# Introduction to General Physics I

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**MO and WE**

**Online / March 2020**

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***Structure of this class***

- Weekly lectures: 3x25 min
- Homework assignments (multiple choice)
- Midterm (April 27-May 1)
- Final (June 22-June 26)

## *Main texts*

***College Physics Volume I*** by Battista, Richardson & Richardson
Same in Korean – brief edition

***Feynman Lectures of Physics*** available online at
www.feynmanlectures.caltech.edu
selected chapters: Ch. 4-6, 8-11, 18-23, 39-46, 50-51

## *Lecture notes (2017)*

Posted on www.mvputten.org

# Contents - Week 1

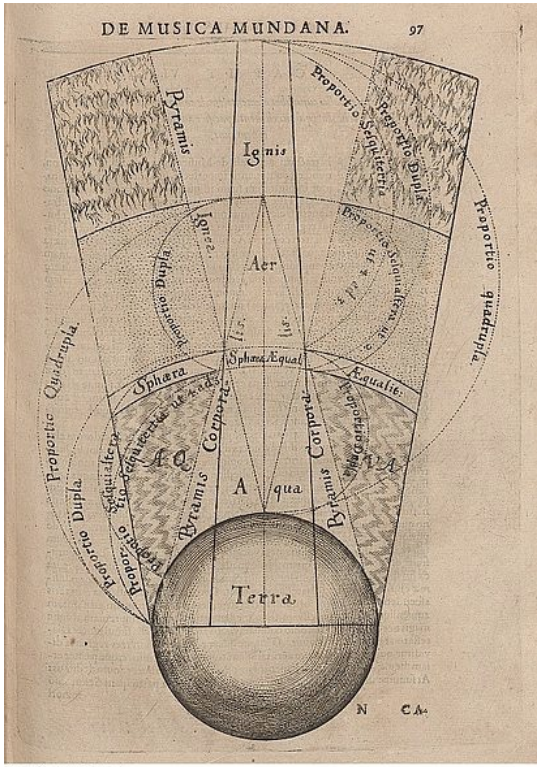
# *“The elements”*

Agnis (fire)

Aer (air)

Aqua (water)

Terra (Earth)




Quelle: Deutsche Fotothek

Robert Fludd (1617) – early cosmologist

*in* Joscelyn Godwin, *Robert Fludd: Hermetic philosopher and surveyor of two worlds* (1979), p. 70.

**What does this explain?**

# *Renaissance*

"The painter has the Universe in his mind and hands."
Leonardo da Vinci

Principles for the Development of a Complete Mind:

*Study the science of art. Study the art of science… especially learn how to see. Realize that everything connects to everything else.*

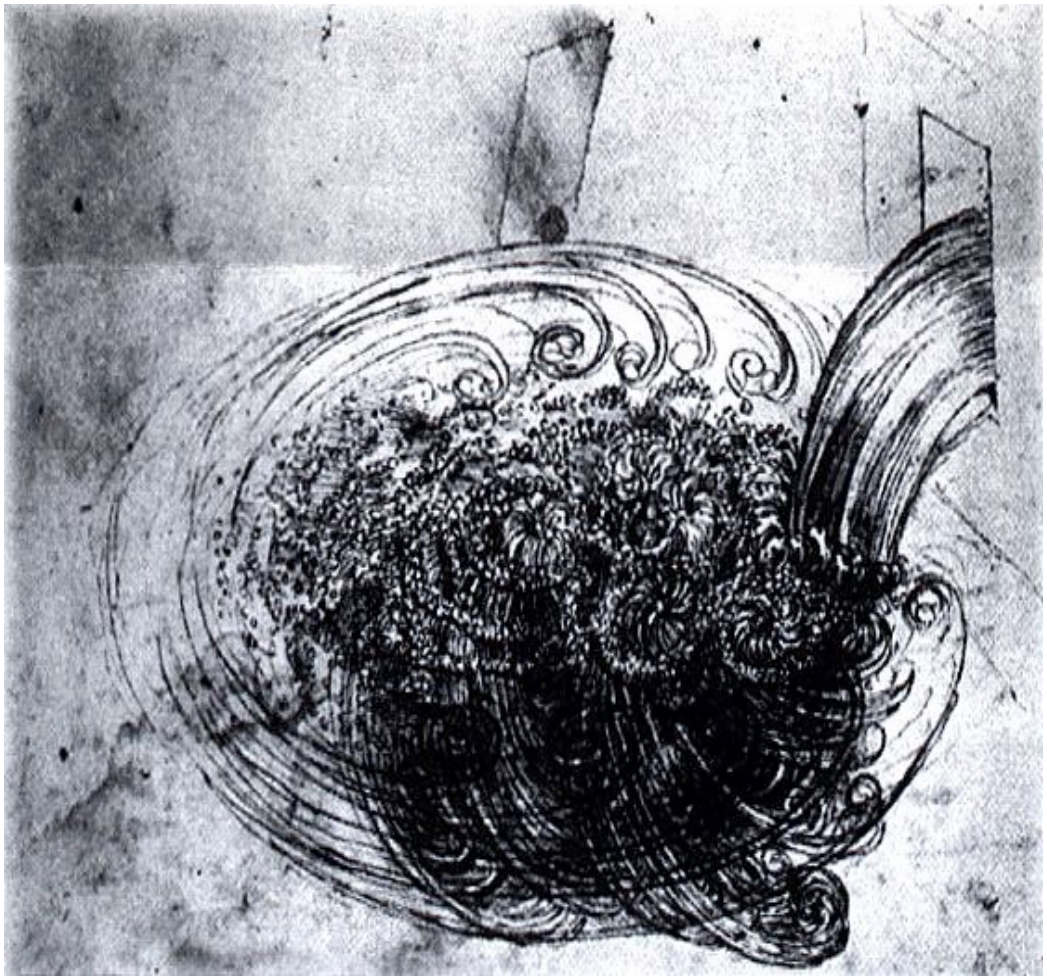
# *Artistic observations*

In his drawings, **Leonardo several times compares curls of hair to swirling water**.

The ringlets that frame Ginevra's face resemble **cascading whirlpools**.

http://www.pinpush.com/stories/Ginevra-DaVinci.htm

# Fluid motion



“A free water jet issuing from a square hole into a pool”

# *Da Vinci's interpretation*

"*Observe the motion of the surface of the water, which resembles that of hair, which has two motions, of which one is caused by the weight of the hair, the other by the direction of the* ***curls****; thus the water has* ***eddying motions****, one part of which is due to the principal current, the other to the* ***random and reverse motion****.*" [Reynolds' turbulence, prior to Osborne Reynolds' flow visualization (J. L. Lumley, Cornell University)]

He notices persistence of motion (**Newton's 2nd law**) and creation of vortices:

