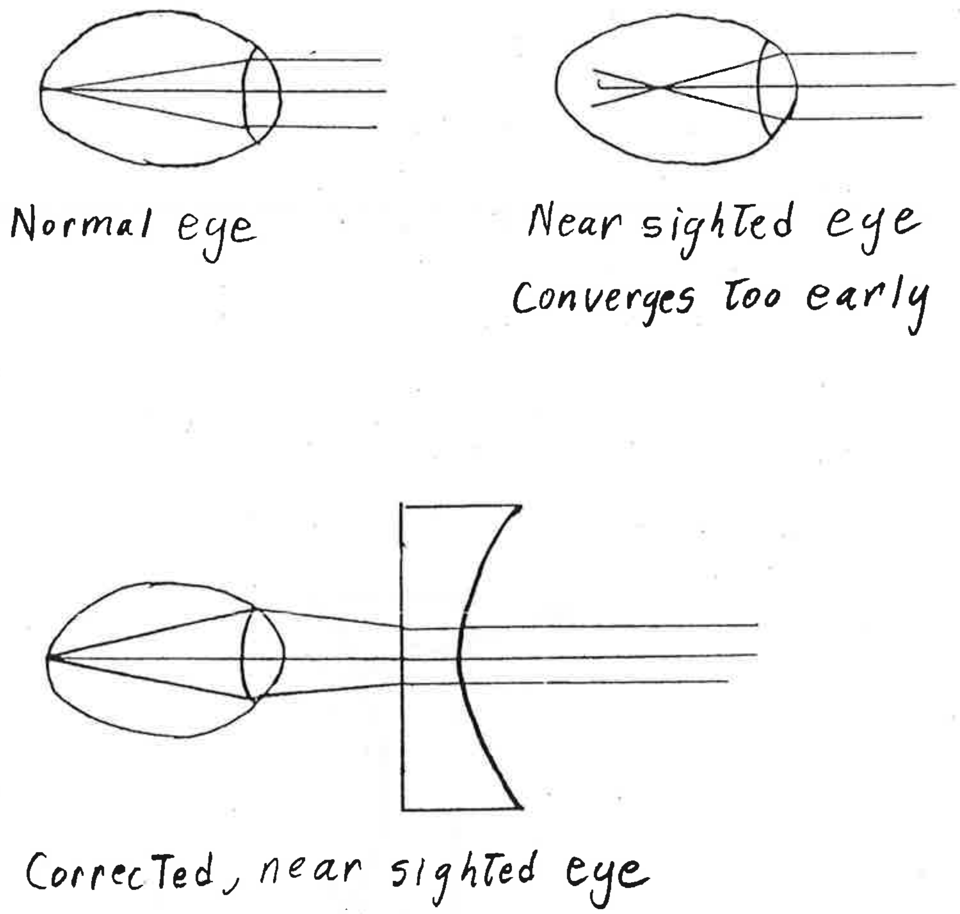


Figure 14.8 Corrected eyesight

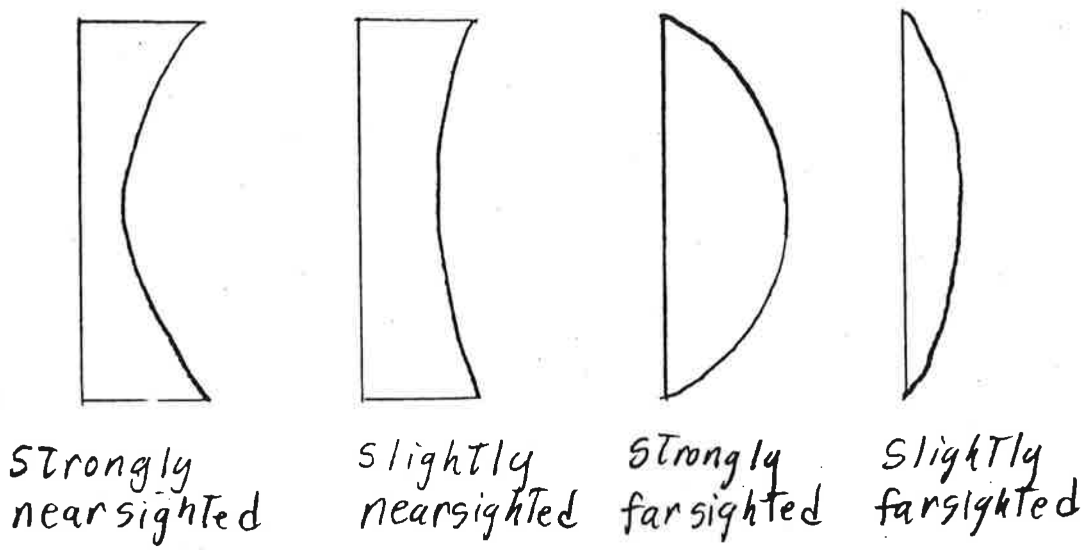


Figure 14.9 Strength of lenses

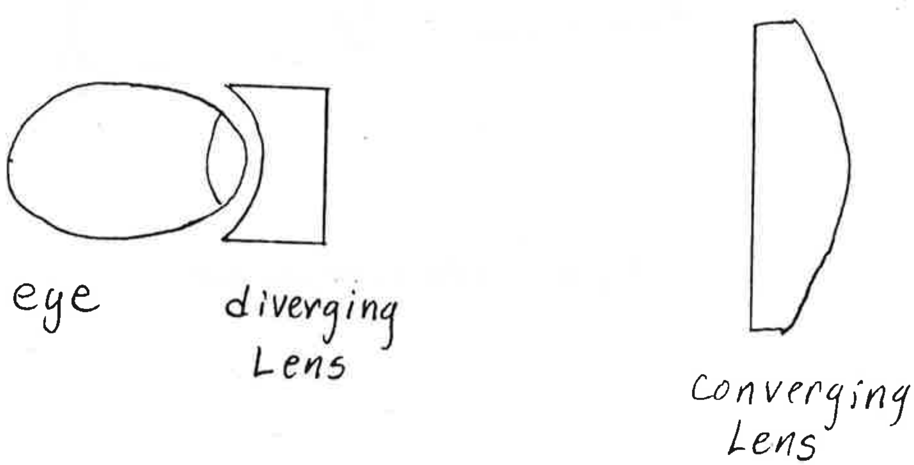


Figure 14.10 Converging-diverging lens pairs

Add a lens to compensate for the curvature of our eye

Use a bigger lens to converge the light instead of our eye

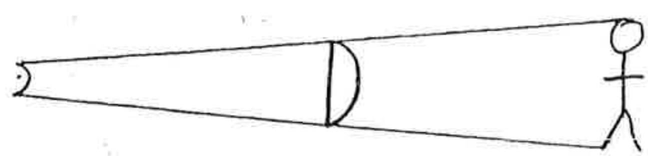
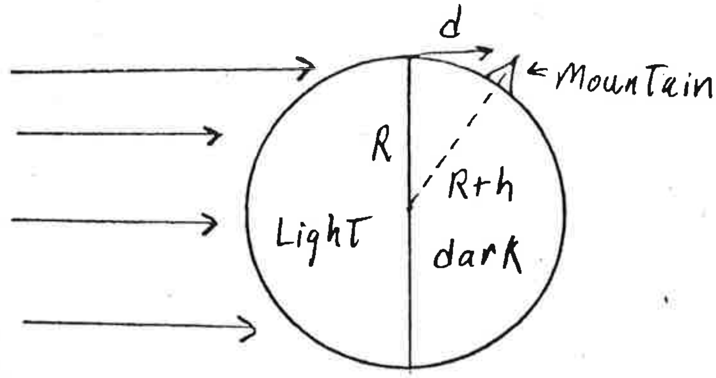


Figure 14.11 Bigger eye sees more

A bigger eye gives the effect of being closer. If you are closer, your eye is larger compared to the object.

Discoveries with telescopes. First new stars, then observed the moon.



R = radius of moon

h = height of mountain

d = Galileo can measure this. 1/20 moon diameter

so $d = R/10$

Use Pythagorean theorem:

$$(R+h)^2 = R^2 + (R/10)^2$$

$$R^2 + 2Rh + h^2 = R^2 + R^2/100$$

$$2Rh\,(1 + h/2R) = R^2/100$$

Assume $2R >> h$ so ignore

$$2Rh = R^2/100$$

$$h = \frac{R}{200} \qquad R \approx 1000 \text{ miles}$$

so $h \approx 5$ miles

Figure 14.12 Mountains on the moon

Notes for Class 15

Discoveries with telescopes, continued
New stars, moon's surface

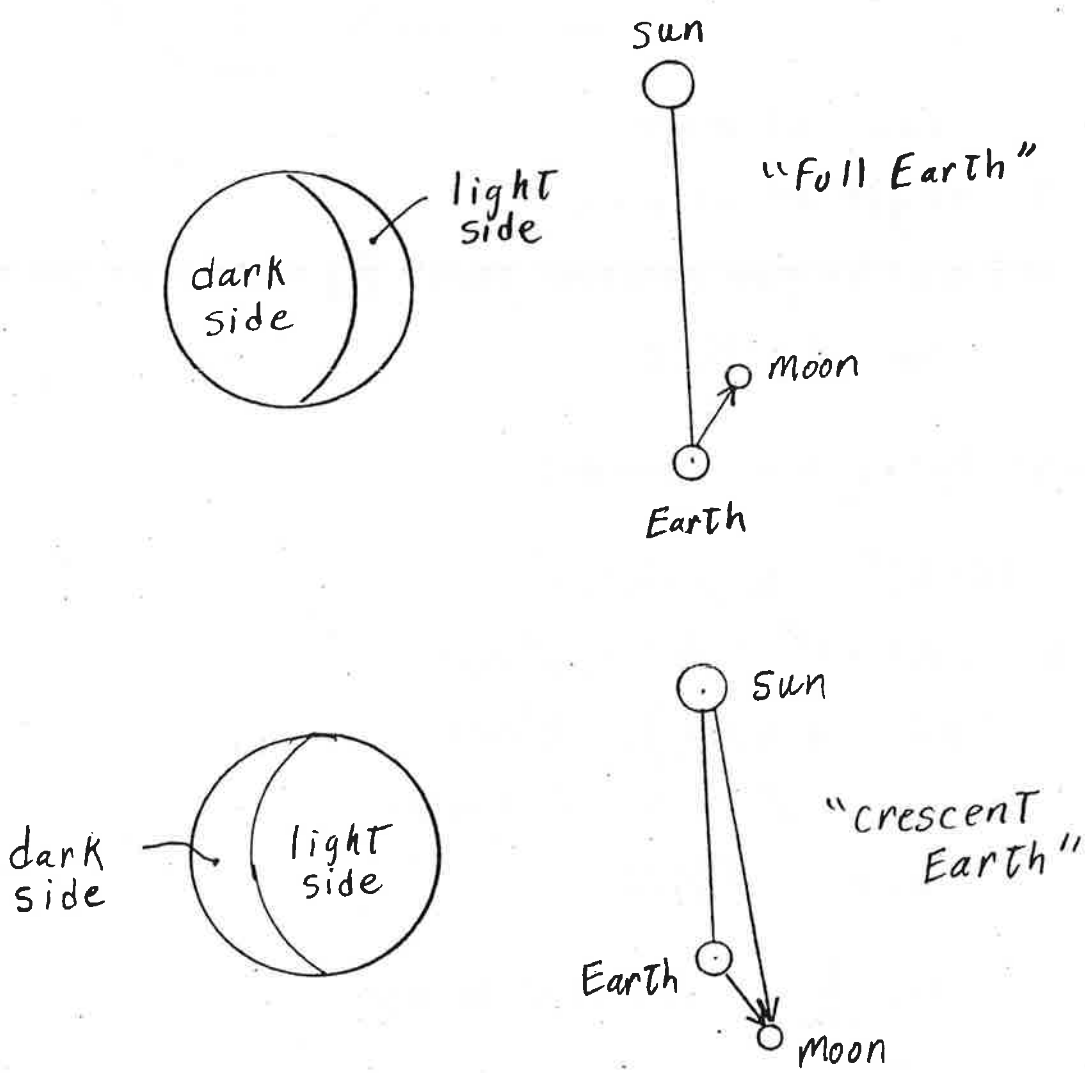


Figure 15.1 Earthshine

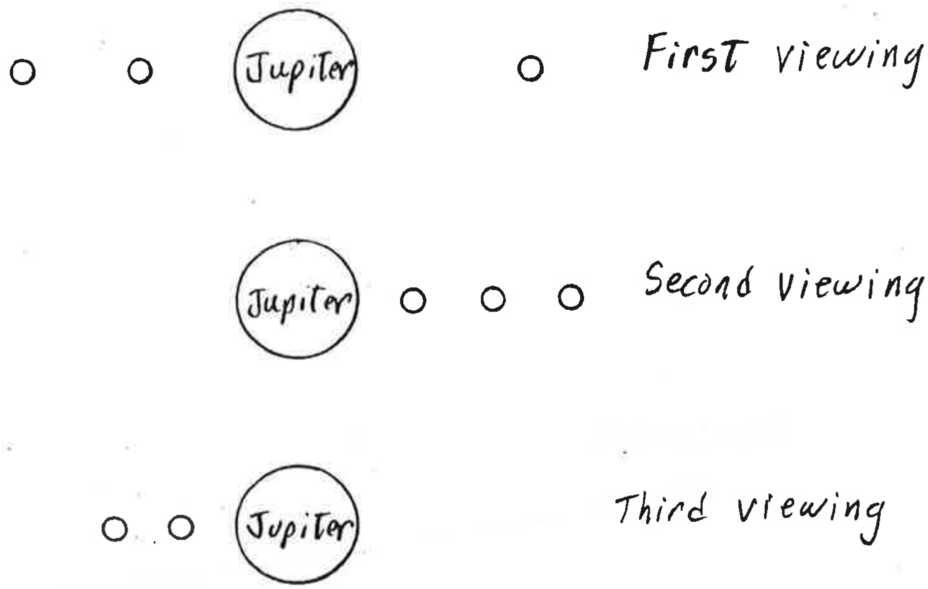


Figure 15.2 Jupiter's moons

Jupiter's moons (1610)

Moon	Period (days)	Radius	R^3/T^2
IO	1.77	5.9R (radius of Jupiter)	66
Europa	3.56	9.4R	66
Ganymede	1.17	15.0R	66
Callisto	16.75	26.4R	66

Uses of knowledge about Jupiter's moons

Supports heliocentric theory

Celestial clock

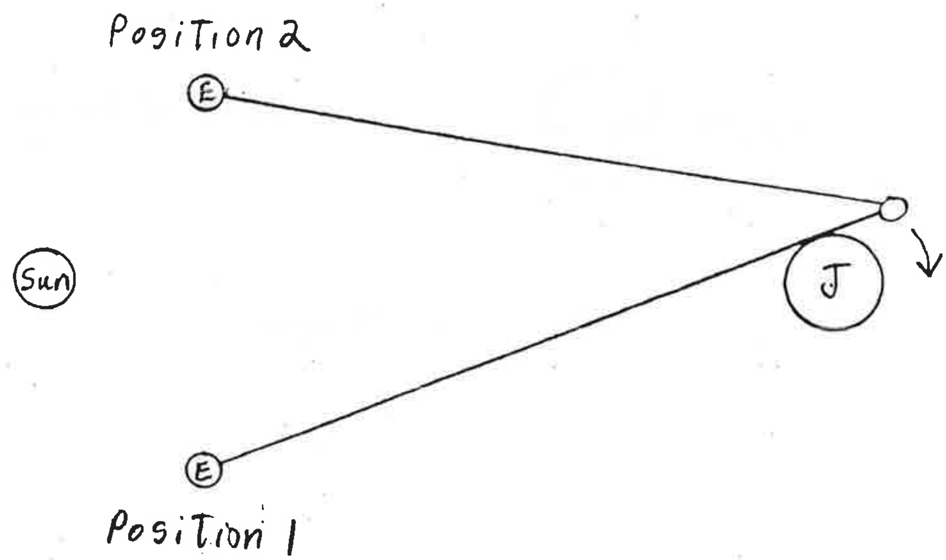


Figure 15.3 Viewing Jupiter's moons from Earth

When Galileo takes into account the orbit of the earth, he gets very accurate results.

Venus

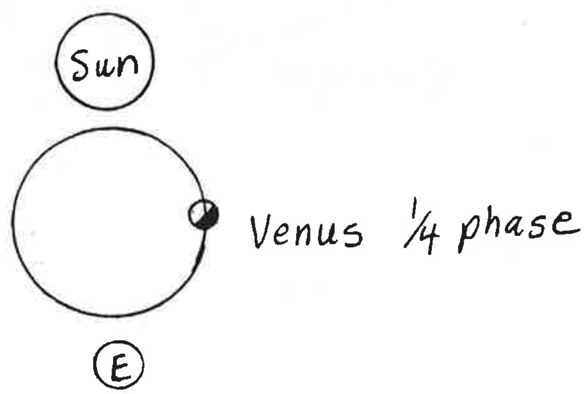


Figure 15.4 Ptolemy's view of Venus

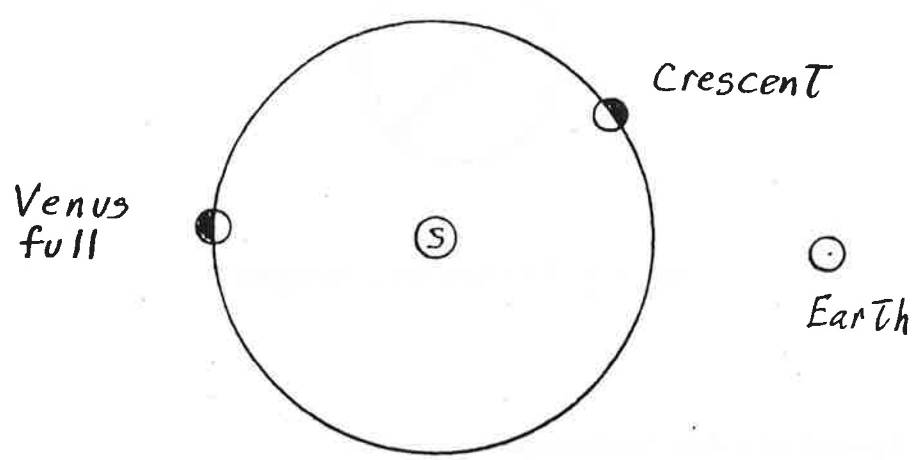


Figure 15.5 Phases of Venus

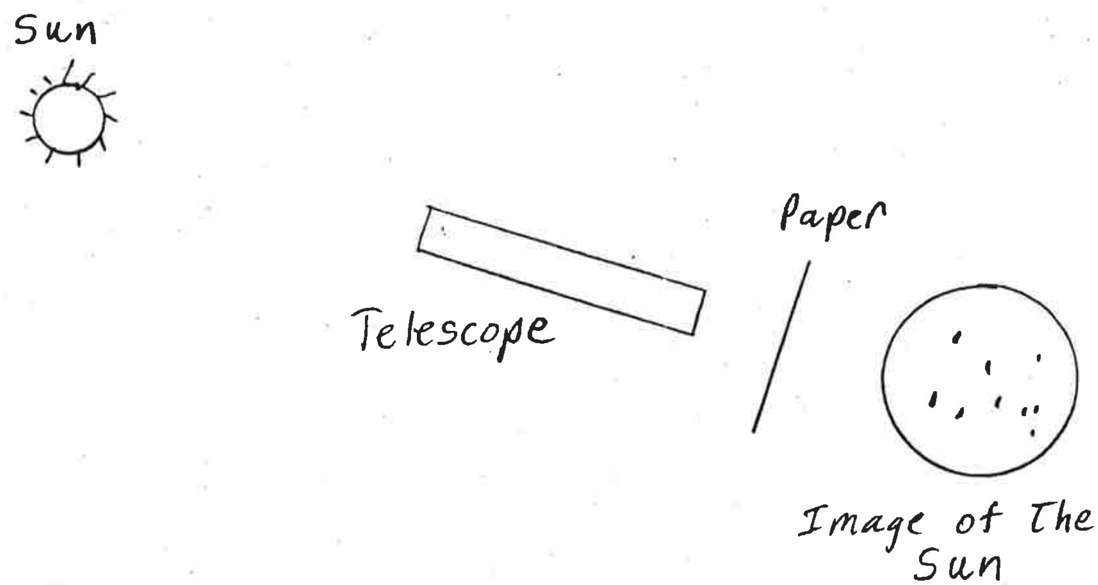


Figure 15.6 Viewing sunspots

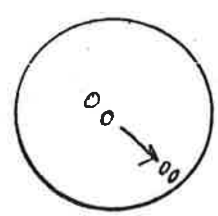


Figure 15.7 Movement of sunspots

1609 – 1613 period of Galileo's telescope discoveries

1609 – Kepler's 1st and 2nd laws were published

1602 – 1608 – Galileo's discover of laws of motion

Notes for Class 16

Galileo thought experiment

Evidence for the heliocentric theory:

1. Small body should move around a large one. (Aristarchus made this argument)
2. Explanation for retrograde motion. (Copernicus)
3. Difference between inner and outer planets. (Copernicus)
4. Variations in brightness of the planets. (Copernicus)
5. Kepler's theory is the only one that fits Tycho's accurate data. (elliptical orbits)
6. Explanation for phases of Venus. (Galileo)
7. Moons of Jupiter make up "miniature Copernican system."
8. Explanation for times of eclipses of Jupiter's moons.
9. Earth is a planet, not unique center of universe.
    - New stars
    - Rough surface of moon
    - Spots on the sun
10. Explanation for movement of sunspots.