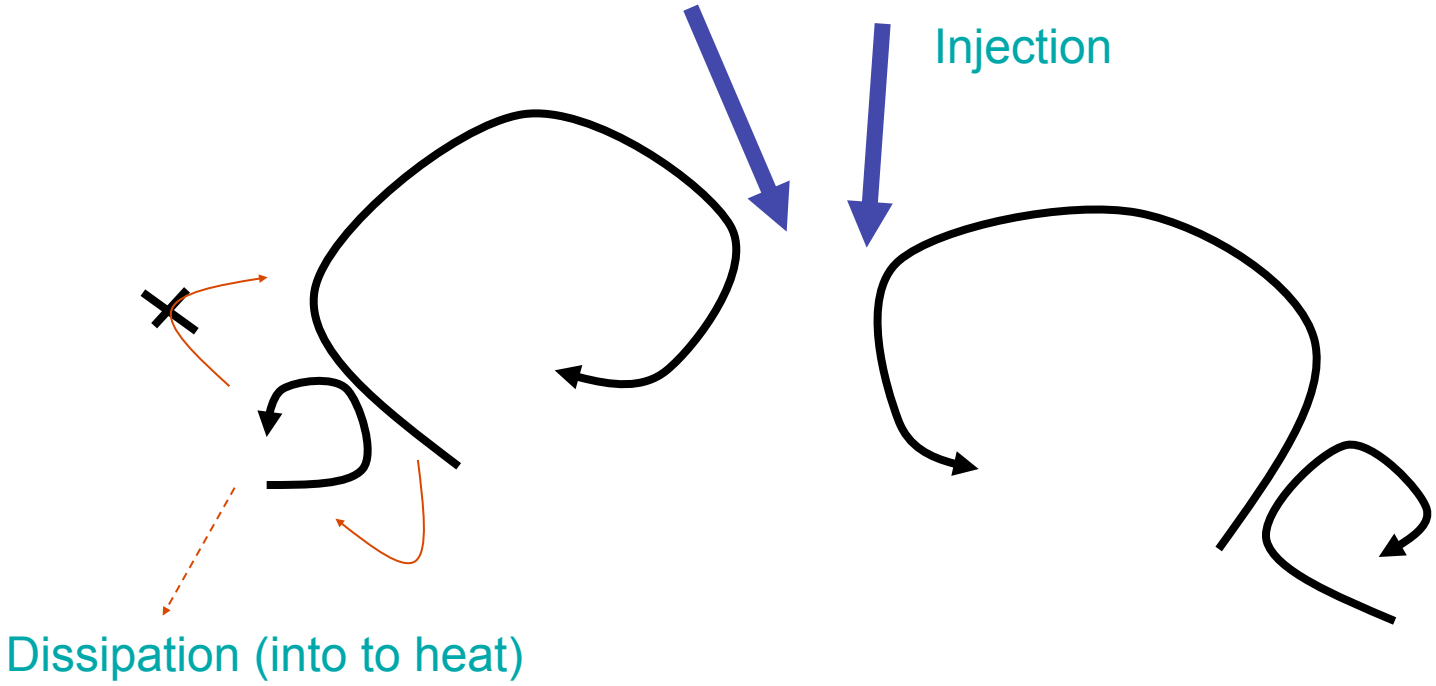
"*So* ***moving water strives to maintain the course*** *pursuant to the power which occasions it and, if it finds an obstacle in its path, completes the span of the course it has commenced by a* ***circular and revolving movement***"

"*... The* ***small eddies*** *are almost numberless, and large things are rotated only by* ***large eddies*** *and not by small ones,*" presaging Richardson's cascade

Excerpts from M. Gad-el-Hak: Flow Control: Passive, Active, and Reactive Flow Management, Cambridge University Press, 2000.

# *A cascade of eddies*

Injection of a water jet powers the creation of eddies ("vortices"), cascading down from large to small scale




Da Vinci's highlights pairwise formation of quasi-stationary, counter-rotating vortices in the midst of the random wake.

# *Galileo's sunspots*

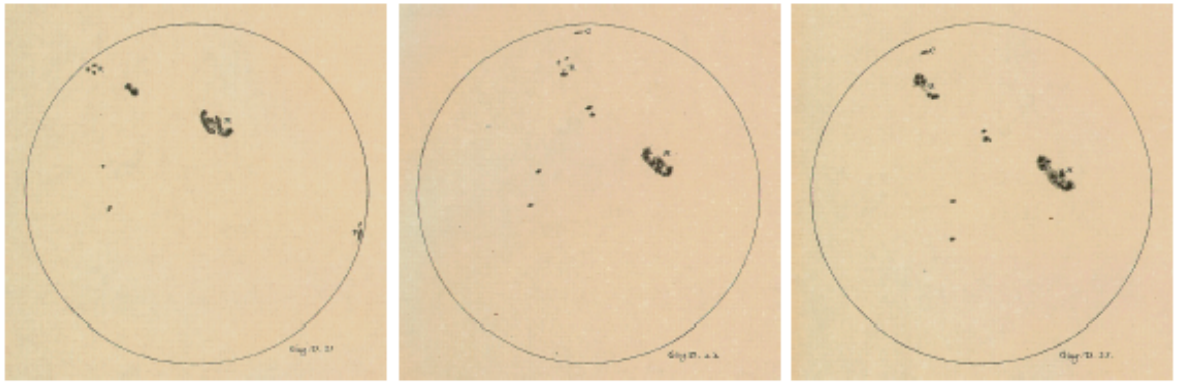
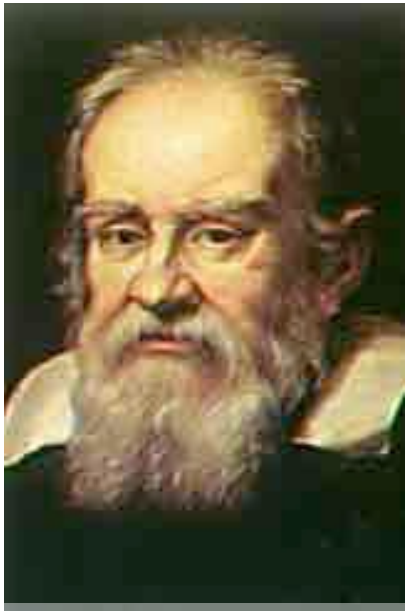


Figure 3.1: Shown are three of Galileo's drawings of sunspots on June 21, 22 and 23, 1613 (*left to right*). The spots vary in size as a function of time, and their motion clearly reveals the rotation of the Sun. (Source: http://galileo.rice.edu/sci/observations/sunspot_drawings.html, animated in http://galileo.rice.edu/sci/observations/ssm_fast.mpg)



Galileo
(1564-1642)

# Sun rotates!

# Galileo's questions


DIALOGO
DI
GALILEO GALILEI LINCEO
MATEMATICO SOPRAORDINARIO
DELLO STVDIO DI PISA.
E Filosofo, e Matematico primario del
SERENISSIMO
GR.DVCA DI TOSCANA.
Doue ne i congressi di quattro giornate si discorre sopra i due
MASSIMI SISTEMI DEL MONDO
TOLEMAICO, E COPERNICANO;

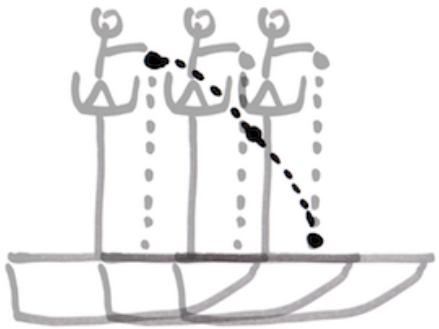
Galileo's dialogue "De motu" begins with a few questions from Dominucus:

1. Does a point of rest intervene "at reflection," where a body thrown upwards begins its descent?
2. What reason can you give that a wooden body of equal size with an iron one will fall faster though it is lighter—if you accept that it will?
3. Why is natural motion faster at the end than at the beginning, and violent motion faster at the beginning than in the middle, and faster in the middle than at the end?
4. Why does the same body descend more speedily in air than in water, yet some bodies fall in air but float in water?
5. What reason can you give that a cannon ball carries further in a straight line if fired at an angle than if fired horizontally, although the vertical is more opposed to natural motion?
6. Why do the same guns shoot heavier balls further than light ones, and iron balls further than wooden ones, although the lighter offer less resistance to the "impelling force"?