Arguments against heliocentric theory:

1. Some people claimed that the telescope images were created by the instrument.
2. Bible says the earth is immobile and the sun goes around it.
3. If you don't accept this we may kill you.

Galileo's trouble with the church

1615 – Galileo first accused of heresy by Lorini.

1543 – Copernicus published heliocentric theory but the church ignored it

Two reasons church ignored heliocentric theory:

1. The theory did not have many adherents.
2. The preface to Copernicus' book

Cardinal Robert Bellarmine

1616 – Church edict declares heliocentric theory to be heresy.

1621 – Bellarmine dies. "With force I have subdued the brains of the proud."

1621 – A new pope is elected: Maffeo Barberini – Pope Urban VIII

Salviati – Smart guy

Simplico – Wrong guy

Sagreto – character who is persuaded by Salviati

1632 – "Dialogue Concerning the Two Chief World Systems"

1633 – Galileo is put on trial

Physical Science
David Harriman

Course Outline Classes 17-31

IV. Newton's Discovery of Universal Laws

- Steps leading to the idea of universal gravitation
  - Circular motion; force and acceleration
  - The sun's force on the planets
  - The falling apple and the acceleration of the moon
- The idea of "mass" and the three laws of motion
- How Newton completed and proved the law of gravitation
  - The evidence: the orbits of planets, comets, and the moon; free fall; the ocean tides; the shape and spin of the Earth
- Other related discoveries
  - The distances from the sun to the planets
  - Determining the gravitational constant

V. Optics and the New Experimental Method

- Snell discovers the law of refraction
- Newton's prism experiments and his theory of colors
- Applications of the theory of colors
  - The reflecting telescope
  - The explanation of rainbows
- Newton's rings and the wave nature of light
- Discovery of the speed of light

VI. Early Discoveries about Gases

- Torricelli's discovery and measurement of air pressure
- Boyle's law of gases
- Fahrenheit's invention of the mercury thermometer
- Charles' law of gases

Notes for Class 17

Review

Willebrord Snel (1621) – Discovered the law of refraction

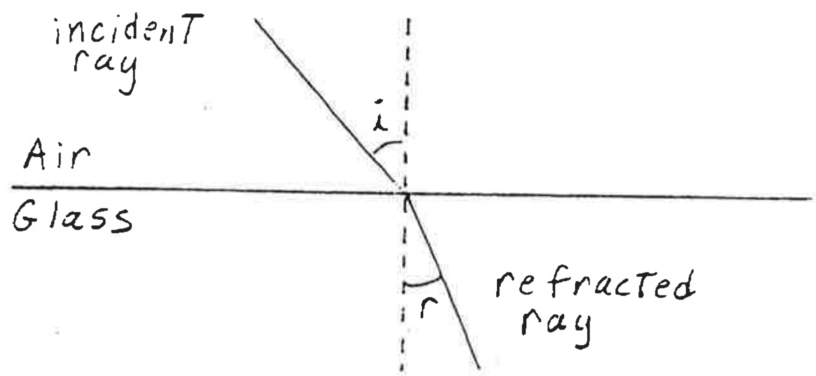


Figure 17.1 – Light bends toward the perpendicular when passing from air to glass.

i	10°	20°	30°	40°	50°	60°	70°	90°
r	6.6°	13.2°	19.5°	25.4°	30.7°	35.3°	38.8°	42°

i / r = constant (for small angles)

Snel's law for glass: sin i / sin r = 1.5

Snel's law for water: sin i / sin r = 1.33

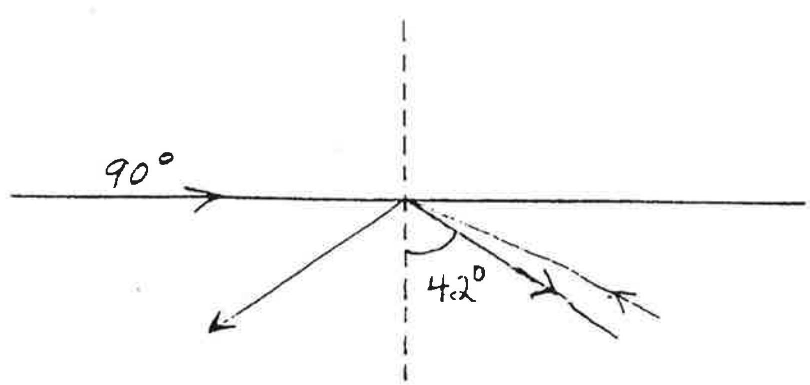


Figure 17.2 – Total internal reflection.

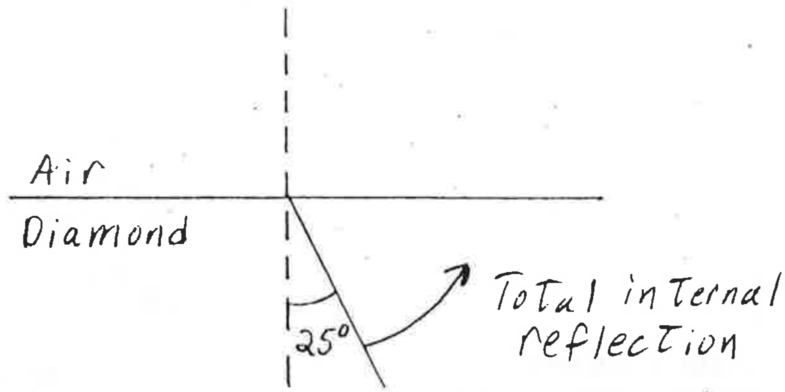


Figure 17.3 – Total internal reflection of a diamond.

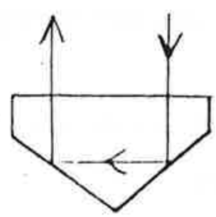


Figure 17.4 – Diamonds are cut to reflect light out the top.

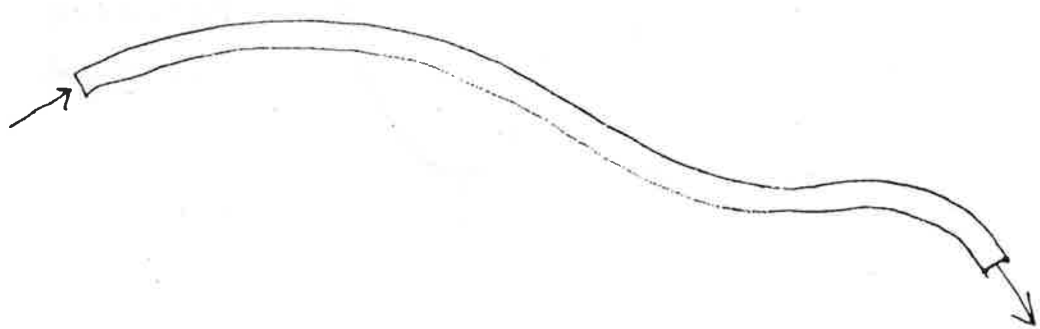


Figure 17.5 – Fiber optics: light pipe.

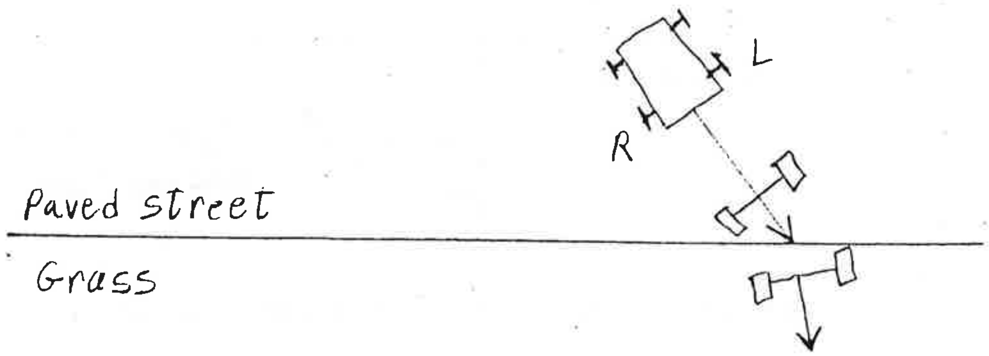


Figure 17.6 – Go cart goes from paved street to grass.

Pierre Fermat – (Active career: 1620's to about 1660)

- Developed analytic geometry

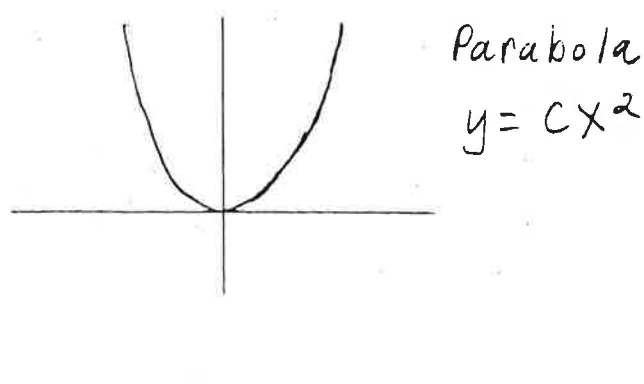


Figure 17.7 – Parabola

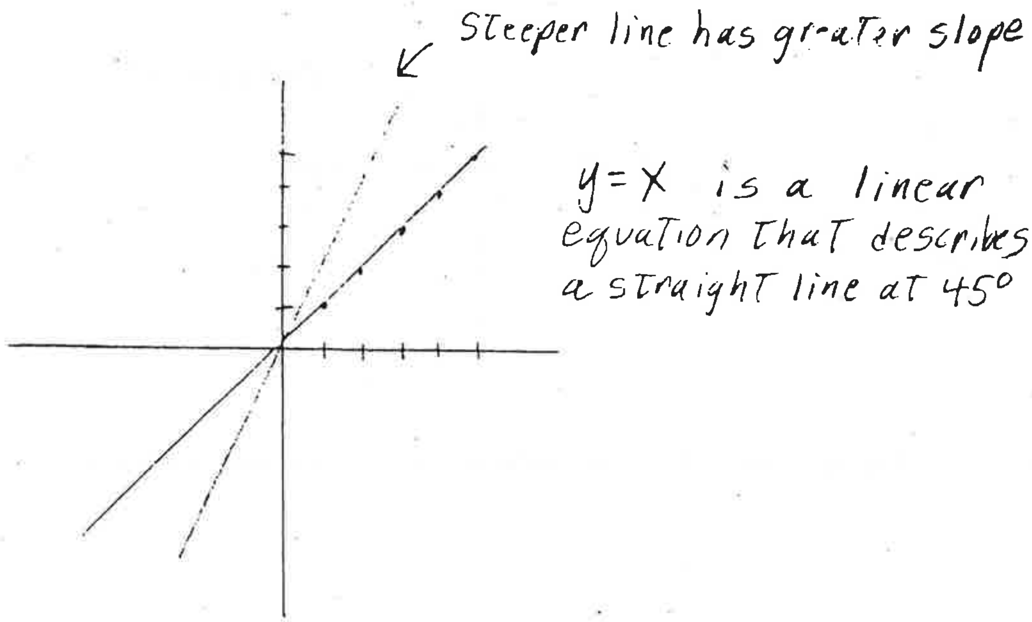


Figure 17.8 – Straight line

Slope = rise / run = Δy / Δx = change in y / change in x

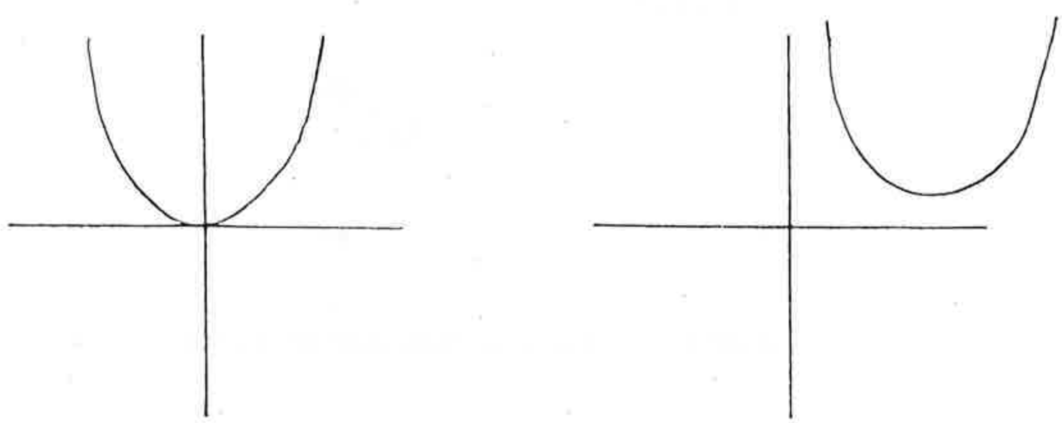


Figure 17.9 – Minimum value of a parabola occurs when slope is zero

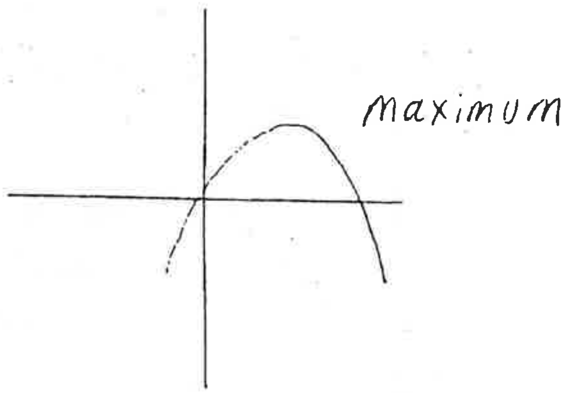


Figure 17.10 – Maximum value of a parabola occurs when slope is zero

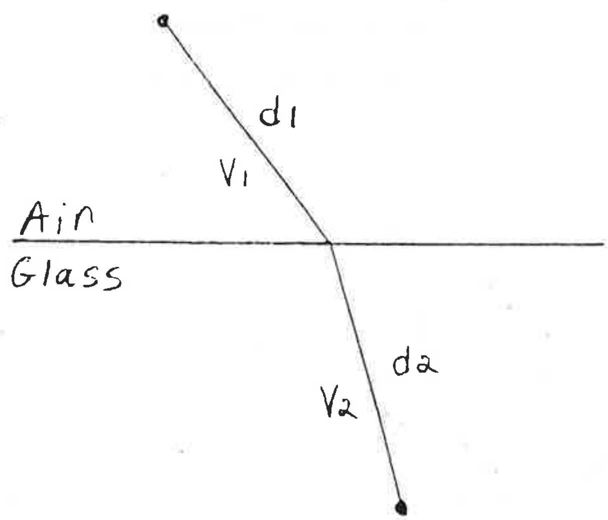


Figure 17.11 – Light traveling from air to glass

time = d1 / v1 + d2 / v2

velocity = distance / time so: time = distance / velocity

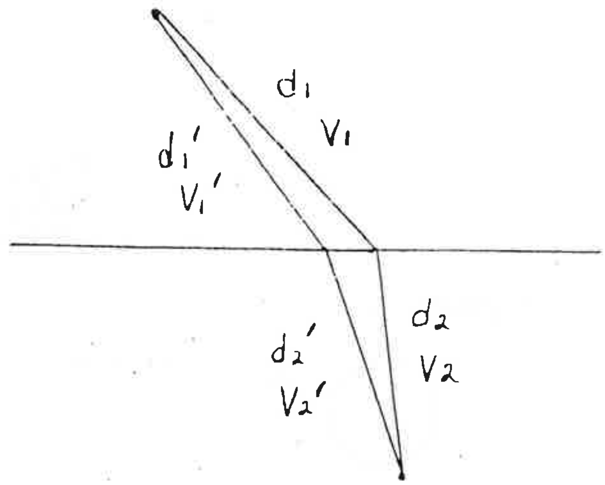


Figure 17.12 – Comparison of two paths of light

time = d1 / v1 + d2 / v2

time' = d1' / v1' + d2' / v2'

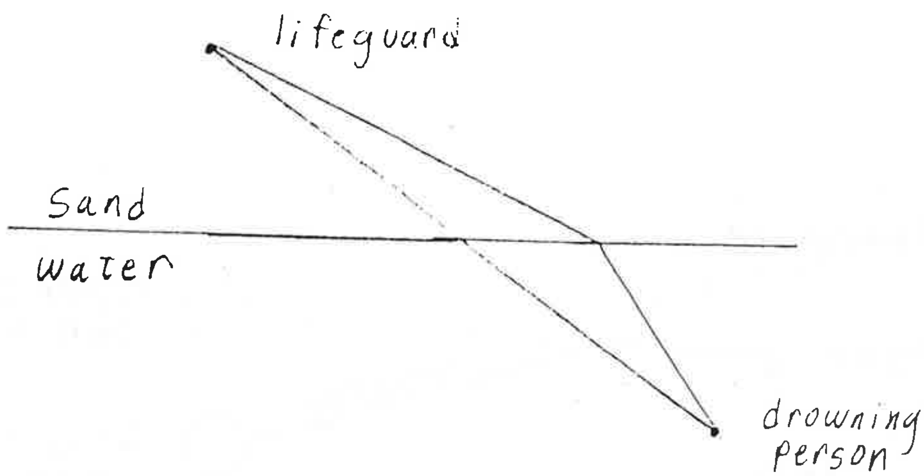


Figure 17.13 – Lifeguard's path to a drowning person

Equation that minimizes the time it takes for the light to go from A to B (initial to final):

sin i / sin r = v1 / v2

For glass: v1 / v2 = 1.5

Kepler notices refraction during a lunar eclipse.