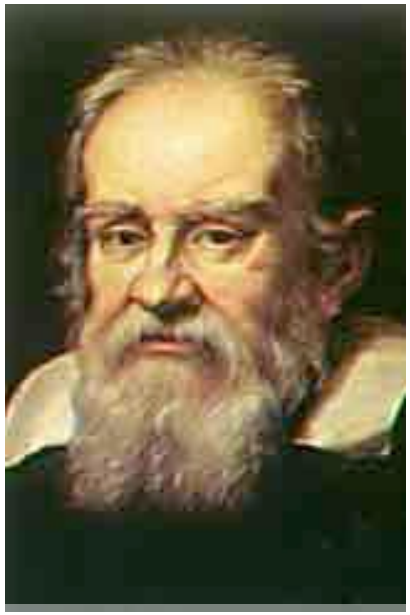
… are precisely answered by Newton's laws of motion, friction and gravitation

# Galilean relativity

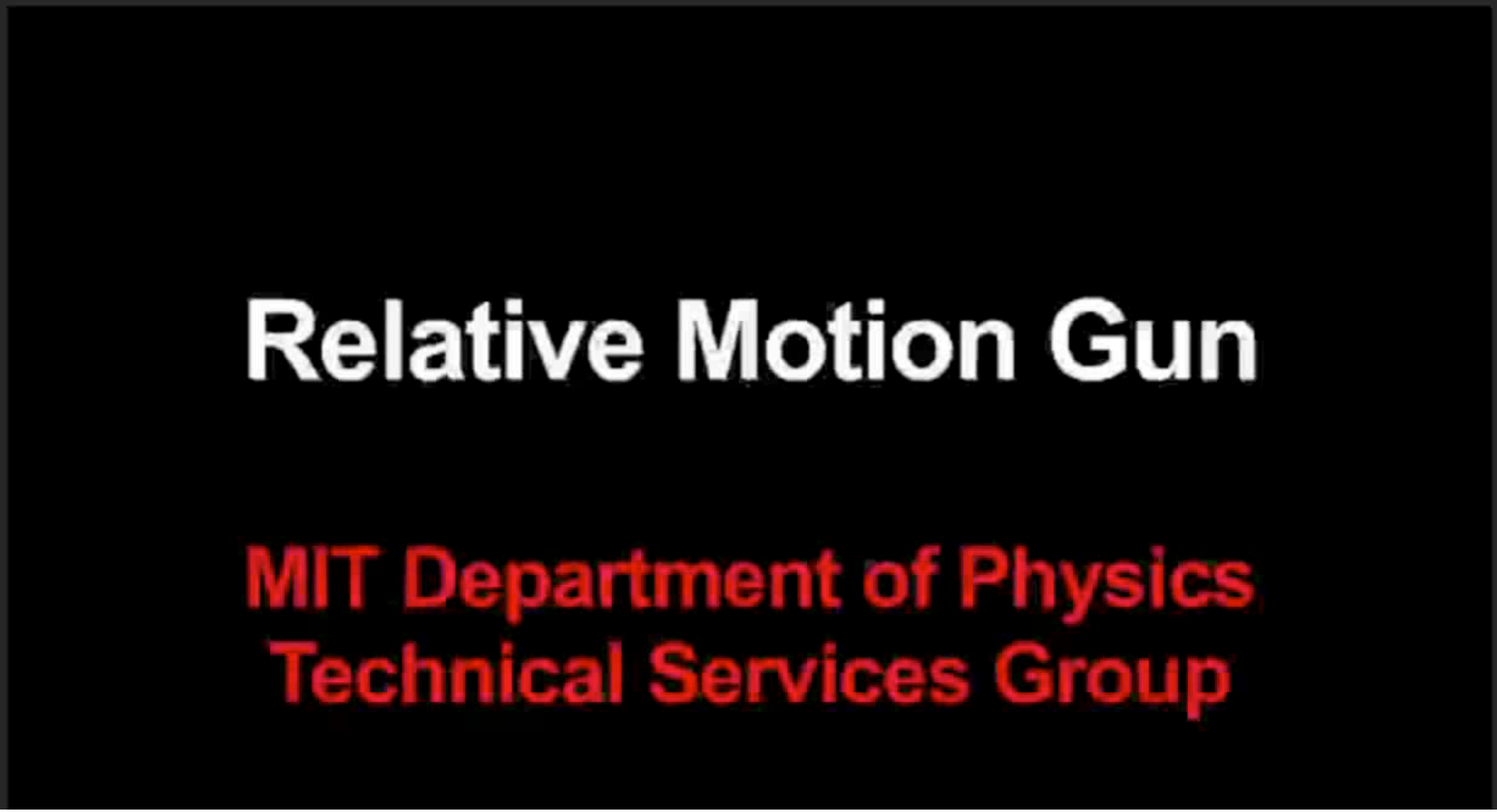
Galileo's Perspective



Bystander's Perspective



Galileo
(1564-1642)


Relative Motion Gun
MIT Department of Physics
Technical Services Group

# Relativity?

http://www.wired.com/2014/04/basketball-physics/

Original formulation:

“From the point of view of the cyclist,

does the ball land in front of, back with or behind the cyclist?”

?

# Invariance

http://www.wired.com/2014/04/basketball-physics/

[“From the point of view of the cyclist,” — in the original article] *superfluous!*

“Does the ball land in front of, back with or behind the cyclist?”

The answer (the ball lands in front of/behind the cyclist) is **observer-invariant**.

# Contents - Week 1

# Solar system

## Heliocentric solar system

Copernicus
(1473-1543)

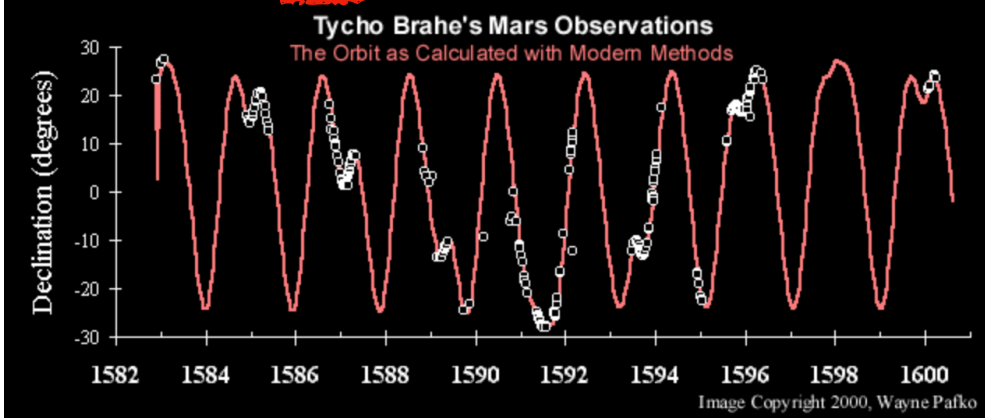
# Scientific data

## Visualizing Tycho Brahe's Mars Data

Home - - - - Hven - - - - Mars - - - - Data - - - - Models - - - - Works Cited

### Mars Observations

"I've studied all available charts of the planets and stars, and none of them match the others. There are just as many measurements and methods as there are astronomers and all of them disagree. What's needed is a long term project with the aim of mapping the heavens conducted from a single location over a period of several years." -Tycho Brahe, 156[illegible] (age 17).




Download an Excel file with this data.

Comments about this site are always welcomed. The author can be contacted at: pafko@excite.com.

pafko.com/tycho/observe.html

Copyright 2000, Wayne Pafko

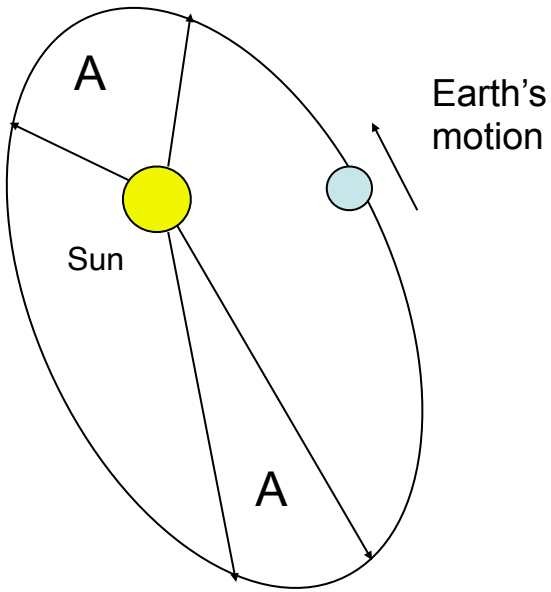
http://www.pafko.com/

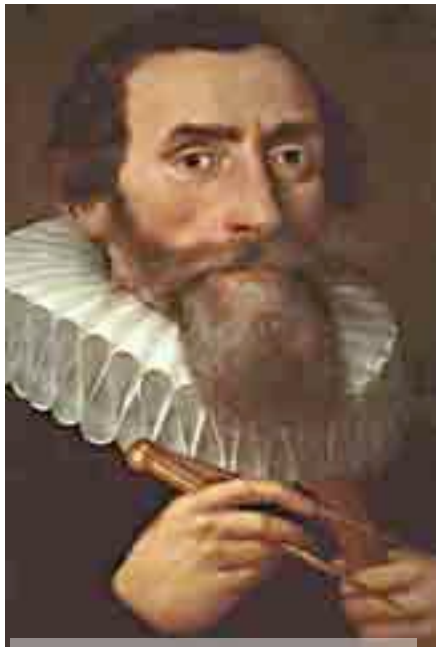
Tycho Brahe
(1546-1601)

https://in-the-sky.org/graphs.php?gtype=2&startday=14&startmonth=3&startyear=2020&duration=10&obj1type=0&obj1txt=Mars&obj2type=0&obj2txt=the+Sun

# Interpretation

***Better data…*** *"Kepler stole the data [from Brahe], and worked with it for nine years"*

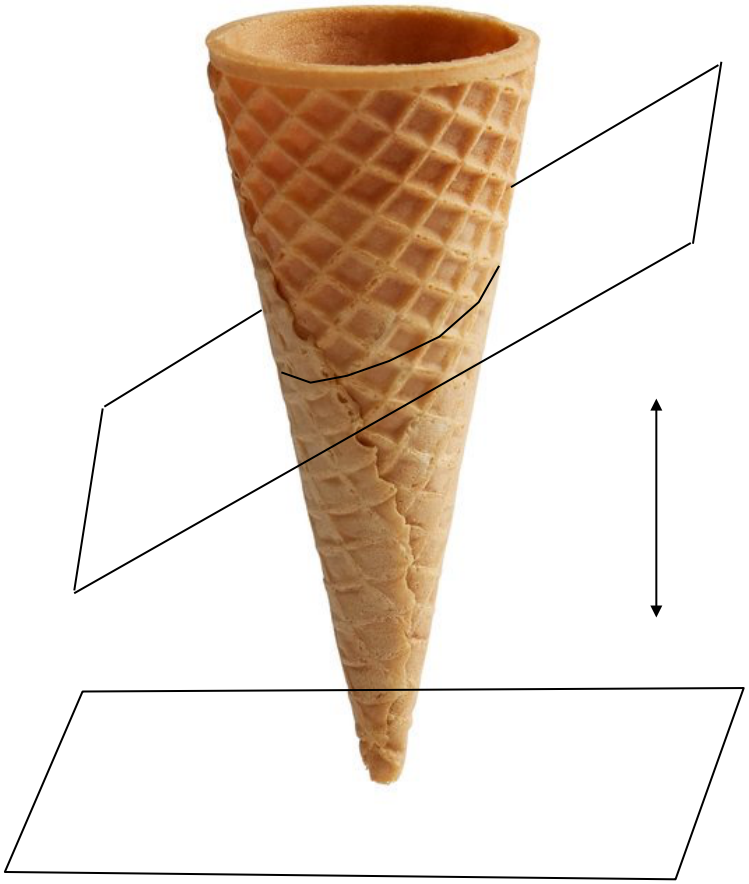


Johannes Kepler
(1571-1630)

*...if you want the exact moment in time, it was conceived mentally on 8th March in this year 1618*