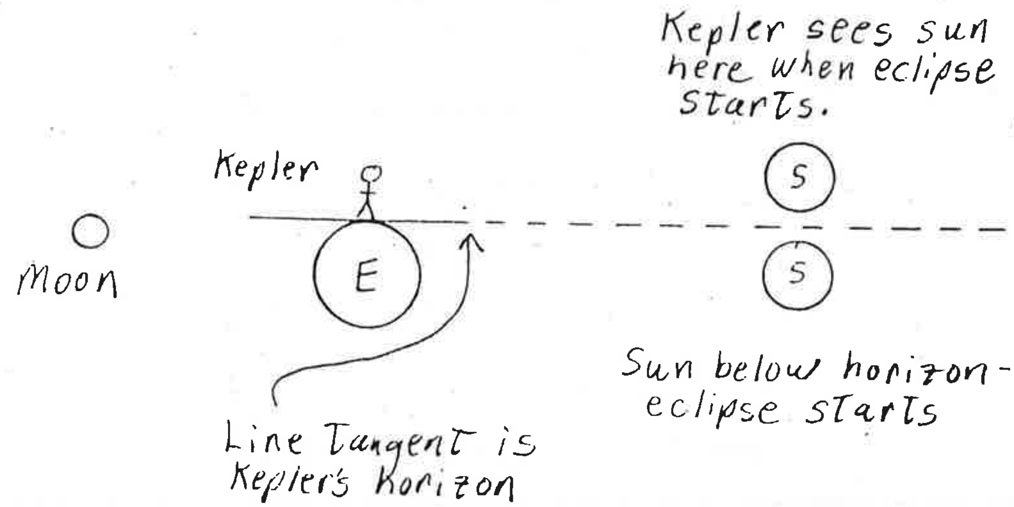


Figure 17.14 – Refraction of sun's rays during an eclipse

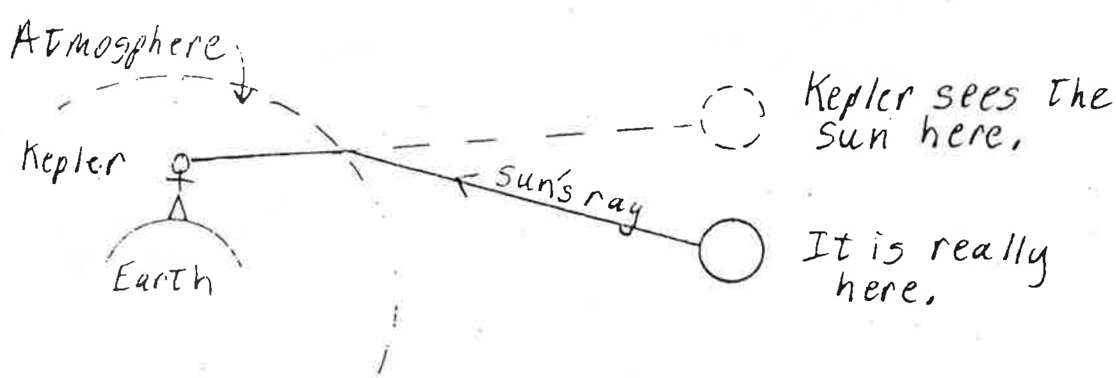


Figure 17.15 – Refraction of sun's rays at sunset

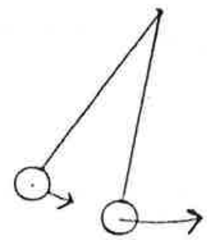


Figure 17.16 – Pendulum's period is dependent only on length for small amplitudes

Christian Huygens (1658) – Invented cycloid pendulum

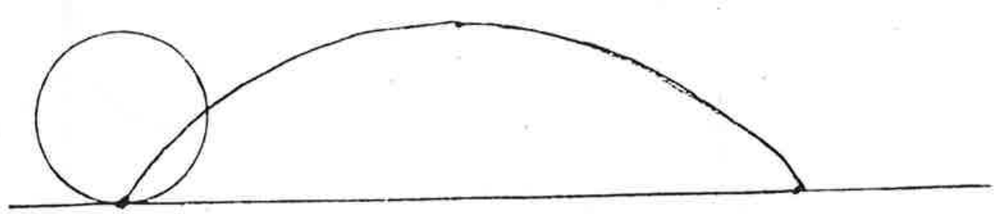


Figure 17.17 –Cycloid

<u>Notes for Class 18</u>

Review

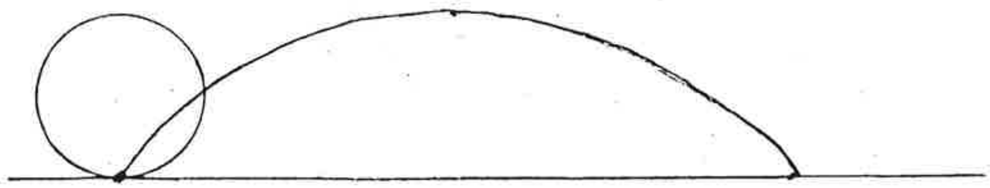


Figure 18.1 – A point on a rolling wheel traces out a cycloid

Figure 18.2 – A cycloid pendulum bob takes the same time to reach the bottom no matter where you release it.

Figure 18.3 - Circular vs. cycloid pendulum path

Huygens improves telescope and discovers:

- Rings of Saturn
- Saturn's moon Titan.

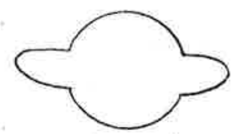


Figure 18.4 – Galileo's view of Saturn

Isaac Newton (1642-1727)

Discoveries on the sheep farm – the "miracle years."

- Discoveries about light
- A new branch of mathematics
- The basic idea for theory of gravitation

Light and Color – Three ways that white light is transformed into colors

1. Prisms
2. Rainbows
3. Soap bubbles, oil on the surface of water

Scientists before Newton:

Descartes – spinning particle theory of colors

Hooke – asymmetrical wave theory of colors

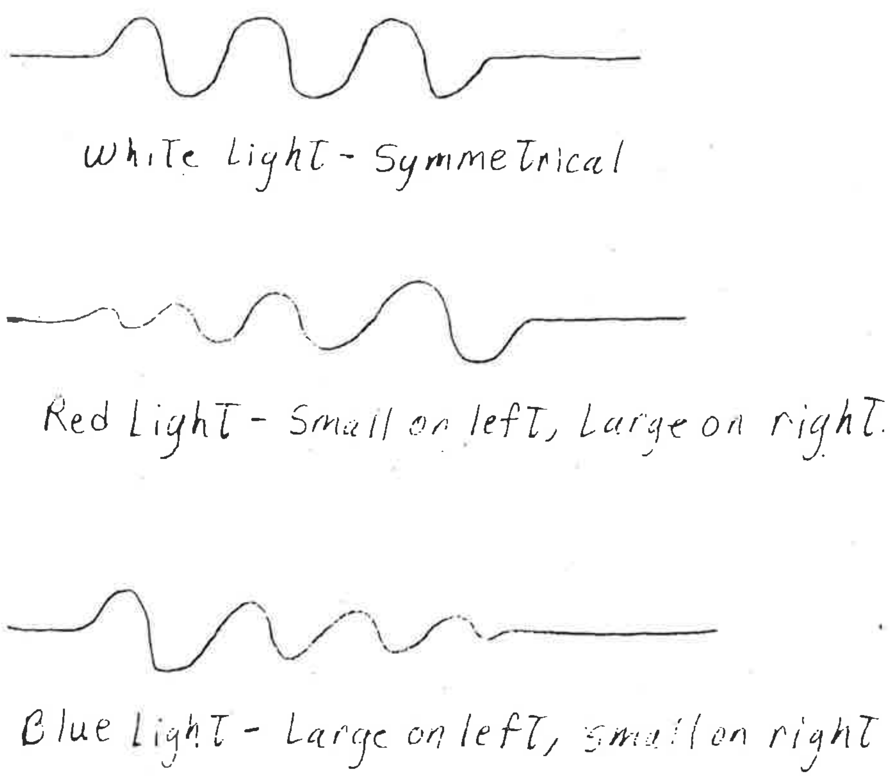


Figure 18.5 – Hooke's asymmetrical wave theory of colors

Newton's approach – experimentation

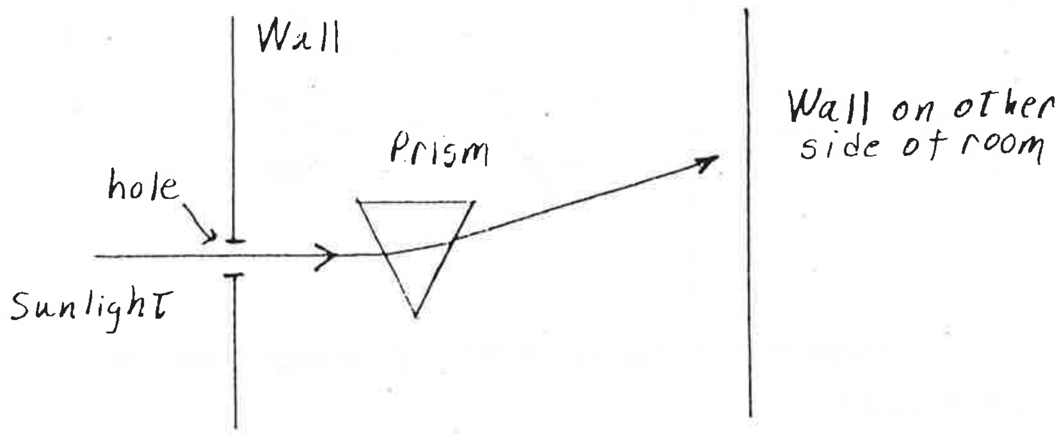


Figure 18.6 – Newton's prism experiment

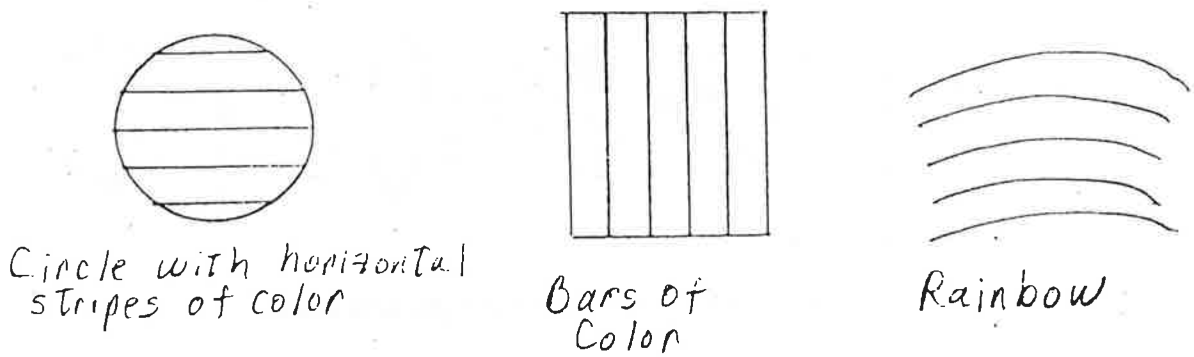


Figure 18.7 – Which pattern did Newton see?

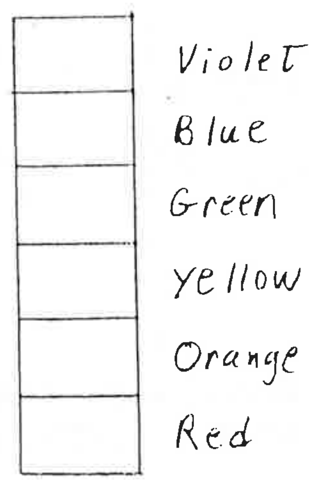


Figure 18.8 – What Newton actually saw

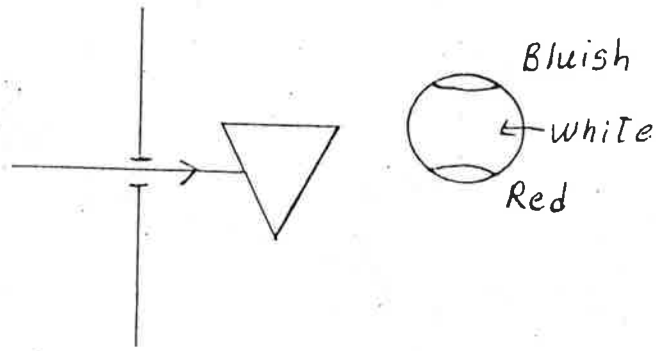


Figure 18.9 – Colors are not distinct if the target is too close

More experiments

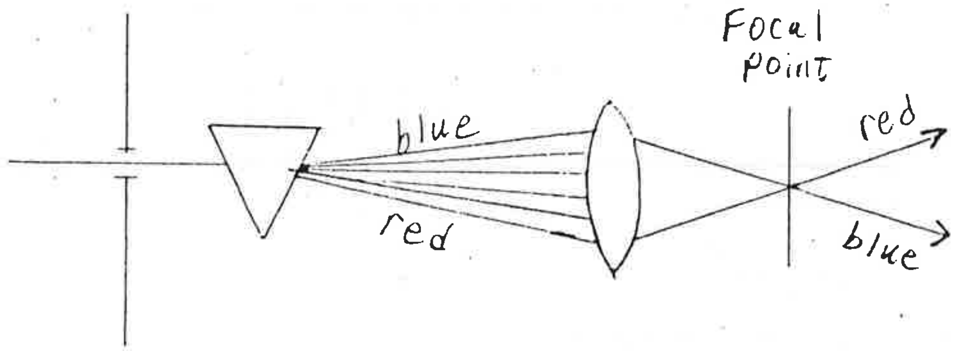


Figure 18.10 – Recombining light with a lens

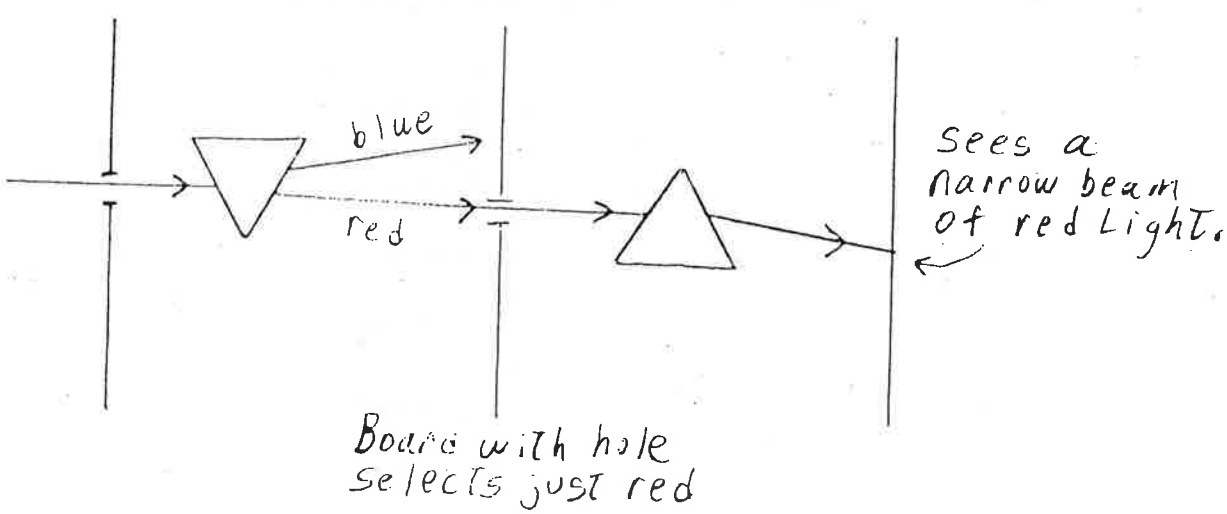


Figure 18.11 – Refracting a single color of light

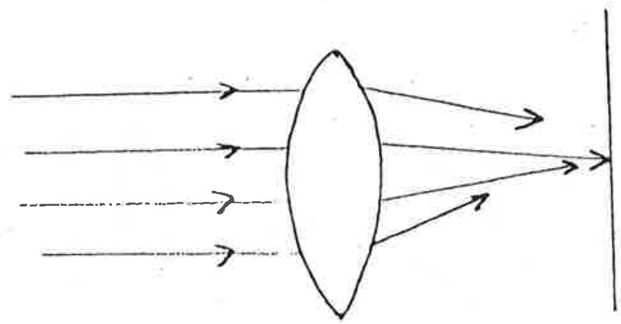


Figure 18.12 – The focal point is different for each color

Newton invents the reflecting telescope

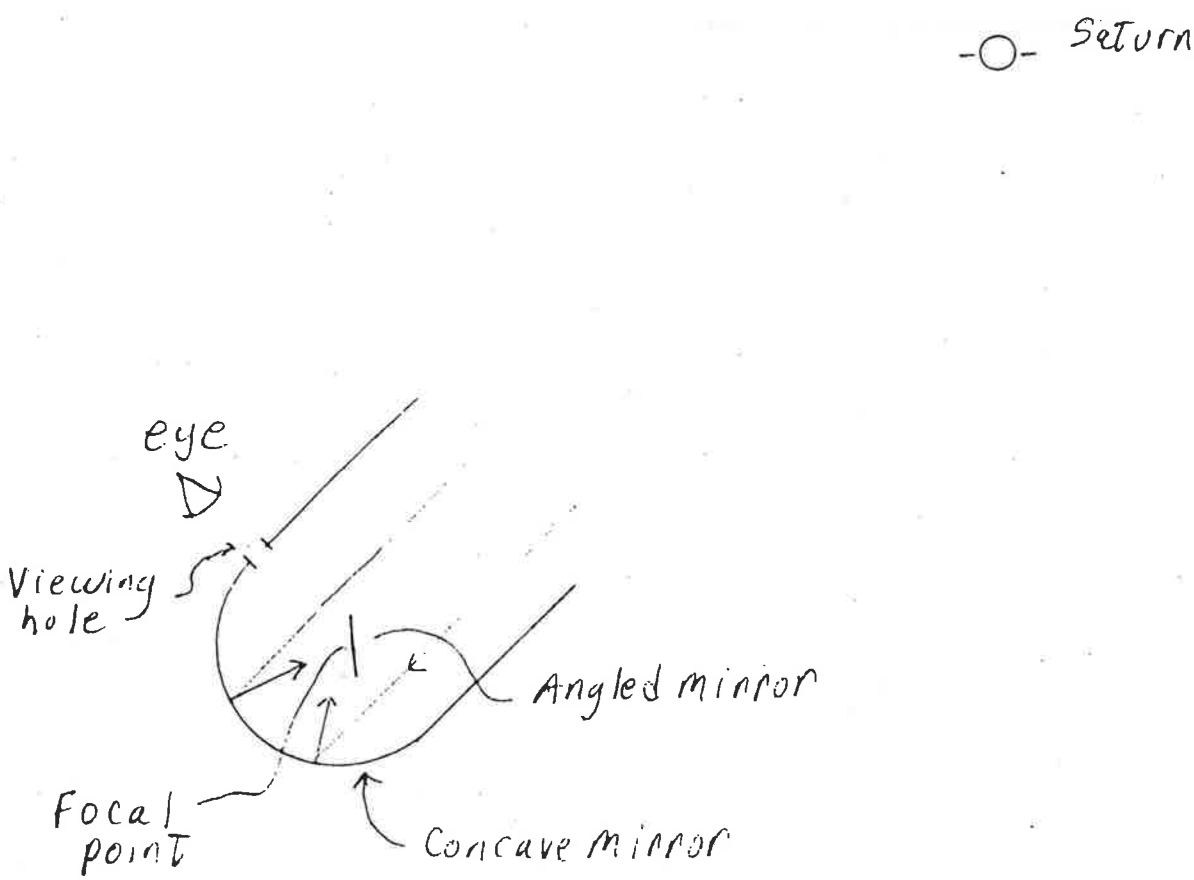


Figure 18.13 – Reflecting telescope

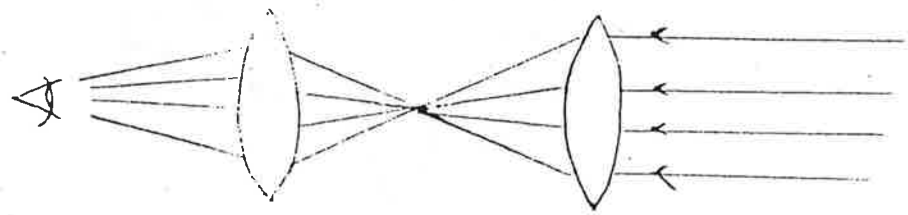


Figure 18.14 – Refracting telescope

Newton returns to graduate school

Notes for Class 19

Newton's optics

More experiments with color

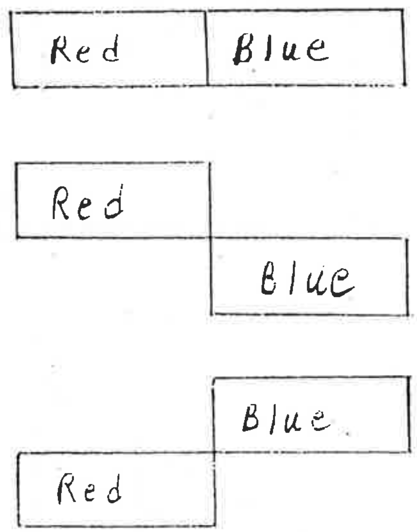
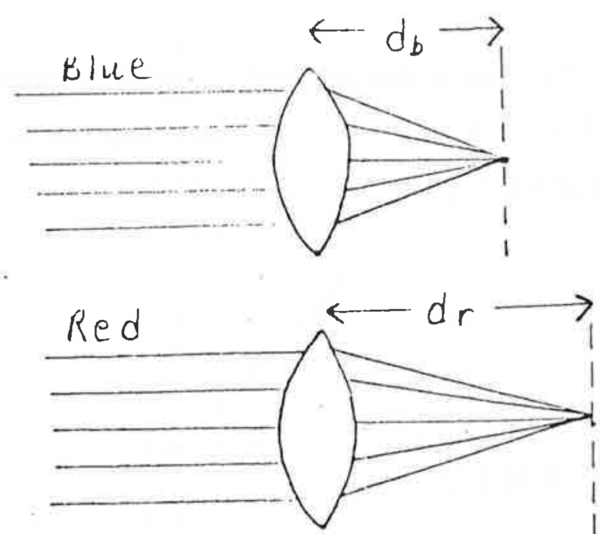


Figure 19.1 – A shift caused by colors refracting different amounts



dr > db

Figure 19.2 –The focal distance of a converging lens is longer for red than for blue

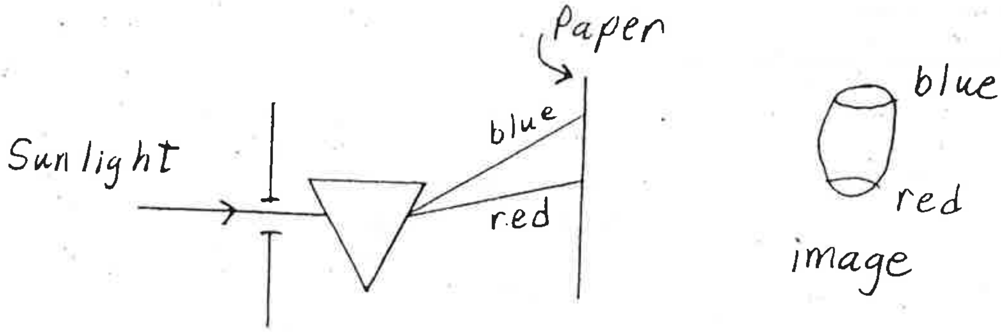


Figure 19.3 – Image through one prism

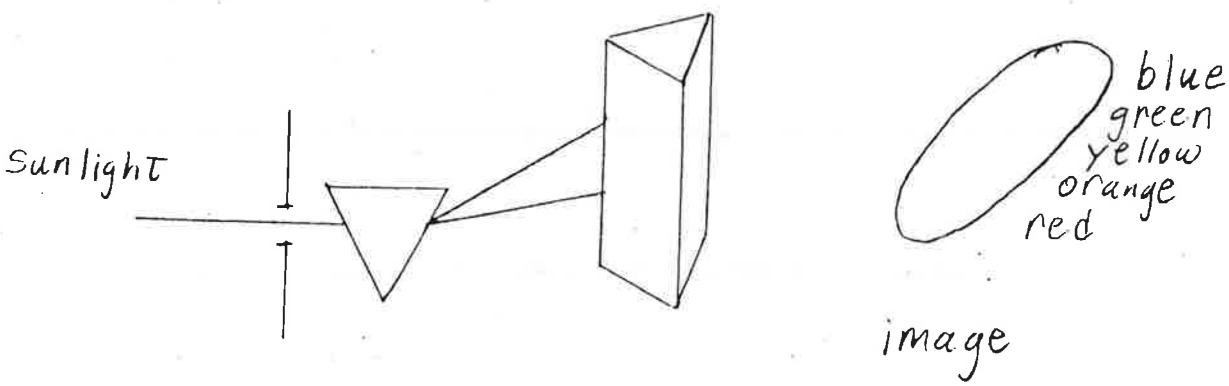


Figure 19.4 – Image through a second prism perpendicular to the first

Snel's Law: sin i / sin r = n where n is a constant called the index of refraction

Each color has its own n, e.g. red – 1.5, blue – 1.55, etc.