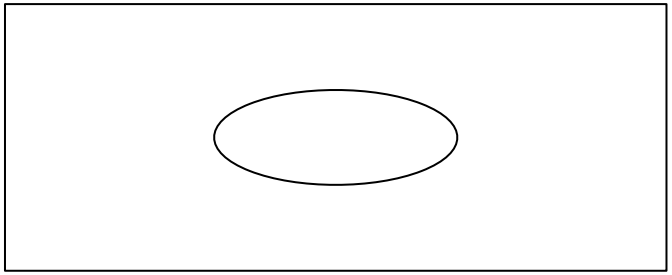
# *Ellipses: conic section*



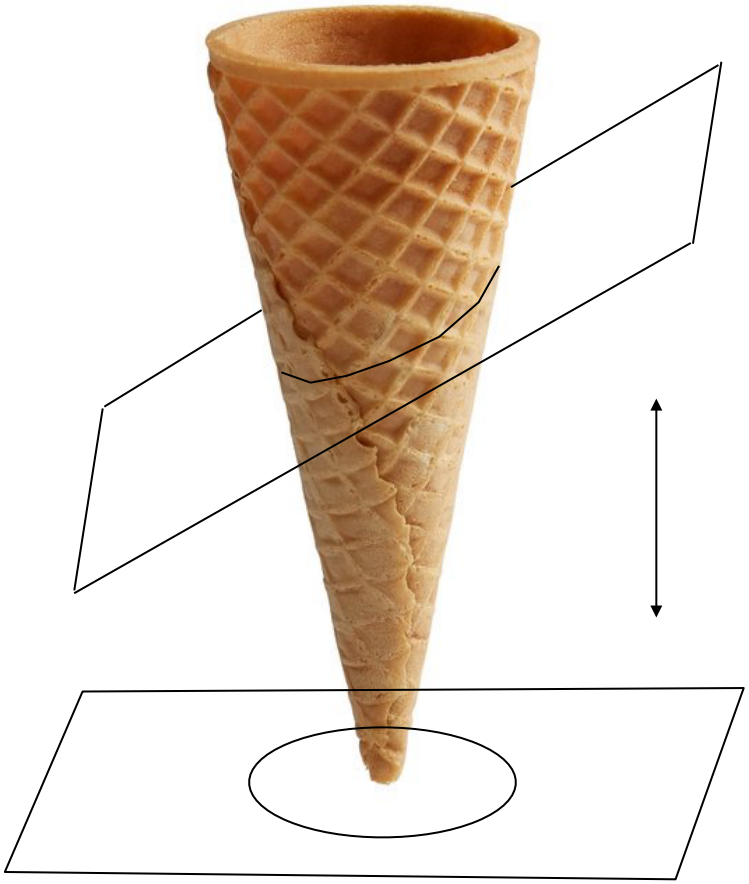
Circle with radius *b*

$\Longleftrightarrow$

Ellipse with semi-major axis *a*



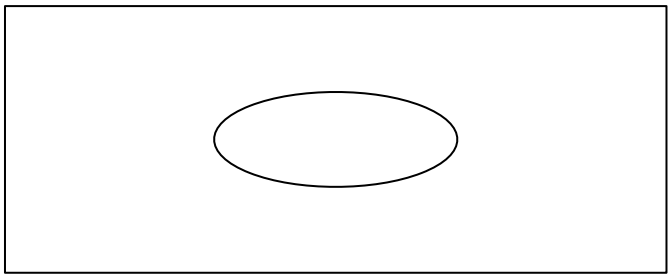
# Ellipses: conic section



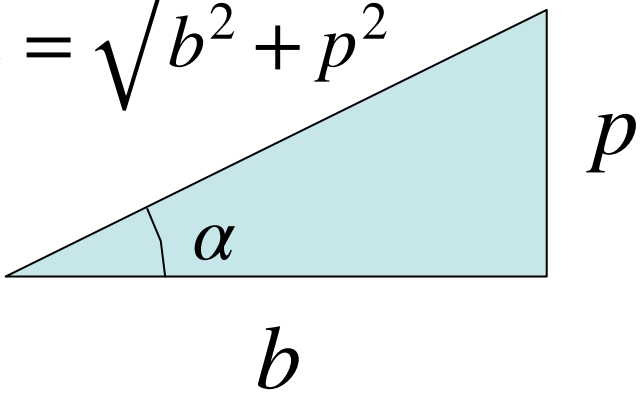
Circle with radius *b*

$\Longleftrightarrow$

Ellipse with semi-major axis *a*

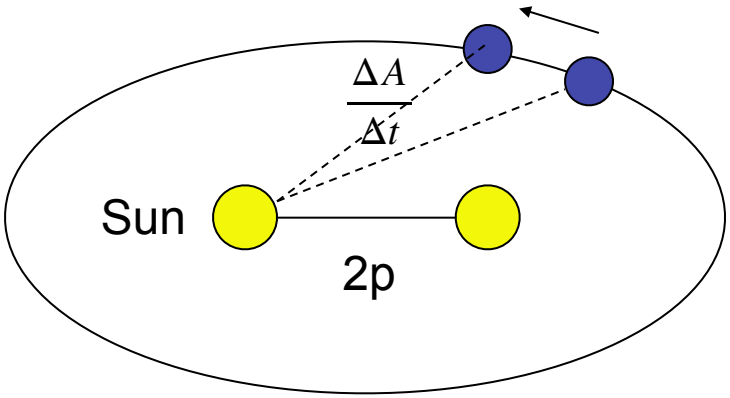


$$a = \sqrt{b^2 + p^2}$$




Ellipticity $e \equiv \dfrac{p}{a} = \sin\alpha$

# Orbital motion




## Kepler's three laws

1. The Sun is located at a focus of the ellipse.
2. Equal areas traced out in equal times.
3. Period scales with semi-major axis to the power 3/2.

$$\frac{\Delta A}{\Delta t} = const.,\ P^2 \propto a^3$$

# Galileo's free fall

Galileo's laws:

-Velocity is relative

-In free fall, all objects experience the same acceleration

# Newtonian free fall

*Newton's genius:*

- Free falling "apple from a tree" (or the tower of Pisa) is by Earth's gravitational pull

- The Moons is in continuous free fall *and* transverse motion about Earth

- Orbits of the Moon and planets are elliptical, derived from Newton's law of gravitation

Newton's theory is amazingly effective and universal, but it does not explain "why" there is mutual gravitational attraction between massive bodices.

# *Newton's laws of motion*

Motion in kinematic variables of
displacement, velocity, acceleration

Newton
(1642-1727)

## Newton's three laws

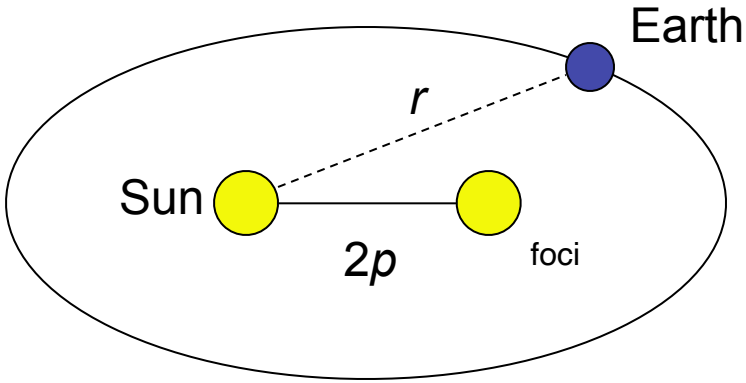
**1.** A body at rest remains at rest; in motion, it continues with constant velocity unless acted upon by an external force ["a body's' inertia resist change in motion"]

**2.** The acceleration of a body is proportional to the applied force (in magnitude and direction) and inversely proportional to the body's mass

**3.** If A exerts a force on B, then B exerts an equal force of opposite magnitude on A ["reciprocity"]

(Newton's 2nd law is empirical and may fail when accelerations become arbitrarily small, as in orbital motion of stars in galaxies.)

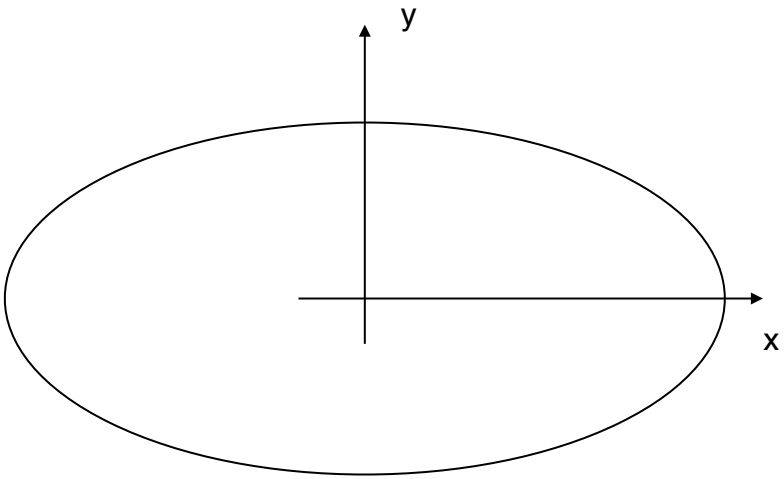
# Newton's theory of gravitation




$$F = -\frac{GM_1M_2}{r^2},\ r = \left|\mathbf{r_1} - \mathbf{r_2}\right|$$

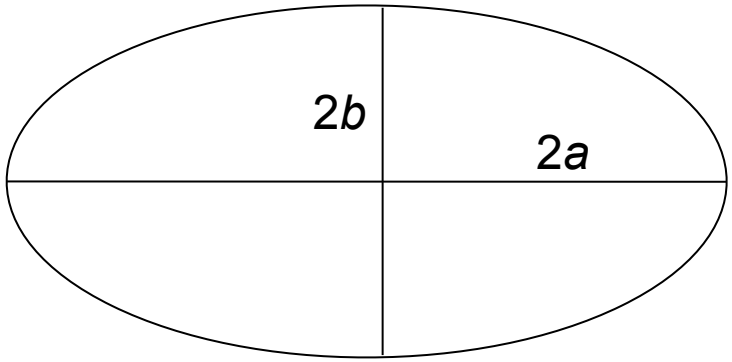
Newton's constant: $G = 6.67 \times 10^{-8}\mathrm{cm}^3\mathrm{s}^{-2}\mathrm{g}^{-1}$

# Ellipses in Cartesian coordinates

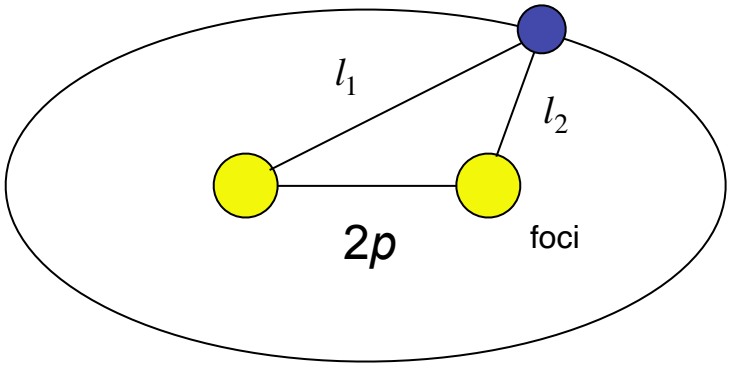



Implicit expression for an ellipse as a scaled circle in a Cartesian coordinates (x,y):

$$\left(\frac{x}{a}\right)^2 + \left(\frac{y}{b}\right)^2 = 1$$




Semi-major axis *a*, semi-minor axis *b*

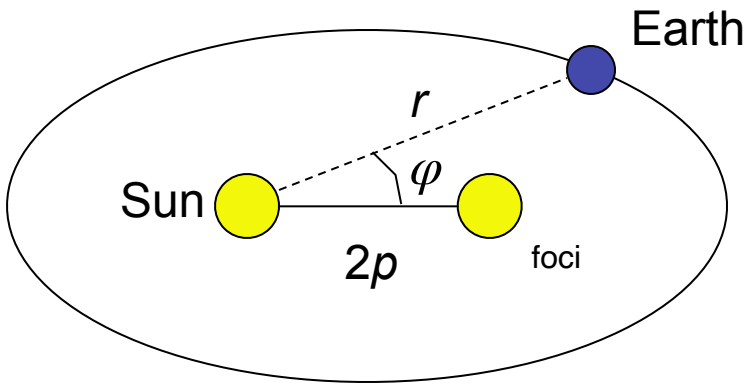



$l_1 + l_2 = \text{const.}$

# Elliptical orbits

Sun at $(-p,0)$

Earth at $(x, y)$




$$r = \left|\mathbf{r_1} - \mathbf{r_2}\right| = \sqrt{(x+p)^2 + y^2}$$

In polar coordinates $(r, \varphi)$: $r = r(\varphi)$

# Newton's theory

Kepler's elliptic orbits are harmonic:

$$u = \frac{1}{r} : \quad u = \text{const.} \times (1 + e\cos\varphi)$$

Kepler's 2nd law is conserved specific angular momentum:

$$j = 2\frac{\Delta A}{\Delta t} = r^2\dot{\varphi} = \sqrt{GMa(1-e^2)}$$

N.B. $\left[a^2(1-e^2) = r_{min}r_{max}\right]$

Kepler's 3rd law:

$$\left(\frac{2\pi}{P}\right)^2 = \frac{GM}{a^3} \; (M = M_1 + M_2)$$

# Gravitation is universal

$$P = 2\pi\sqrt{\frac{a^3}{GM}}$$

Scaled to Earth's orbit around the Sun:

$$P = P_1 \text{year} \qquad \text{year} = 3.15 \times 10^7 \text{s}$$

$$M = M_1 M_\odot \qquad M_\odot = 2 \times 10^{33} \text{g}$$

$$a = a_1 \text{AU} \qquad \text{AU} = 1.5 \times 10^{13} \text{cm}$$

$$\boxed{P_1 = a_1^{\frac{3}{2}} M_1^{-1/2}}$$

# *Newton's theory is universal*

Apply to the Moon orbiting Earth by scaling to 1AU and $M_\odot$:

$$a \simeq 385{,}000\text{km} = 3.85 \times 10^{10}\text{cm}$$

$$a_1 = \frac{a}{AU} = 2.57 \times 10^{-3}$$

$$M \simeq 5.97 \times 10^{27}\text{g}$$

$$M_1 = \frac{M}{M_\odot} = 2.98 \times 10^{-6}$$

$$P_1 = a_1^{\frac{3}{2}} M_1^{-1/2} = 0.0753 : \;\; P = 0.0753 \text{ yr} = 27.5\text{d}$$