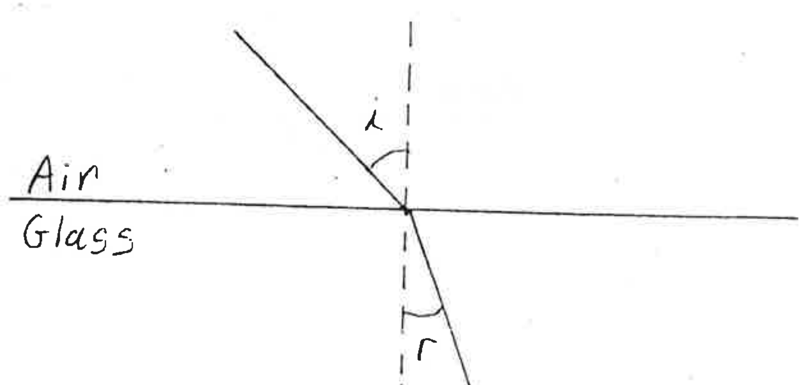


Figure 19.5 – Image through a second prism perpendicular to the first

We see colors because of selective reflection.

light	ruby	turquoise
red	bright red	dull, faded red
blue	dark, dull blue	bright blue

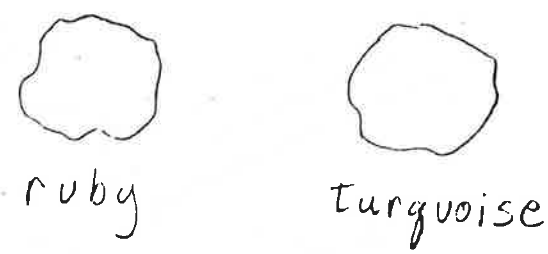


Figure 19.6 – Ruby and turquoise reflect different colors

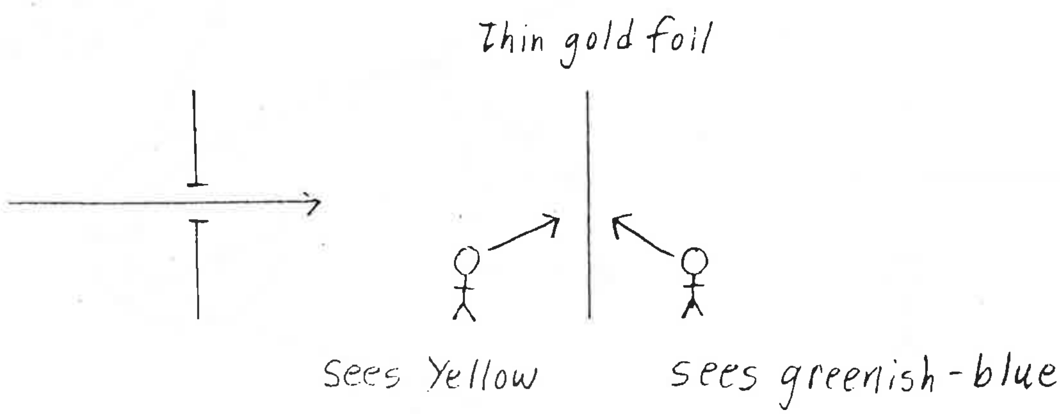


Figure 19.7 – Thin gold foil selectively reflects and transmits

Rainbows

Where does the colored light we see come from?

1. Light that passes through the raindrop is irrelevant because we never see it.
2. Light could reflect off the front of the raindrop.
3. Light could reflect off the back surface of the raindrop.

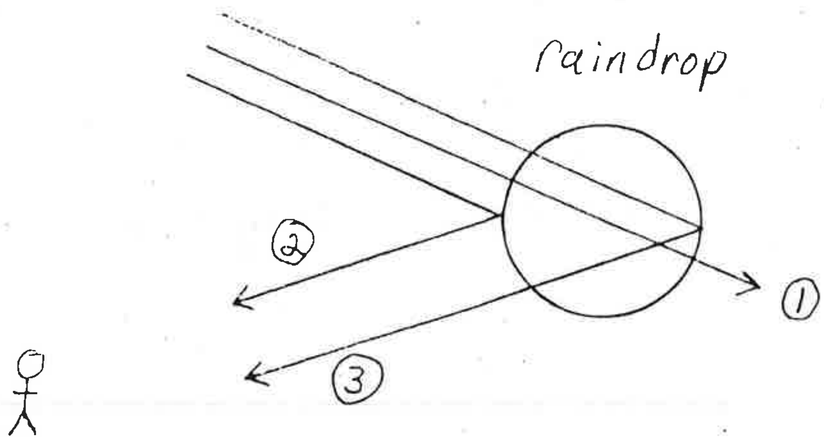


Figure 19.8 – Three possibilities for the source of colored light from a rainbow

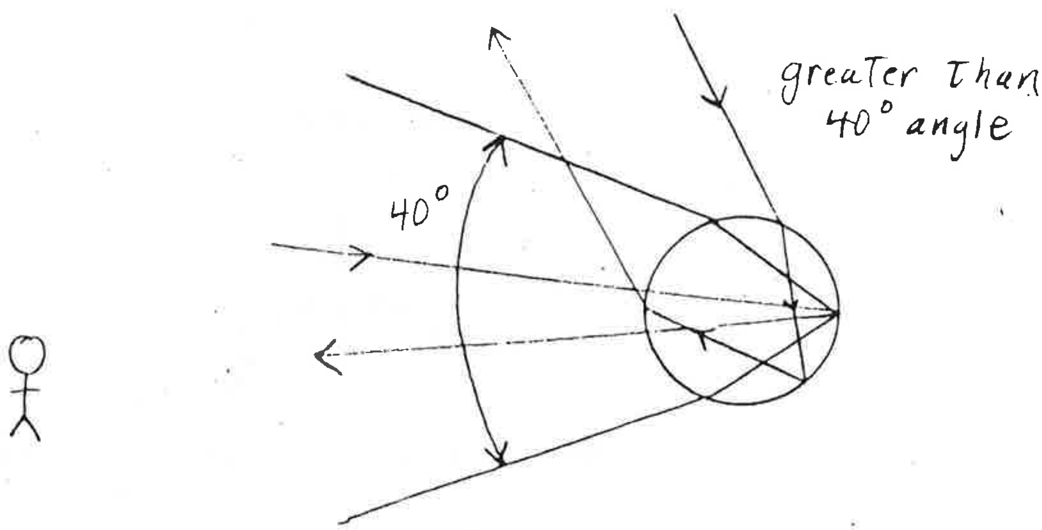


Figure 19.9 – Only light entering the drop at certain angles is reflected to you

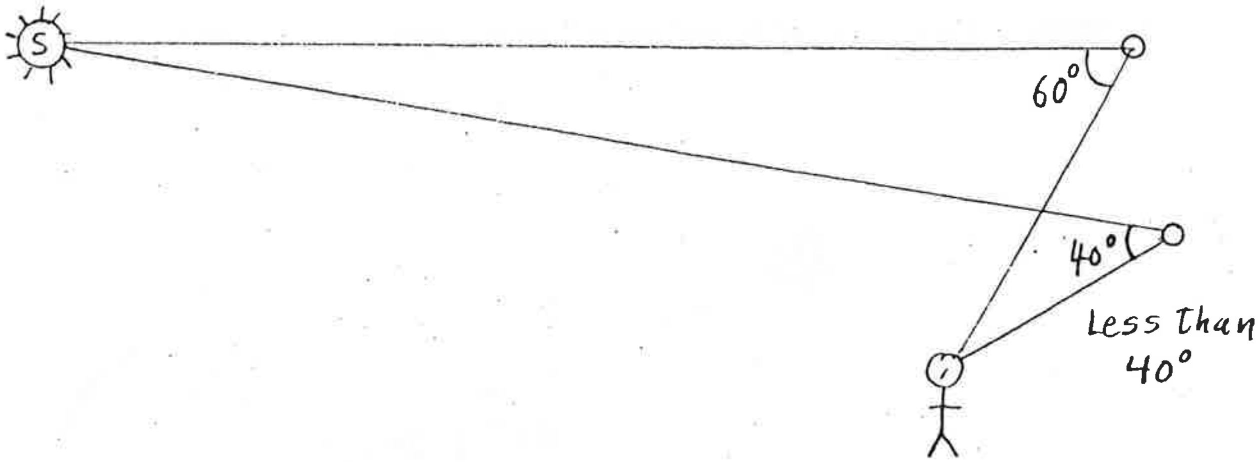


Figure 19.10 – What you see depends your angle relative to the sun and raindrop

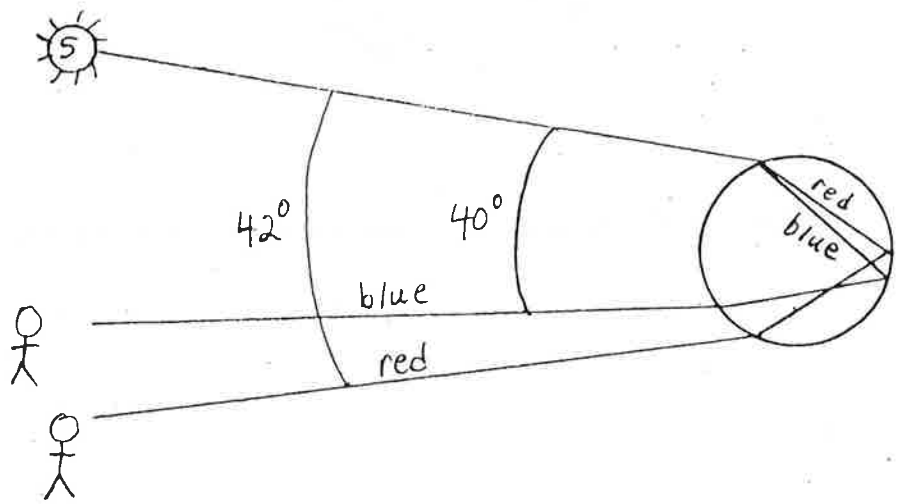


Figure 19.11 – Blue light forms a narrower cone than red

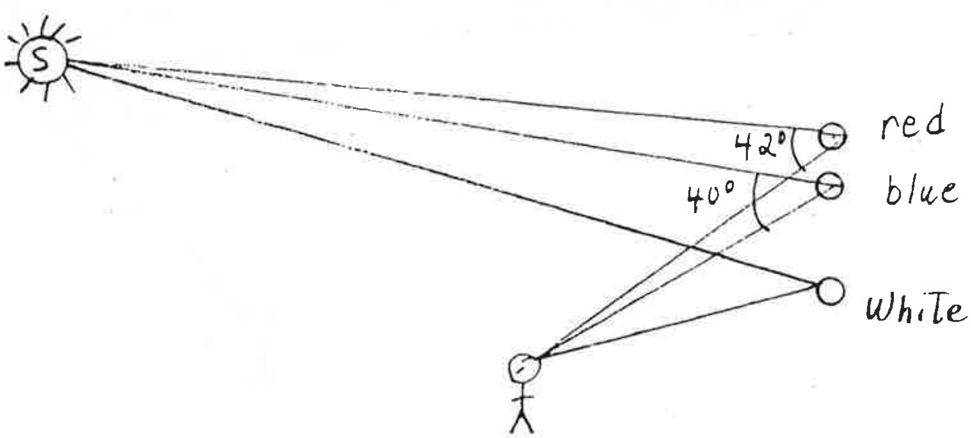


Figure 19.12 – You see different colors from different raindrops depending on your viewing angle

Secondary rainbows – caused by multiple reflections; dimmer and reversed.

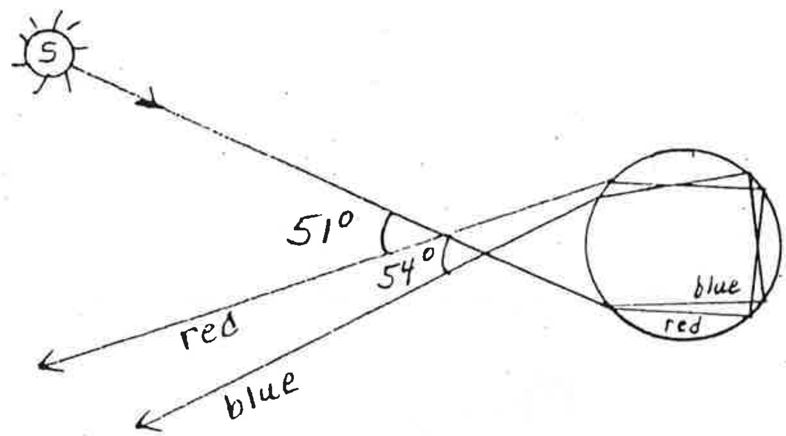


Figure 19.13 – Secondary rainbows are caused by multiple reflections

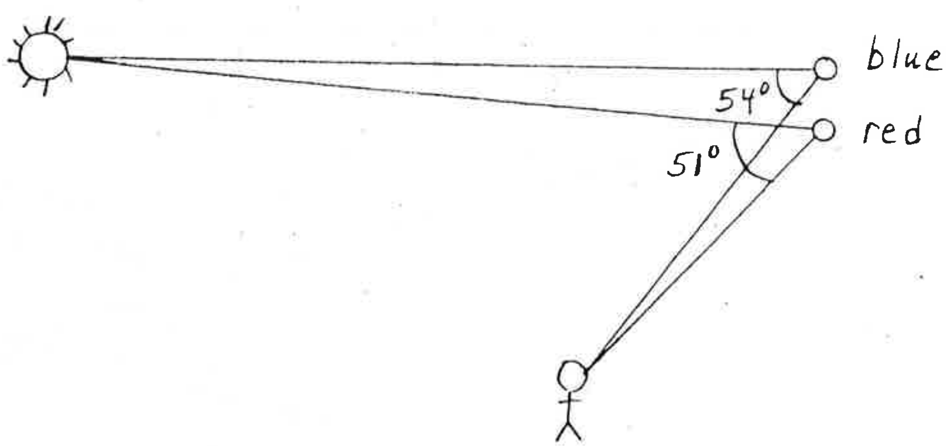


Figure 19.14 – Viewing angles for secondary rainbows

Soap bubbles, oil films

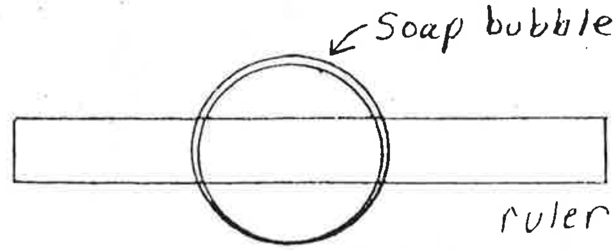


Figure 19.15 – Impractical method of measuring soap bubble thickness

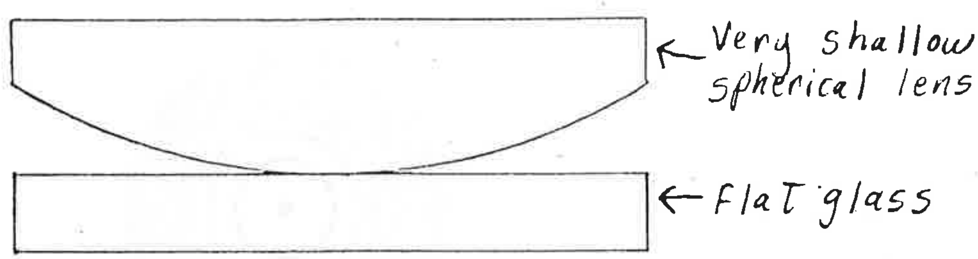


Figure 19.16 – Shallow spherical lens on a flat glass plate

Notes for Class 20

Reflection from Thin Films

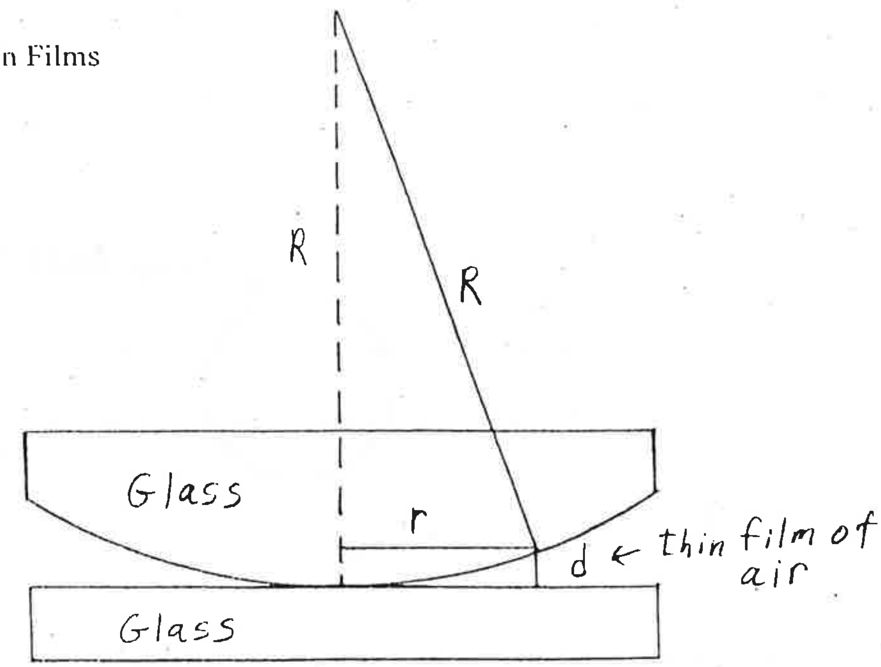


Figure 20.1 – Shallow spherical lens on a flat glass plate

Use the Pythagorean theorem: $R^2 = r^2 + (R - d)^2$

Newton invented the binomial theorem which shows that when R is much larger than r:

$d = r^2 / 2R$

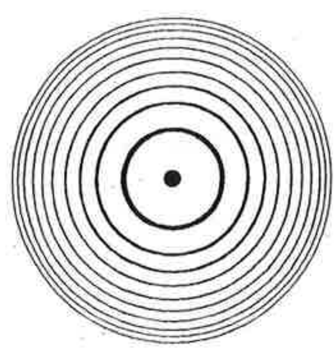


Figure 20.2 – Newton's rings

Waves can add, making a large amplitude or subtract, canceling each other out.