# Contents - Week 1

# *A language of mechanics*

## Dimensional analysis:

Dimensionless: counting, angles, probability, …

Dimensional: length, time, mass, charge, …

## Elements of calculus:

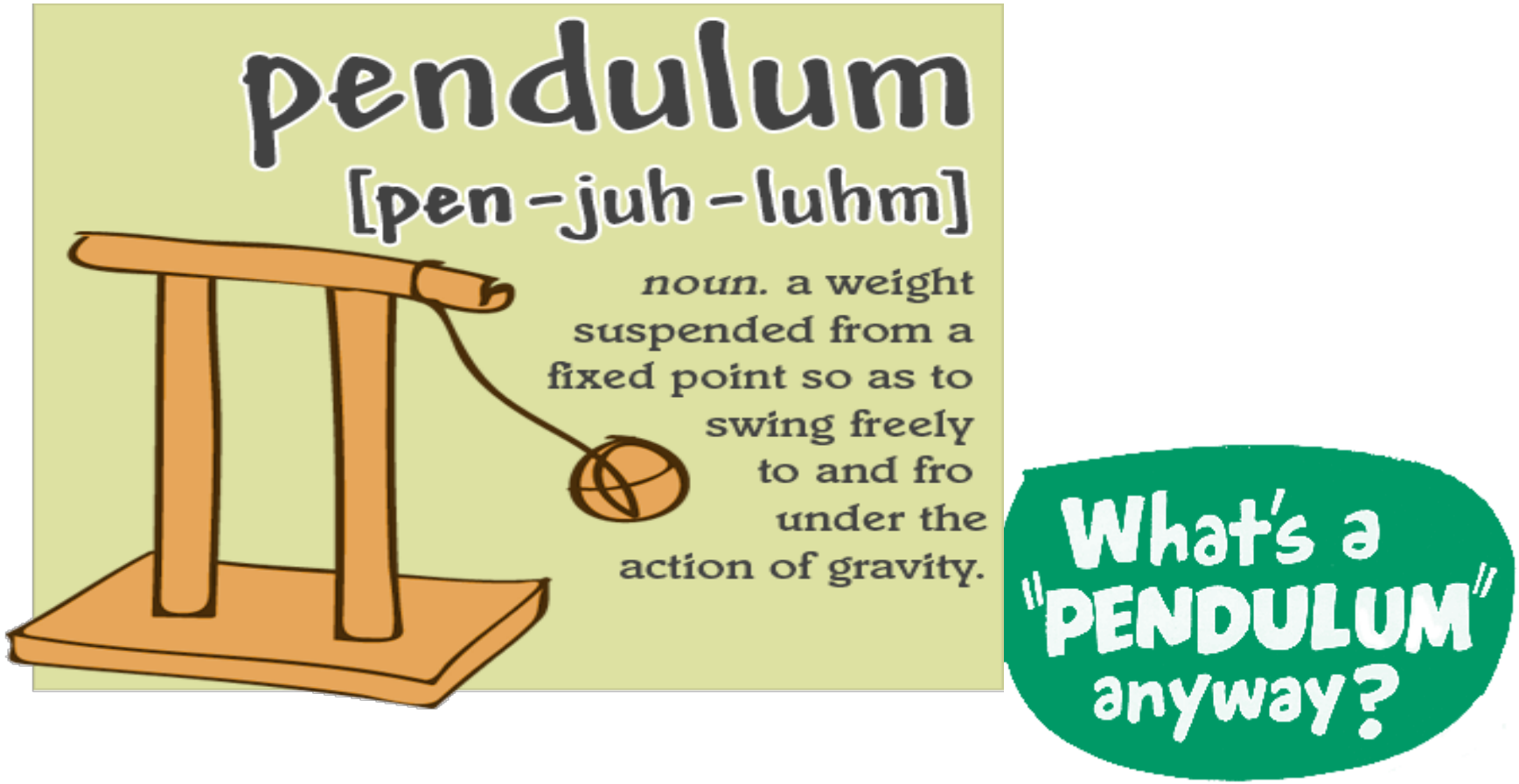
Euclidean geometry

Particle position, velocity and acceleration (vectors)

Calculus of differentiation (Newton)

Calculus of integration (Riemann)

# Example




Z. Beynon (1999)

Museum of Life and Science, Durham, NC

## Seismometer

Quake excites pendulum, drops a ball along P-wave (Zhang Heng, 132 A.D.)

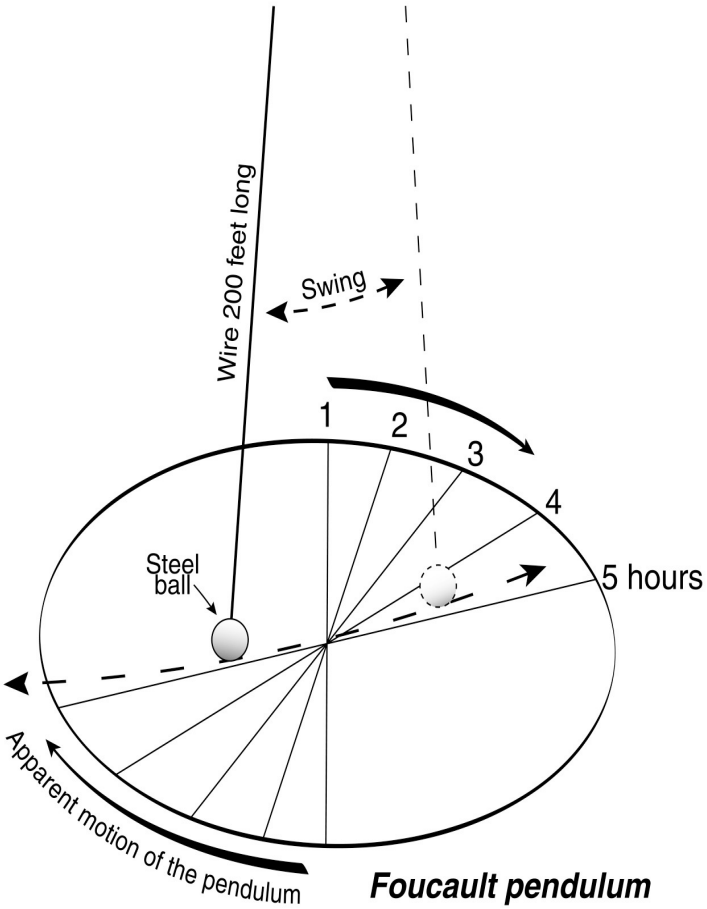
## Clocks

Galileo, 1602

Huygens, 1652

# **Foucault's pendulum** (1851)

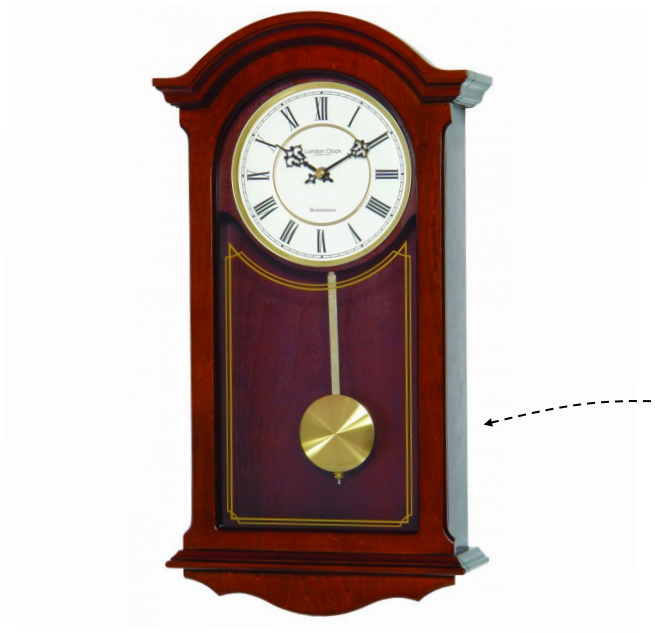
Measure Earth's rotation (Pantheon, Paris)