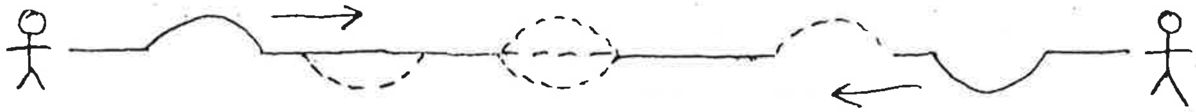


Figure 20.3 – Opposite waves cancel when they meet in the middle

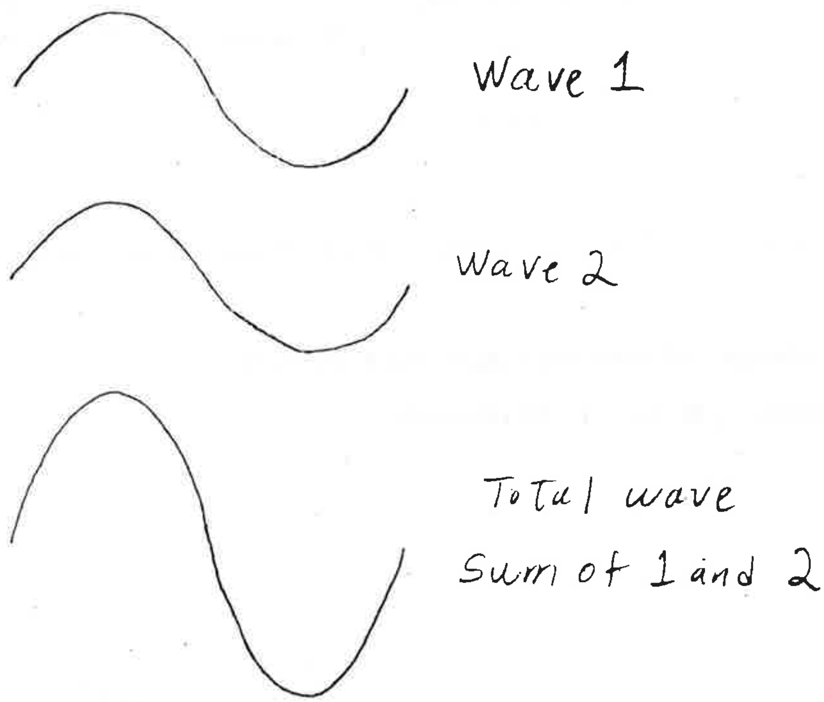


Figure 20.4 – Waves add when in phase

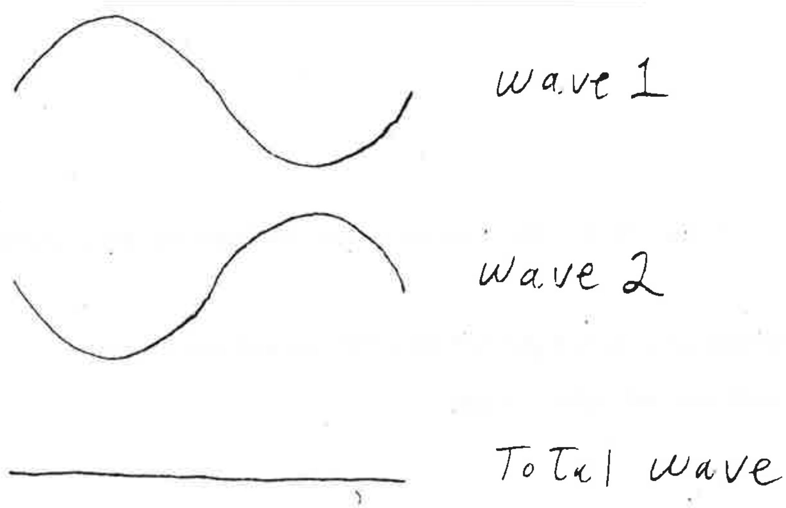


Figure 20.5 – Waves subtract when out of phase

Discovery of Newton's rings.

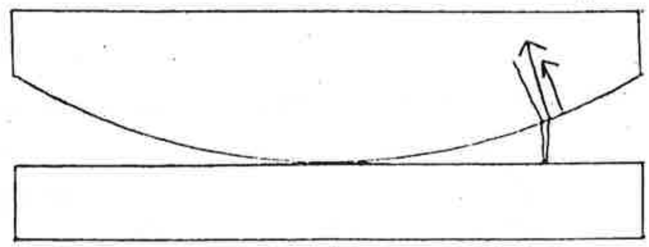


Figure 20.6 – Some of the light bounces off the lens and some off the bottom glass

Δd = change in d from one bright ring to the next

for yellow light: $\Delta d = 1 / 89{,}000$ inch

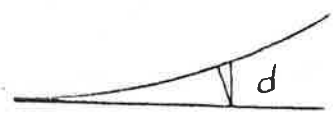


Figure 20.7 – The extra distance the light travels is equal to 2d

The wavelength of yellow light is 570×10^{-9} meters (nanometers)

blue light 430 nm, red light 650 nm.

Gravity

Newton studies circular motion

Figure 20.8 – Kepler thought force was in the direction of motion

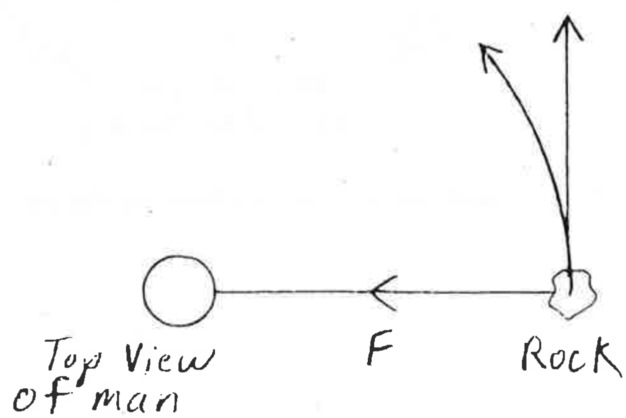


Figure 20.9 – To keep the rock moving in a circle, you have to keep tension on the rope

Circular motion is caused by an attractive force pulling the body toward the center.

Newton's mathematical analysis of circular motion

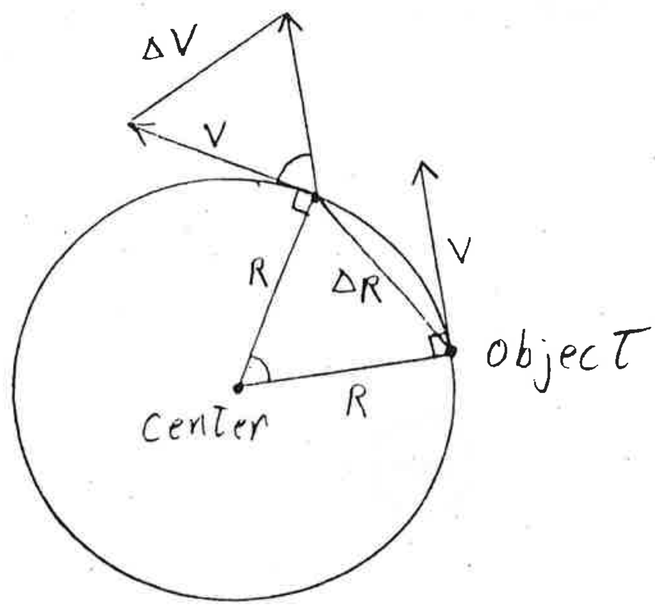


Figure 20.10 – Vector representation of circular motion

ΔR = change in position of the object

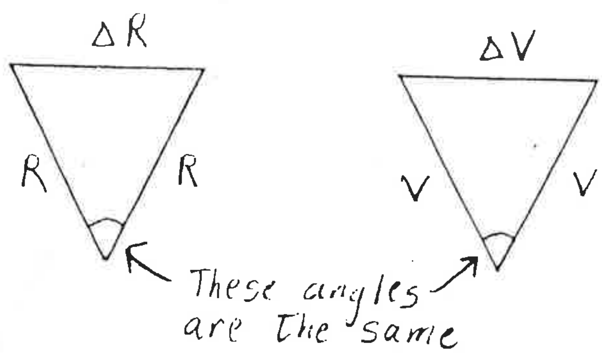


Figure 20.11 – Radius and velocity vectors form similar isosceles triangles

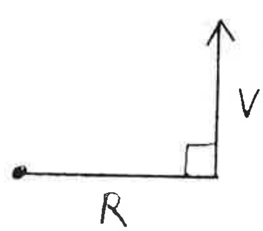


Figure 20.9 – Vectors R and v rotate together but don't move relative to each other

So: $\Delta R / R = \Delta v / v$

Notes for Class 21

Review: Newton's rings, wave theory of light

Analysis of circular motion

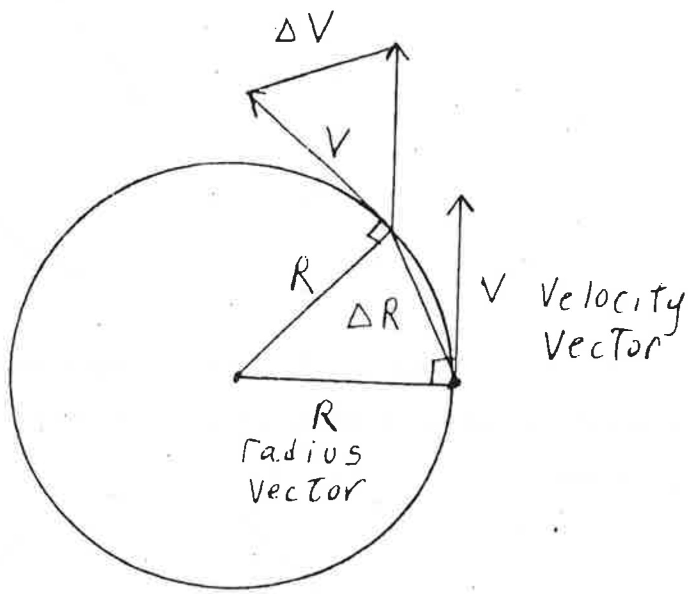


Figure 21.1 – Vector representation of circular motion

ΔR = change in radius vector

ΔV = change in velocity vector

ΔR must equal ΔV because they rotate together

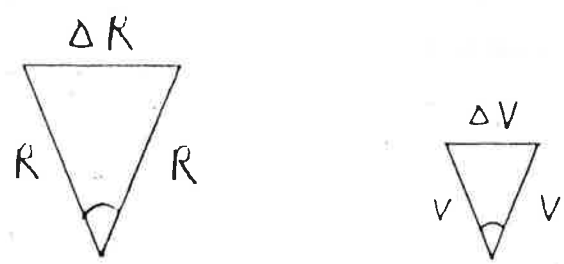


Figure 21.2 – Radius and velocity vectors form similar isosceles triangles

Radius and velocity vectors create two similar isosceles triangles

$\Delta R / R = \Delta V / V$

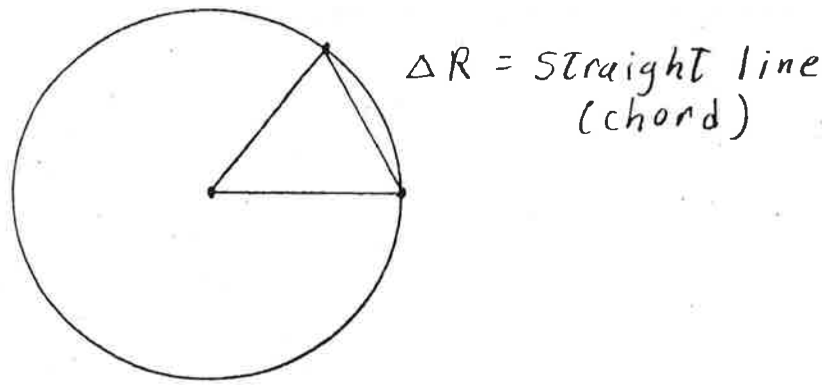


Figure 21.3 – ΔR is a straight line or "chord"

V = distance traveled / time where distance traveled is the length of the arc

= arc length / Δt

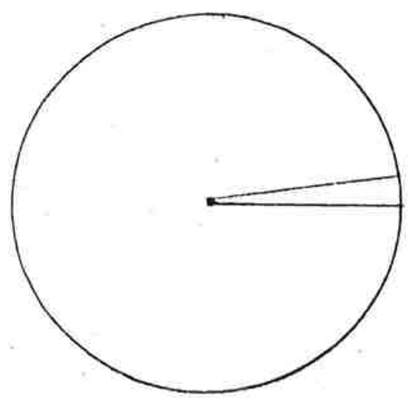


Figure 21.4 – Small arcs are equal to the chord

$V = \Delta R / \Delta t$ (for small arcs)

$\Delta R = V\Delta t$

$\Delta R / R = \Delta V / V$

$V\Delta t / R = \Delta V / V$

$\Delta V = (V^2 / R)\, \Delta t$

$\Delta V / \Delta t = V^2 / R$

The rate that position changes with time is called velocity

$\Delta V / \Delta t$ is the rate that velocity changes with time called acceleration.

so: $a = V^2 / R$

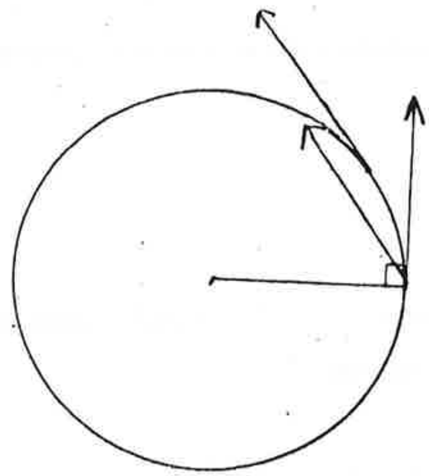


Figure 21.5 – Change in the velocity vector is toward the center

Acceleration is directed inward toward the center of the circle.

$a = V^2 / R$

Force: $F \propto a$

$F \propto V^2 / R$ (for uniform circular motion)

Newton knows the planets travel in approximate circles around the sun.

Kepler's 3rd law: $R^3 / T^2 = \text{constant}$

$V = \text{circumference of orbit} / \text{Period of orbit} = 2\pi R / T$

$T = 2\pi R / V$

$T^2 = 4\pi^2 R^2 / V^2$

Substitute into Kepler's 3rd law:

$R^3 / 4\pi^2 R^2 / V^2 = \text{constant}$

$R^3 V^2 / 4\pi^2 R^2 = \text{constant}$

$RV^2 / 4\pi^2 = \text{constant}$

$RV^2 = \text{constant}'$ (a different constant so constant prime)

$V^2 = \text{constant} / R$

Substitute constant/R for V^2 in the proportion: $F \propto V^2 / R$

Force $\propto$ constant / R^2

Force is proportional to the inverse of the distance squared!

Summary:

The attractive force of the sun on the planets is inversly proportional to the square of the distance.

Force ∝ constant / R^2

Galileo discovered:

In free fall a body's speed increases by 32ft/sec each second. In other words, the body has a constant acceleration of 32ft/sec/sec.

If acceleration doubled and radius doubled then a ∝ R so F ∝ R

The moon and the apple:

Acceleration of the apple: 32ft/sec^2

Acceleration of the moon: V^2 / R_{moon} = .1 inches/sec

Apple's acceleration / Moon's acceleration

$= (1 / RE^2) / (1 / R_m^2) = (1 / R_E^2) / (1 / (R_E)^2) = 60^2 = 3600$

32(12) / .1 = (32)(32)(10) = 3840 very close!

Problems with the idea:

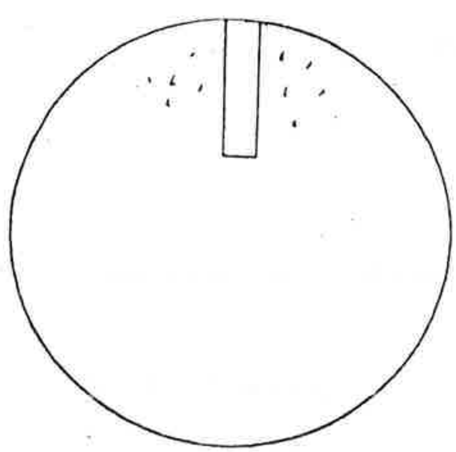


Figure 21.6 – Is gravity stronger in a deep hole?

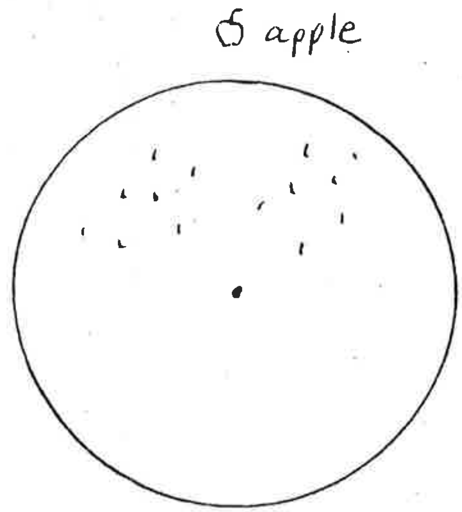


Figure 21.7 – Each piece of Earth is at a different distance from the apple

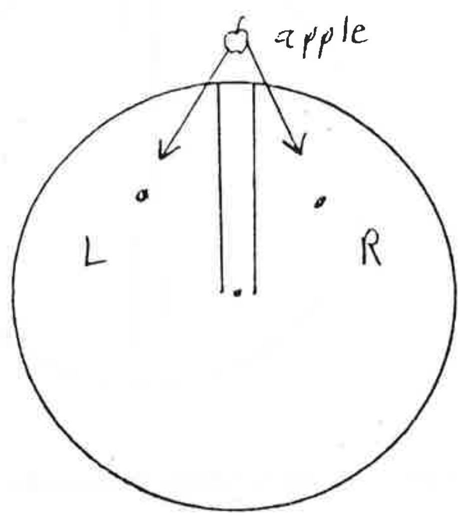


Figure 21.8 – From symmetry left and right forces cancel out

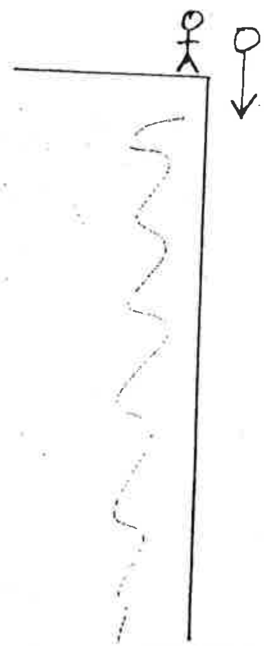


Figure 21.9 – The sideways pull of the cliff is small compared to the massive Earth

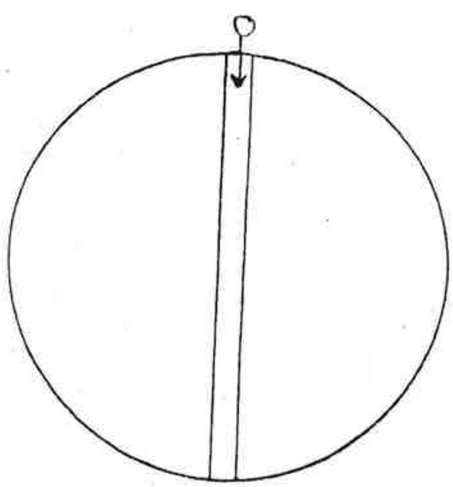


Figure 21.10 – An apple falling through the Earth to China

Newton is not 100% sure because he assumed that the Earth attracts as if all the mass is in the center.

<u>Notes for Class 22</u>

Review: Newton's discovery of gravity

Reasons for Newton's uncertainty:

1. He has <u>assumed</u> that the Earth attracts the apple as if all the Earth's mass is at the center.
2. He has approximated the orbits of the planets and the moon as circles at constant speed.
3. His moon/apple calculation was in error by about 10%.

Isaac Barrow

1669 – Newton becomes math professor at Trinity College.

1672 – Newton presents his theory of colors. He gets a hostile reaction, and retreats into silence.

1684 – Halley visits Newton

1687 – Newton publishes "The Mathematical Principles of Natural Philosophy" ("Principia")

Newton's laws of motion

Ancient Greeks: $V \propto F / R$

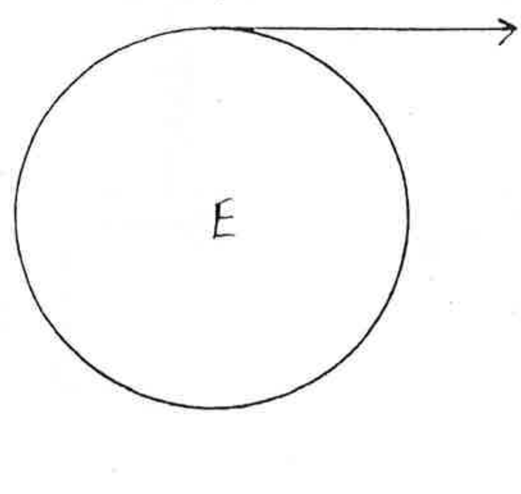


Figure 22.1 – Extend the horizontal indefinitely

Newton's 1st law:

"Every body continues in its state of rest or of uniform motion in a straight line unless it is compelled to change that state by forces impressed on it."

Background for 2nd law:

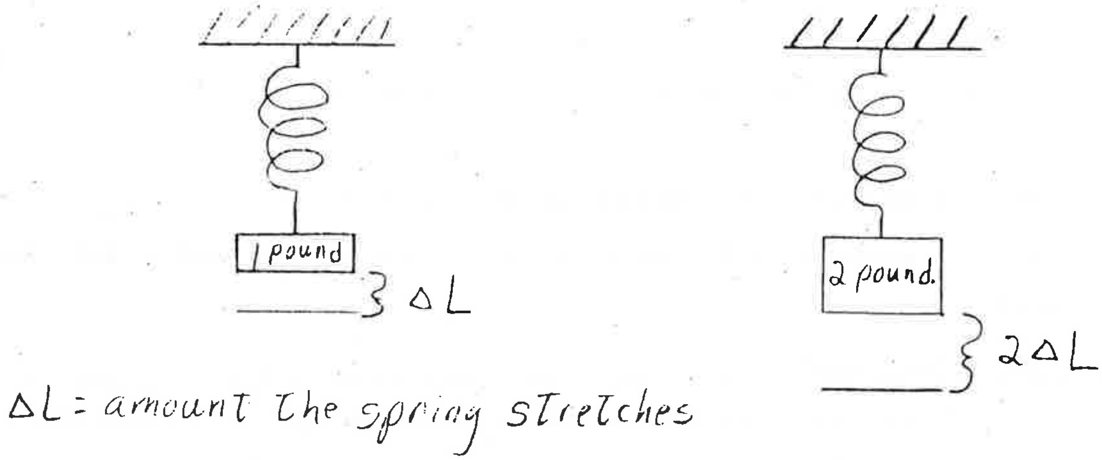


Figure 22.2 – Hooke's experiment with springs

Hooke's law of springs: $F \alpha \Delta L$

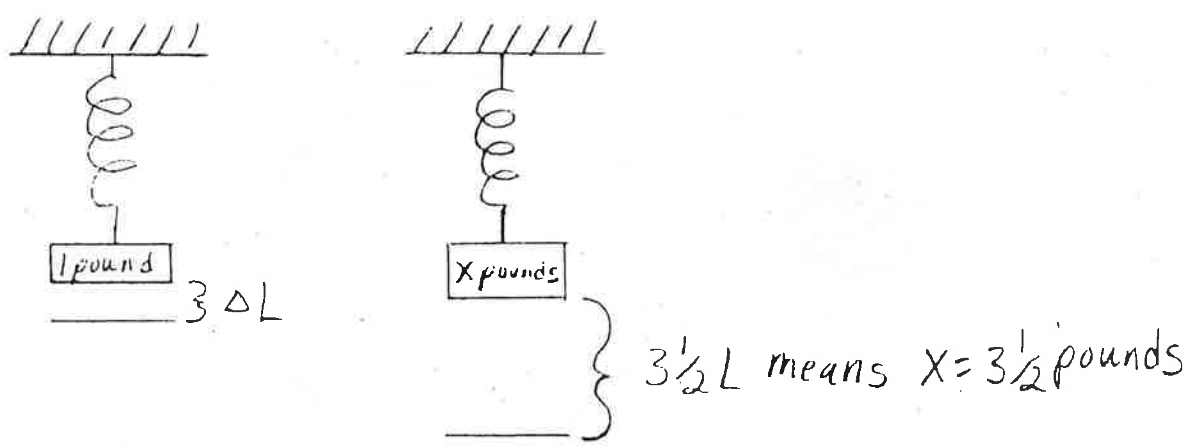


Figure 22.3 – Hooke's law used to measure forces

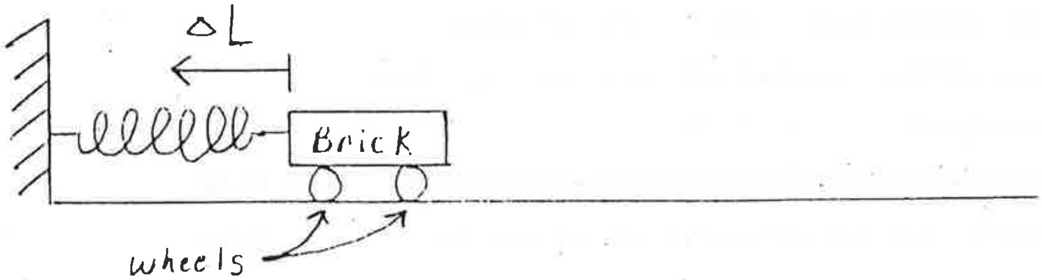


Figure 22.4 – Compress the spring ΔL, then let go. Measure the velocity.

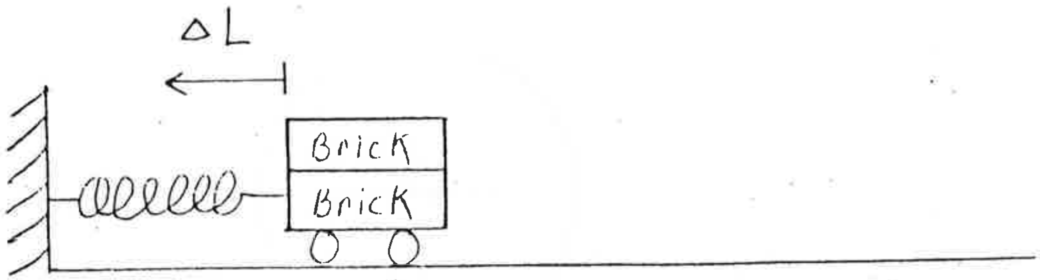


Figure 22.5 – Double the mass and repeat experiment in figure 22.4.

$\Delta V = a = F / M$

Newton's 2nd law:

The applied force is equal to the body's mass multiplied by its acceleration. ($F = ma$)

Newton's Mathematics

Xeno's paradox

$S = \frac{1}{2} + \frac{1}{4} + \frac{1}{8} + \frac{1}{16} + \ldots$

Multiply the sum by ½

$\frac{1}{2} S = \frac{1}{4} + \frac{1}{8} + \frac{1}{16} + \frac{1}{32} + \ldots$

Now subtract 2nd equation from the 1st

$\frac{1}{2} S = \frac{1}{2}$

So: $S = 1$

Notes for Class 23

Newton wants to be more clear on laws of motion

Newton's 1st law – constant velocity in absence of force.

Ancient Greeks: $V = F / R$

First problem: Greeks should have had a instead of V: $a = F / R$

Second problem: resistance is internal not external: $a = F / m$

Newton's third law:

"The mutual actions of two bodies on each other are always equal in magnitude and opposite in direction."

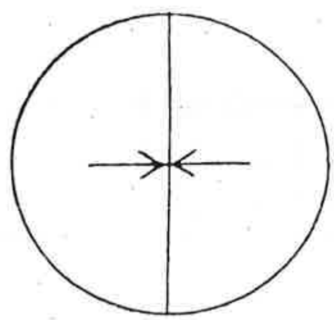


Figure 23.1 – Consider the Earth divided into 2 halves

Newton considered colliding pendulums

$F = ma$

$m_1 \Delta V_1 = m_2 \Delta V_2$

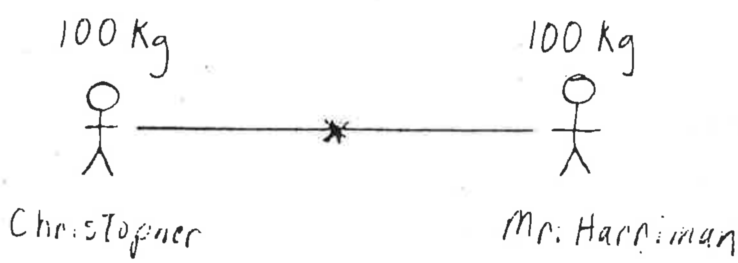


Figure 23.2 – Thought experiment: two people of equal mass in space with a rope

1687 – The start of modern physics

Back to gravitation

$F_g \propto 1 / R^2$ $F_g = ? / R^2$ (F_g is the force of gravity)

acceleration due to gravity = $g = F_g / m$ = contstant = 32 ft/sec^2

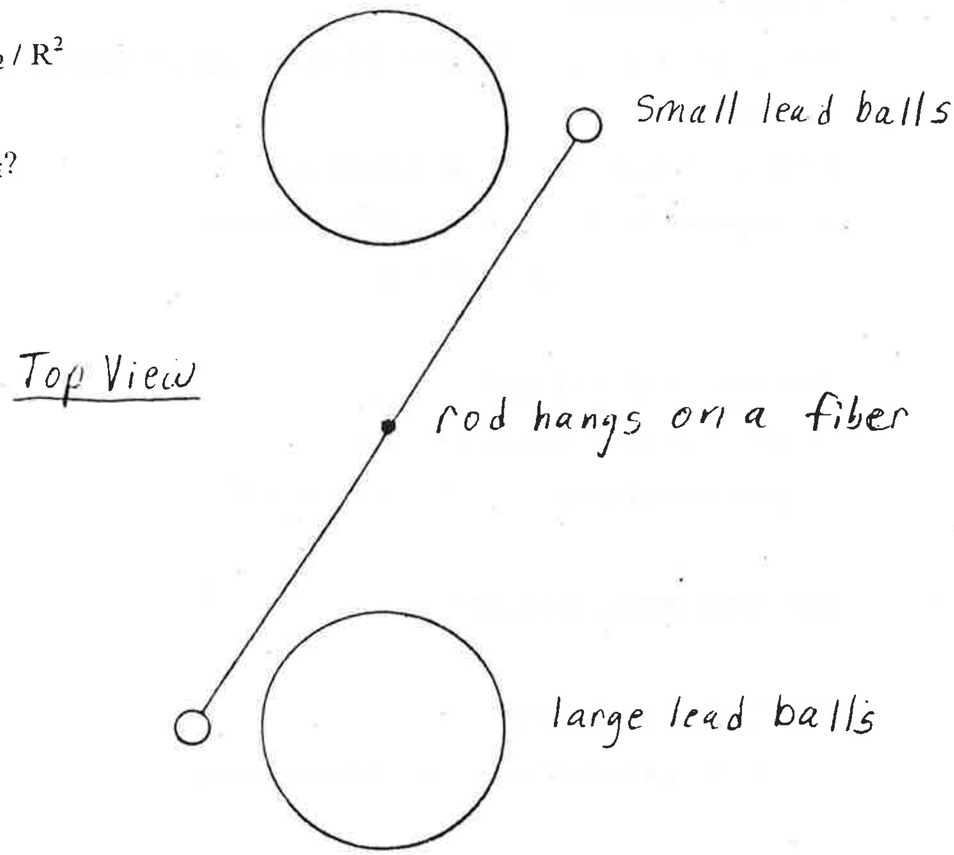
$F = (?)m / R^2 = ?Mm / R^2$

$F_g = (?)m_1m_2 / R^2 = G\ m_1m_2 / R^2$

32 ft/sec^2 = GM_E / R^2

How do you find G <u>and</u> M_E?

Henry Cavendish (1798)



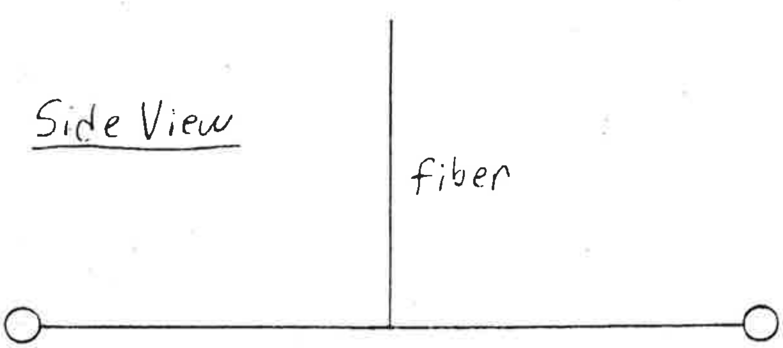


Figure 23.2 – Cavendish's experiment to find the universal gravitational constant

$F = G m_1 m_2 / R^2$ Units: mass (kilograms), distance (meters), time (seconds)

$G = 6.67 / 100,000,000,000 = 6.67 \times 10^{-11}$

Mass of Earth = 6×10^{24}

Mass of the sun = 2×10^{30}

Thought experiment:

Two people in space. 100 kg each, 10 meters apart. How long will it take for them to come together?

$F = m_1 a = G m_1 m_2 / R^2$ m_1 cancels out

acceleration of m_1: $a = 6.67 \times 10^{-11} (100) / 10^2$

$a = 6.67 \times 10^{-11}$

Two different ideas of mass:

1. resistance to acceleration $F = ma$
2. gravitational mass $F = G m_1 m_2 / R^2$

Are the two masses the same?

$T^2 \propto L$ (for a pendulum)

$T^2 = 4\pi^2 (L / g)$(inertial mass / gravitational mass)

Notes for Class 24

Newton has universal gravitation and laws of motion.

Newton revisits moon and apple calculation.

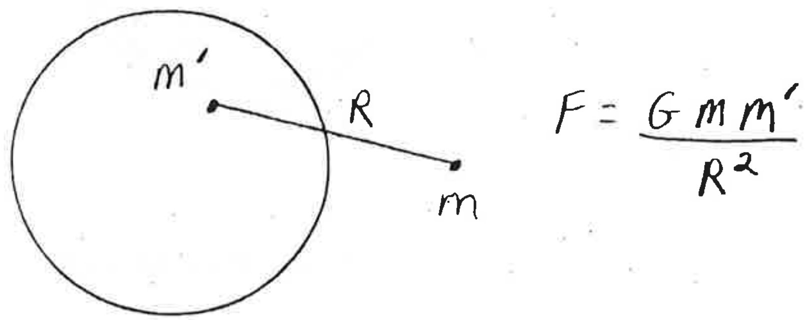


Figure 24.1 – Gravitational attraction of a piece of the Earth not at the center

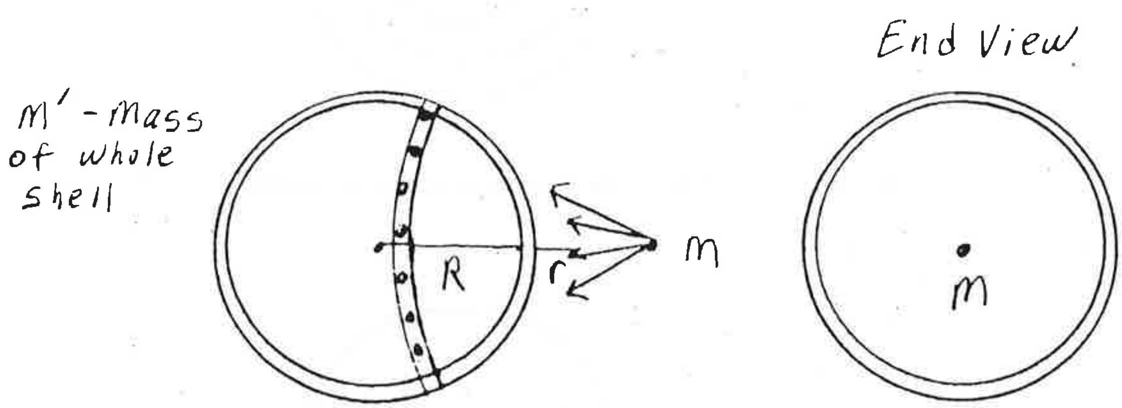


Figure 24.2 – The Earth split into shells and the shells split into rings

Integral calculus – break up a continuum into finite pieces then sum the pieces

Attraction of a spherical shell:

$F = GMm / R^2 = GMm / (R+r)^2$

R is the distance from mass to center of spherical shell

There is no force on m when it is inside the shell

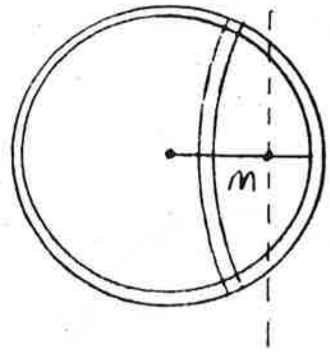


Figure 24.3 –A mass inside the shell

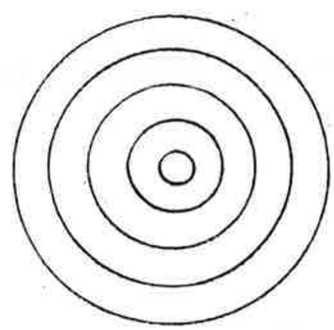


Figure 24.4 – The Earth's mass as a sum of shells

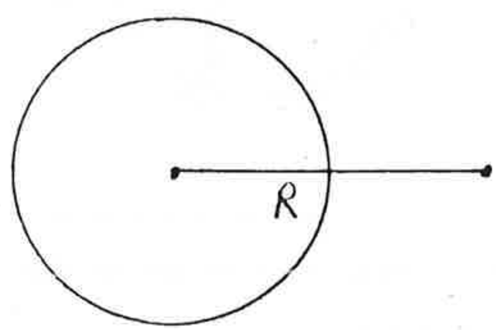


Figure 24.5 – Spherical Earth pulling on a mass outside it

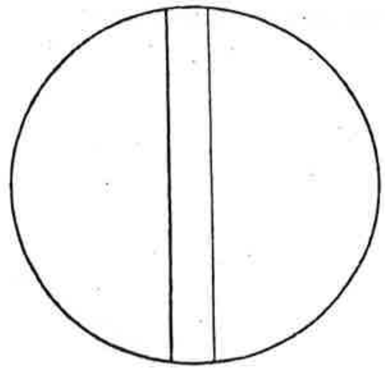


Figure 24.6 – Dropping an apple through the Earth revisited

Newton explains Kepler's laws

Kepler's law of areas

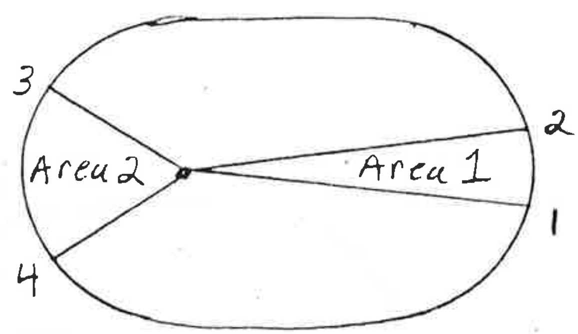


Figure 24.7 – The planets sweep out equal areas in equal times

Rotational motion

R = distance from the center

Vt = tangential speed

RVt = constant

If you increase R you must increase V, if you decrease R you must decrease V

Kepler's law of elliptical orbits

Conic sections: ellipse, parabola, hyperbola

Newton starts with: $F = ma$ and $F = GMm / R^2$

and shows: $a = GM/R$

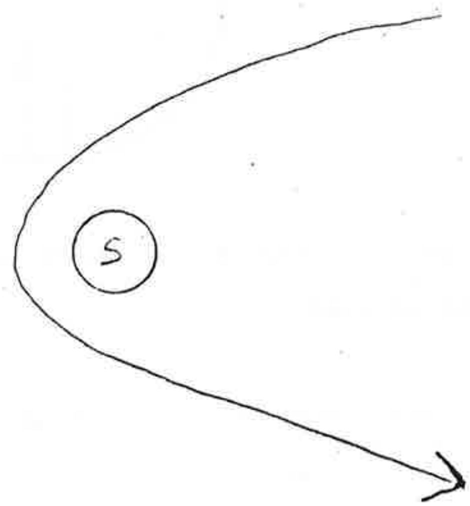


Figure 24.8 – A fast-moving comet travels in a parabola or hyperbola

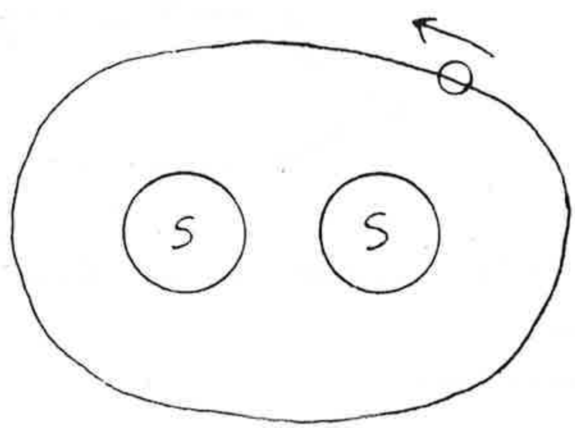


Figure 24.9 – A binary sun system

Notes for Class 25

Inverse square law necessitates all objects moving in conic sections.

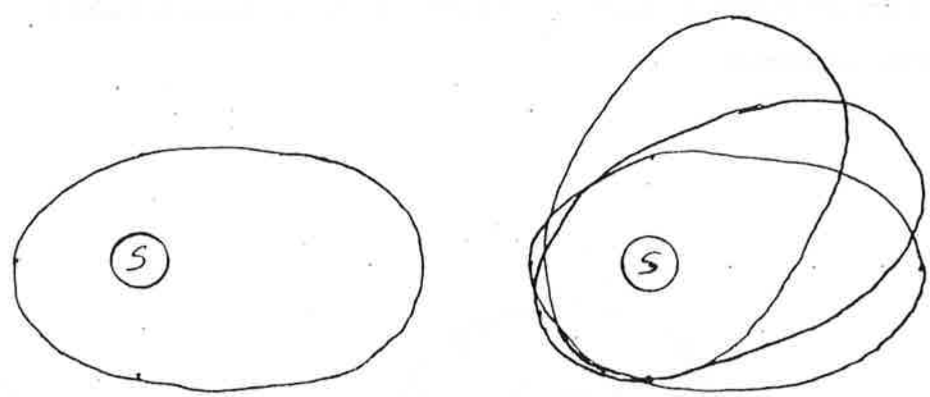


Figure 25.1 – Fixed vs. rotating major axis

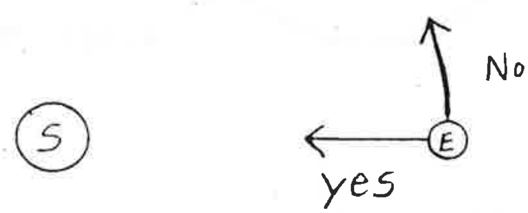


Figure 25.2 – Purely attractive force, no tangential component

Newton explains Kepler's 3rd law: R^2 / T^3 = constant

R is the average of closest and farthest points: $R = r_1 + r_2 / 2$

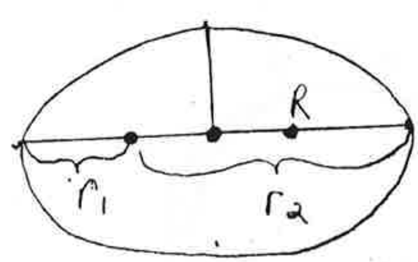


Figure 25.3 – R is the average of r_1 and r_2

Newton could calculate the constant in Kepler's 3rd law for any system

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

M = mass of large object, G = Universal gravitational constant, $4\pi^2$ = constant

Ocean tides

1. High tide (or low tide) occurs almost twice a day. (actually 25 hours)
2. Tides are bigger during full and new moon and smaller during half moon.
3. Tides are bigger in October and March; smaller in December and June.

Newton's approach

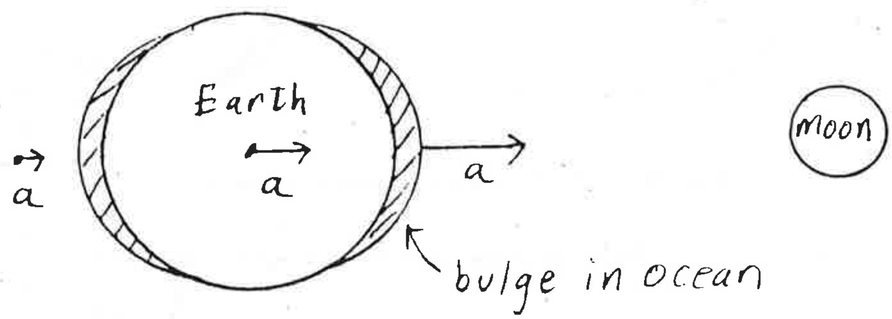


Figure 25.4 – Acceleration varies with distance from the moon

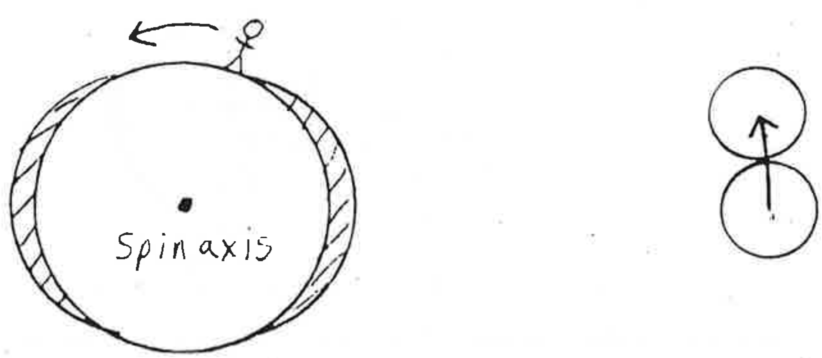


Figure 25.5 – The moon moves about 1 hour in a 24 hour period

Figure 25.6 – The moon's speed changes because of the sun's gravity

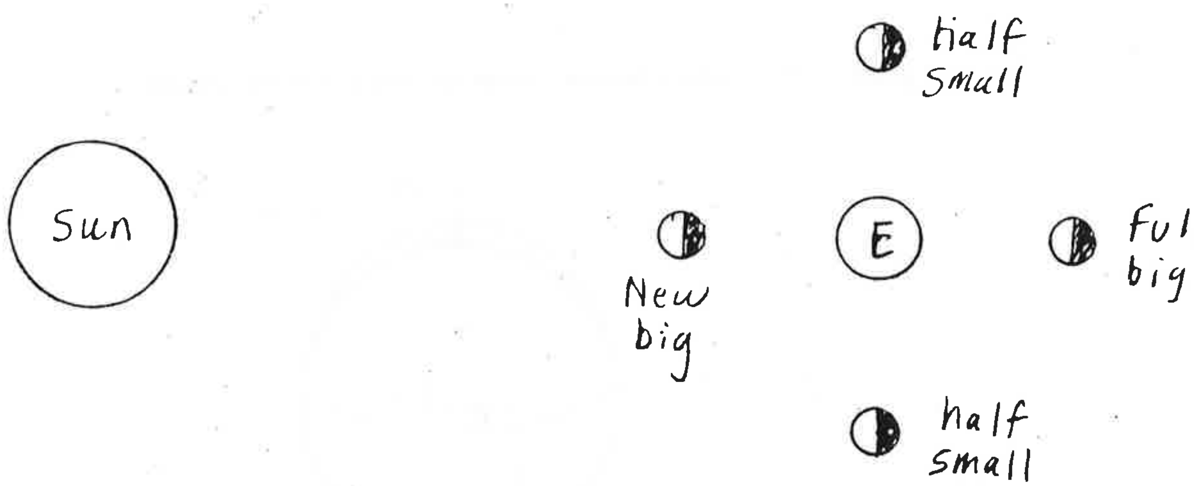


Figure 25.7 – Tides are bigger during full and new moon and smaller during half moon

Figure 25.8 – Sun tide and moon tide

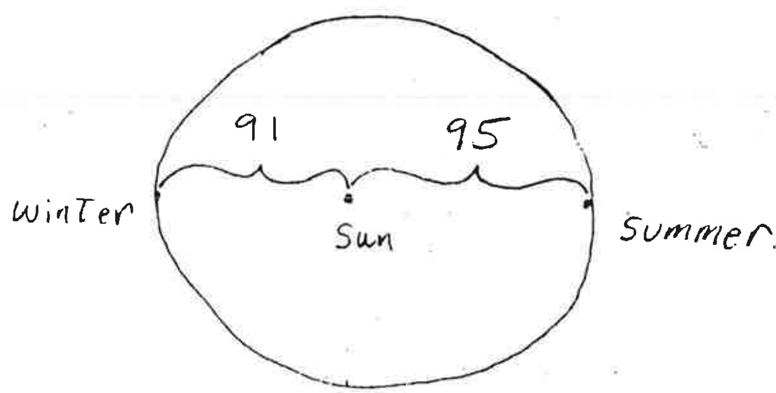


Figure 25.9 – Earth's distance from the sun varies by season

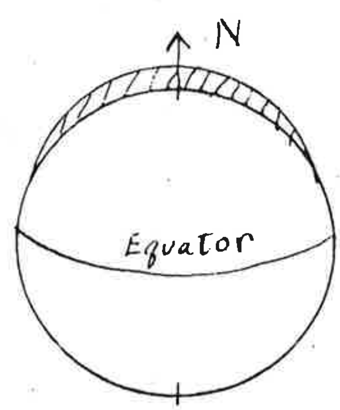


Figure 25.10 – Consider the moon at the North pole

Figure 25.11 – Earth's spin axis is not perpendicular to its orbital plane

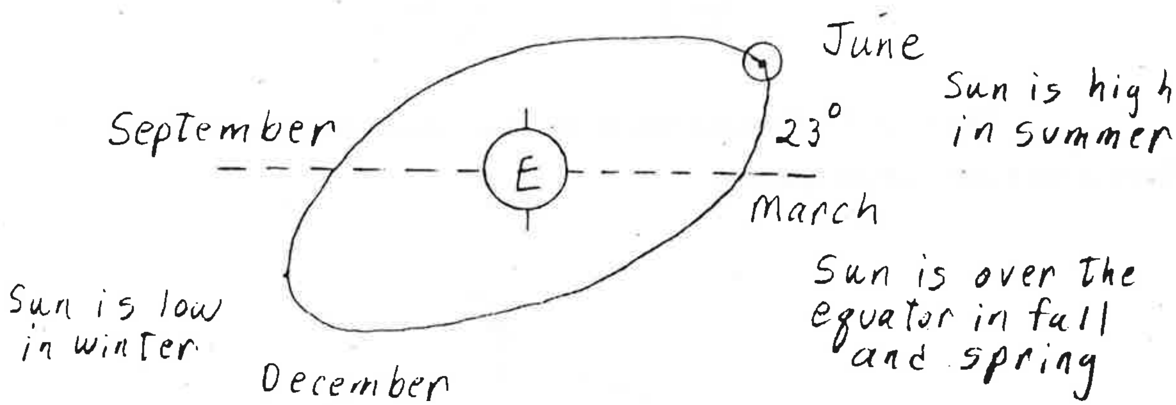


Figure 25.12 – Geocentric view of moon's effect on tides

Notes for Class 26

Revisit tides

Figure 26.1 – Bulges add during full and new moons

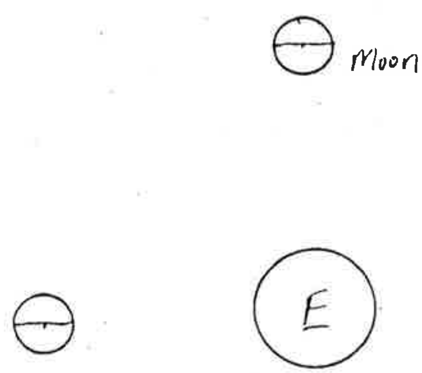


Figure 26.2 – The same side of the moon always faces Earth

Shape of the Earth – oblate spheroid

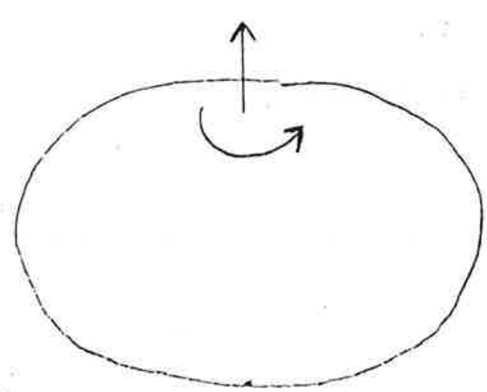


Figure 26.3 – Planets bulge at the equator

$a = V^2 / R$

if speed is small (near pole) then a is small

if speed is large (near equator) then a is large

For Earth: C ≈ 25,000 miles, so speed is ≈ 1000 miles per hour

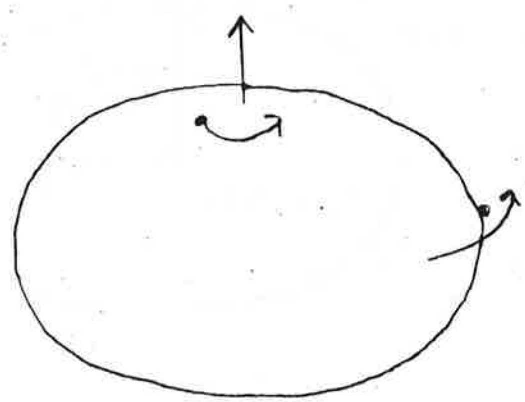


Figure 26.4 – A point on the equator spins faster than one near the pole

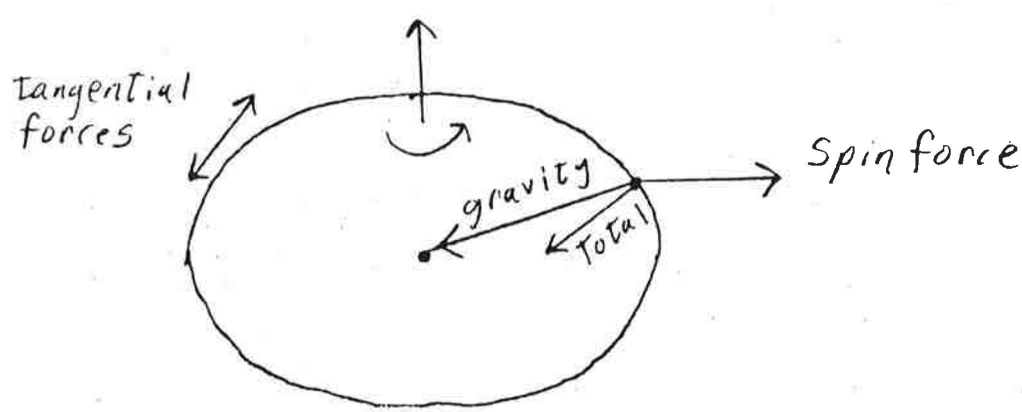


Figure 26.5 – Forces that cause planets to bulge

equatorial radius of Earth = 3963 miles

polar radius of Earth = 3950 miles

so equatorial bulge is 13 miles

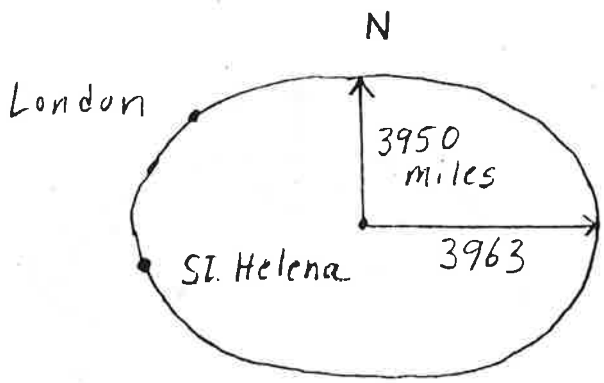


Figure 26.6 – Size of the equatorial bulge of Earth

Gravitational acceleration:

equator: 32.09 ft / sec^2

poles: 32.26 ft / sec^2

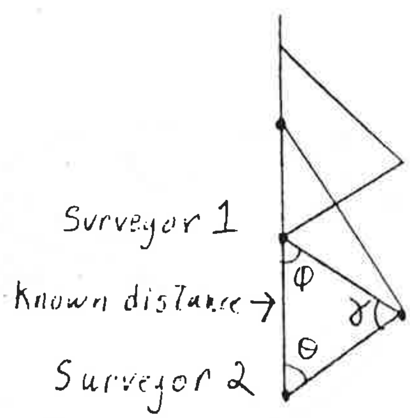


Figure 26.7 – Measuring by triangulation

Precession of the Earth

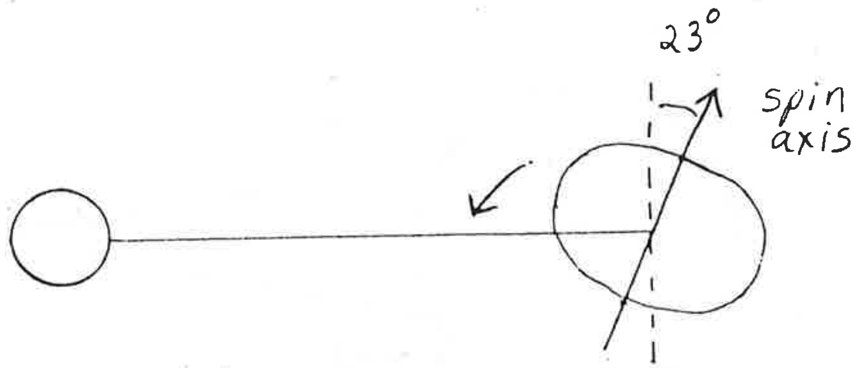


Figure 26.8 – Precession is caused by the bulge

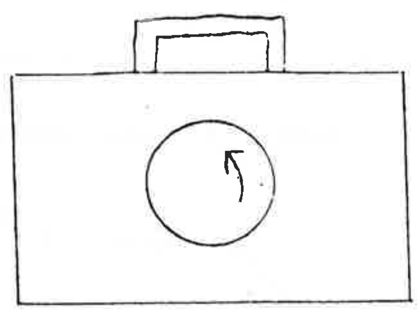


Figure 26.9 – Feynman's suitcase

Notes for Class 27

Still on Principia

In 1577 Tycho observes a comet

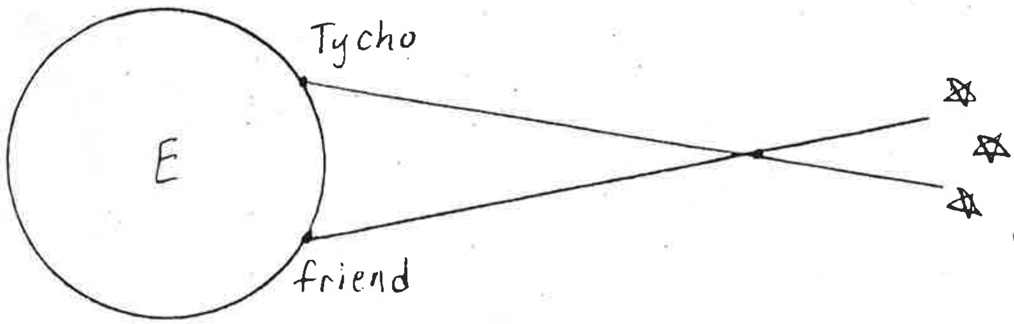


Figure 27.1 – Parallax of the moon

Comets

Two comets appeared in Newton's time: 1680 and Halley's in 1682

Flamsteed and Halley worked out their orbits

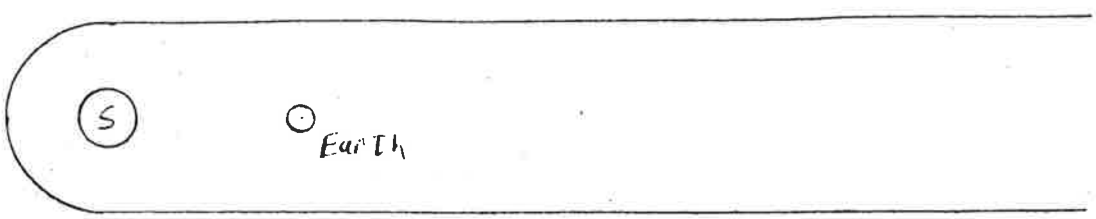


Figure 27.2 – Halley's comet

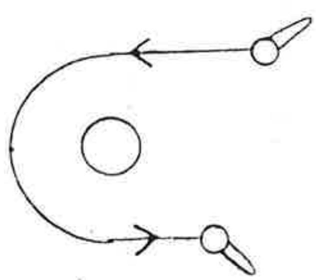


Figure 27.3 – Comet's tail points away from the sun

Absolute distances in the solar system

1672: time of closest approach between Earth and Mars

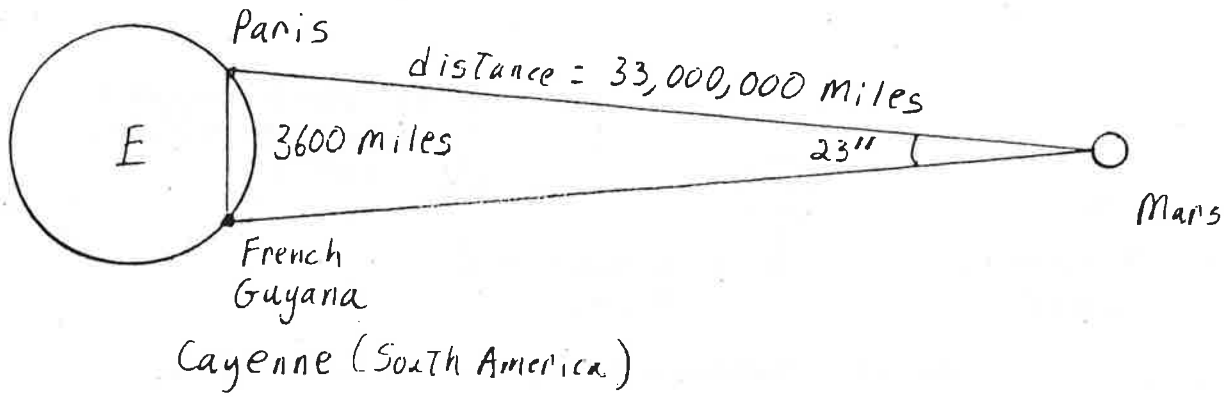


Figure 27.4 – Parallax of Mars

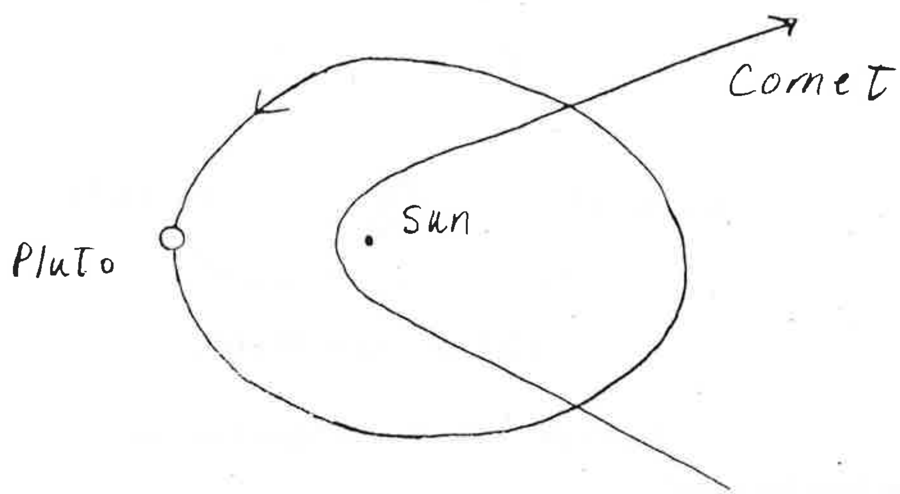


Figure 27.5 – Comets travel in any direction

Notes for Class 28

Light and astronomy Olaus Roemer – Danish astronomer

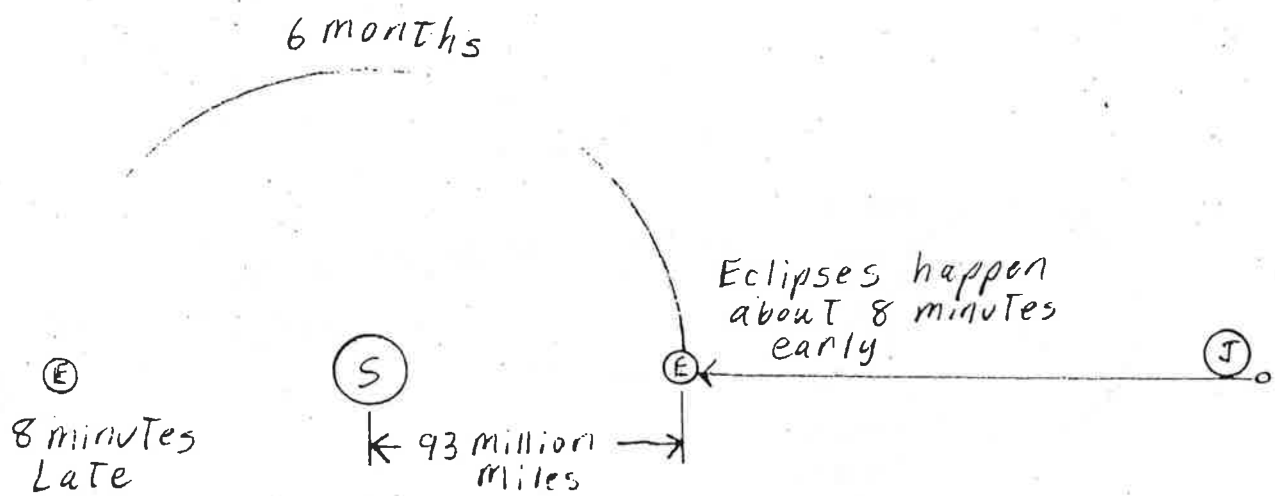


Figure 28.1 – Variation in the eclipse times of Jupiter's moons

Speed of light = 186,000 miles / sec discovered in 1675

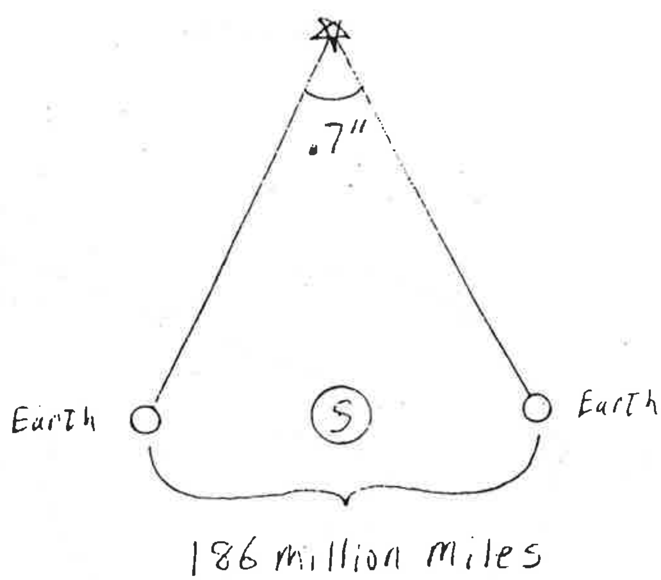


Figure 28.2 – Parallax of Alpha Centauri

William Herschel (1780's)

- Discovered the next planet (Uranus)
- A great telescope builder. Built a 4 foot reflecting telescope that magnified 6000x.

Uranus: R = 19.2 x Earth's radius of orbit, T = 84 years

Notes for Class 29

Uranus, Neptune, Pluto

Evangelista Torricelli (1643)

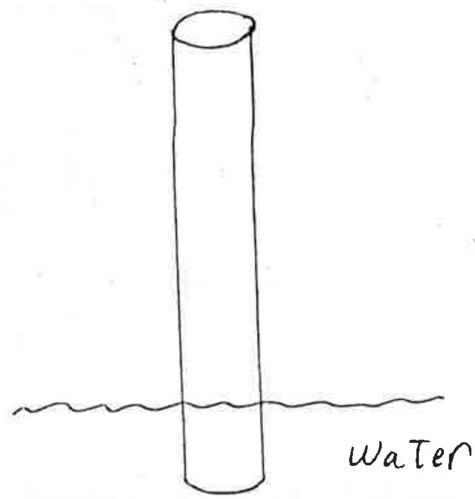


Figure 29.1 – Why does water rise in a straw?

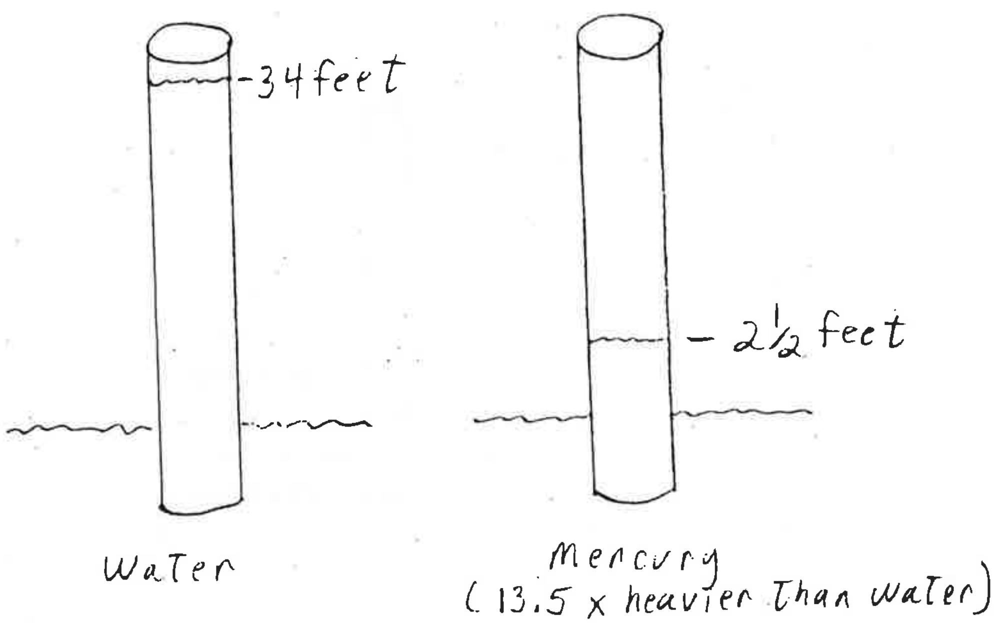


Figure 29.2 – Air pressure lifts equal weights of water and mercury

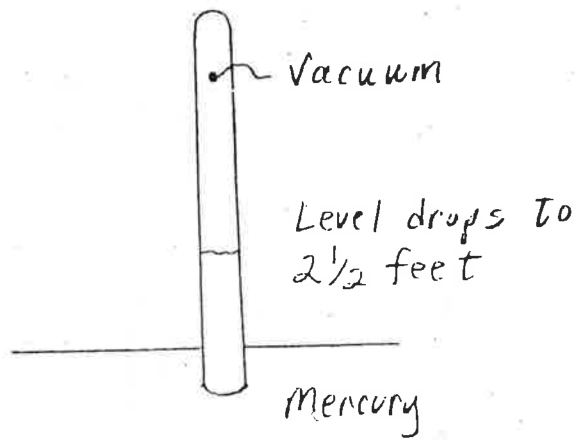


Figure 29.3 – Six-foot glass tube filled with mercury

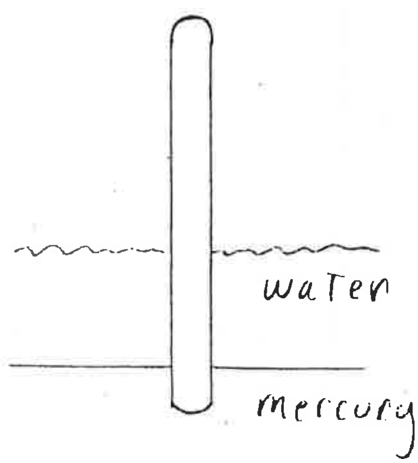


Figure 29.4 – Water fills the tube

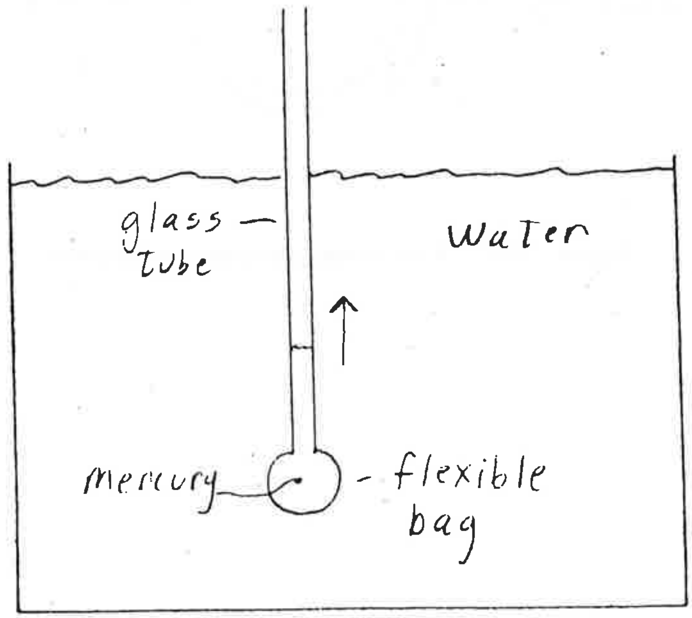


Figure 29.5 – Pascal's barometer

1648 Pascal proved that the barometer reading decreased from 30 to 27 inches of mercury in going from sea level to 850 meters.

Otto Von Guericke

- Greatly improved design of air pumps.
- Determined the density of air ≈ $^1/_{800}$ (density of water)
- Animals can't breathe without air
- Candles can't burn without air
- No sound in a vacuum
- Light can pass through a vacuum

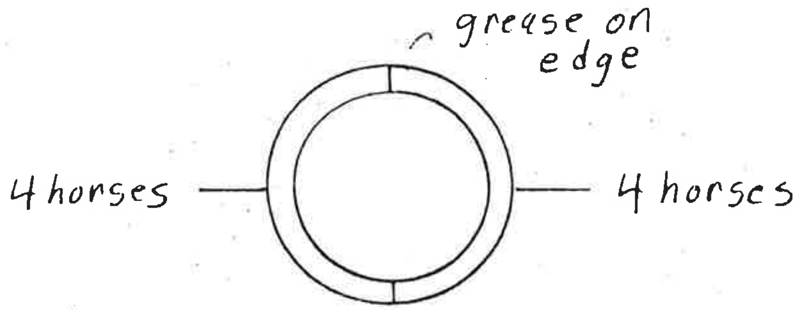


Figure 29.6 – Von Guericke's demonstration

Robert Boyle

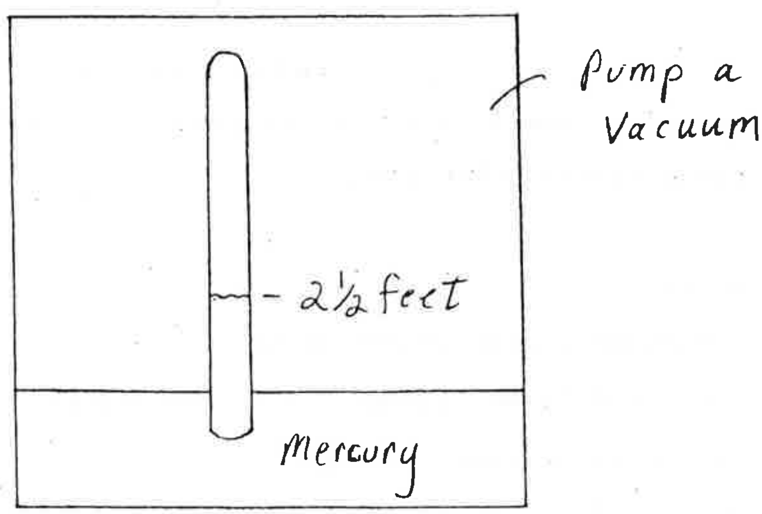


Figure 29.7 – Boyle's experiment

Notes for Class 30

Robert Boyle (1660's)

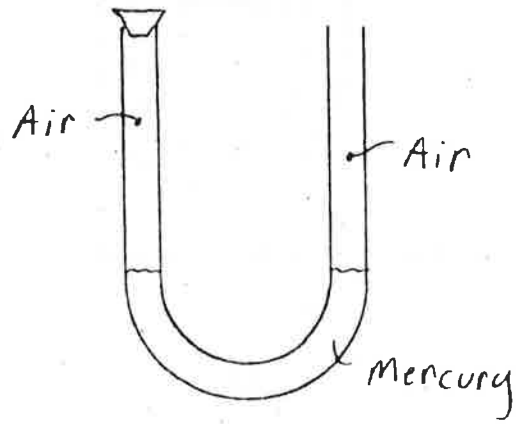


Figure 30.1 – Mercury in a tube

1. Fill the bottom of a u-shaped tube with mercury.
2. Close one end and pour more mercury into the other side.

PV = constant

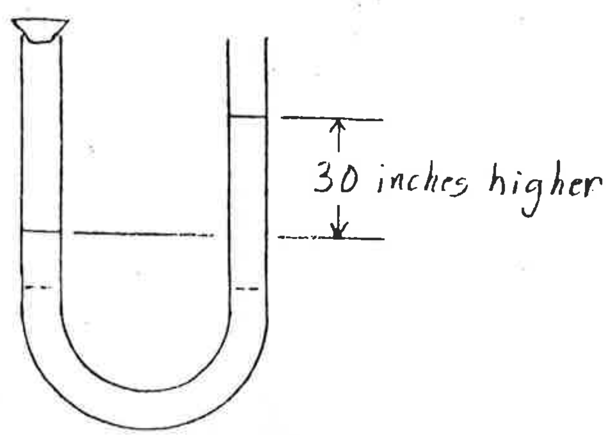


Figure 30.2 – Pressure doubles while volume is halved

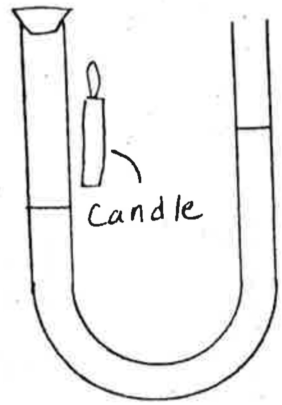


Figure 30.3 – Heat is relevant

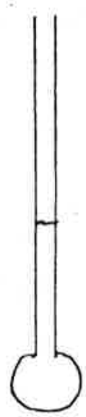


Figure 30.4 – Galileo's water thermometer

Daniel Fahrenheit (1714) – invented the thermometer

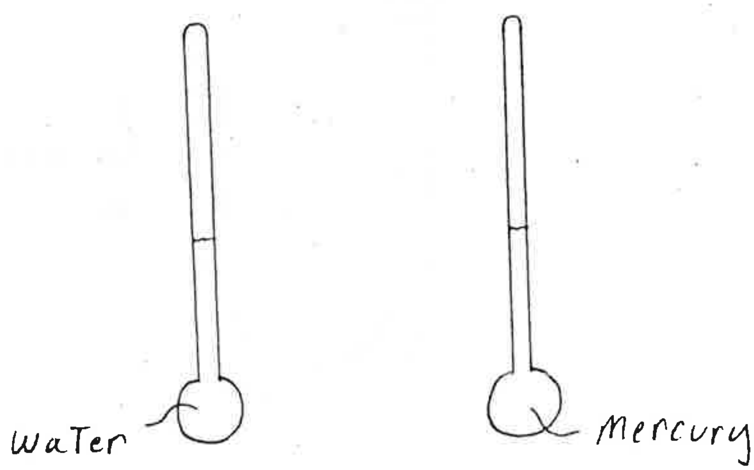


Figure 30.5 – Replace water with mercury

Fahrenheit's scale

Freezing point of ammonia = 0°F

Freezing point of water = 32°F

Boiling point of water = 212°F

Anders Celsius (1742)

Freezing point of water = 0°C

Boiling point of water = 100°C

Conversion: $T_f = 32 + 9/5\ T_C$

Jacques Charles (1785)

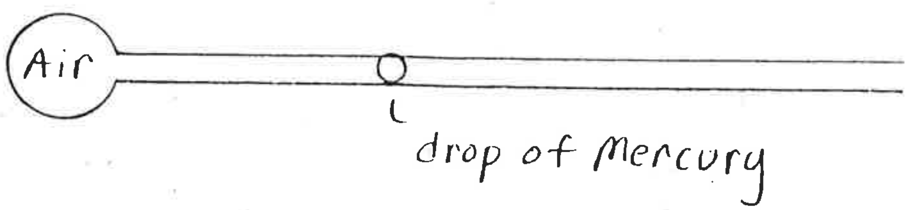


Figure 30.6 – Charles' experiment

When temperature was increased by 1°C, the volume increased by $^1/_{273}$

So: $V_f = 1 + {}^1/_{273}\ V_{initial}$

for 2°: $V_f = 1 + {}^2/_{273}\ V_{initial}$

$V \propto T_C + 273$

Lord Kelvin

$PV = \text{constant } T_K$

This equation works for all gases: air, "fixed air" (carbon dioxide), oxygen, nitrogen, hydrogen. $T_K = T_C + 273$

$T_F = 32 + 9/5\ T_C$

$T_F - 32 = 9/5\ T_C$

$5/9\ (T_F - 32) = T_C$

$T_K = 5/9(T_F - 32) + 273$

$5/9(T_F - 32) = -273$

$T_F = -491 + 32$

$T_F = -459$