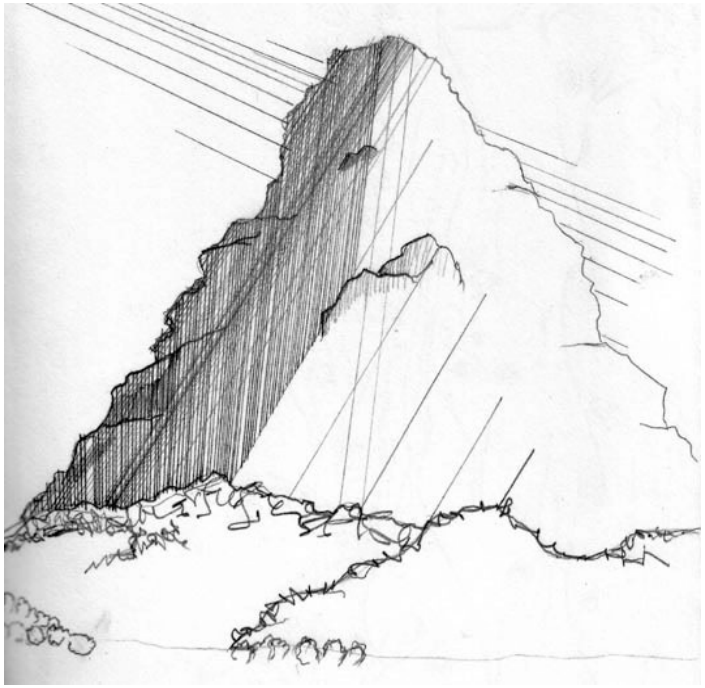



Plane of "swing" is fixed to the distant stars (the normal angular momentum vector maintains a fixed orientation), while Earth rotates "underneath

# Gravimeters

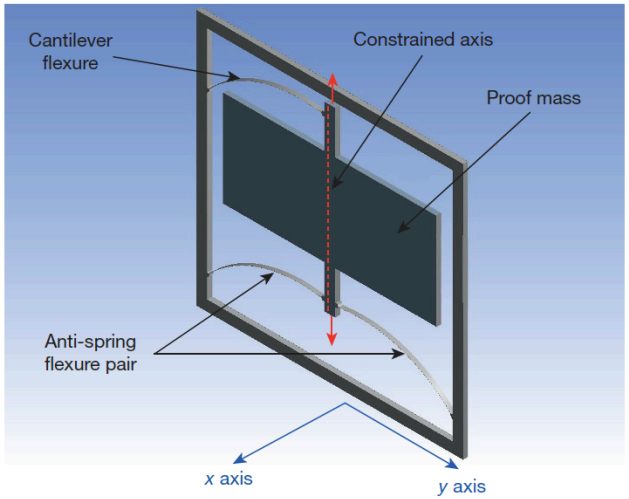
In gravity surveys, measure deviations from Earth's uniform gravitational field (e.g. by geological composition such as an oil field, a nearby mountain, or the tides)

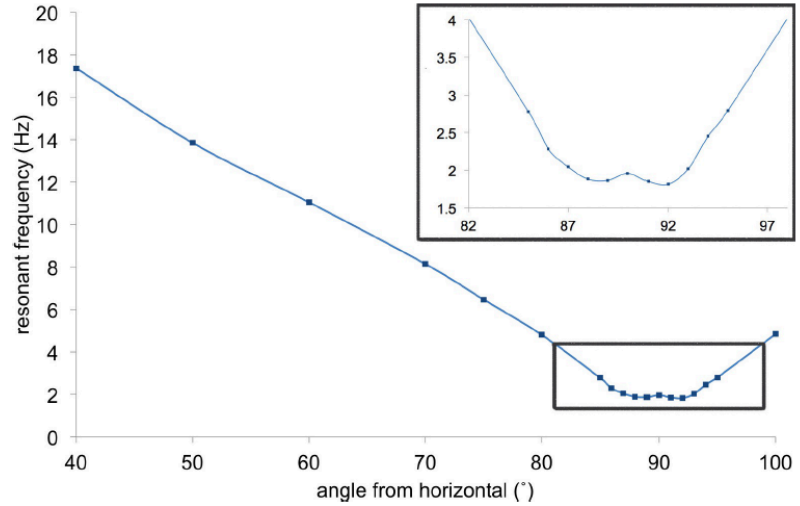




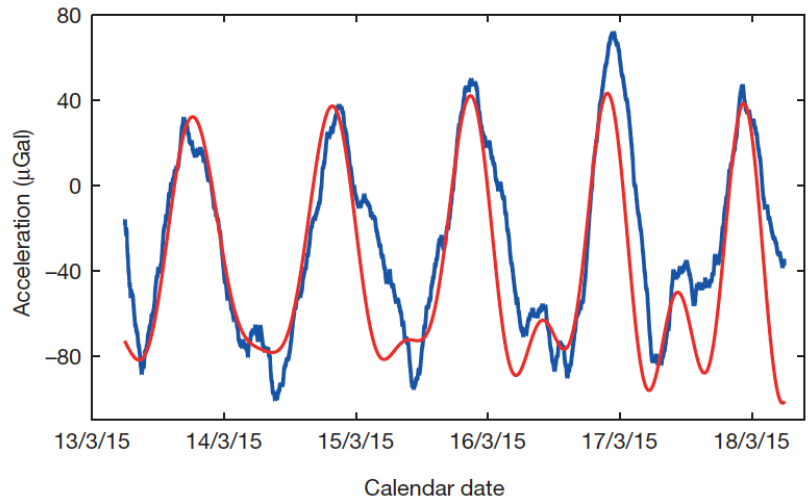
# Gravimeter in Silicon (MEMS)

Middlemiss, R.P., et a., 2016, Nature, 531

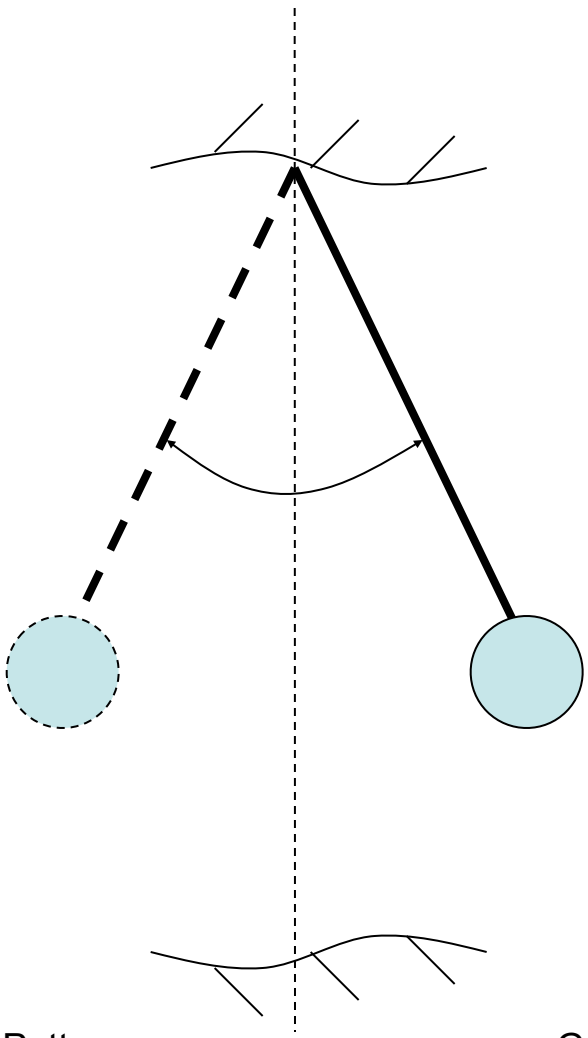



Gal = cm $s^{-2}$



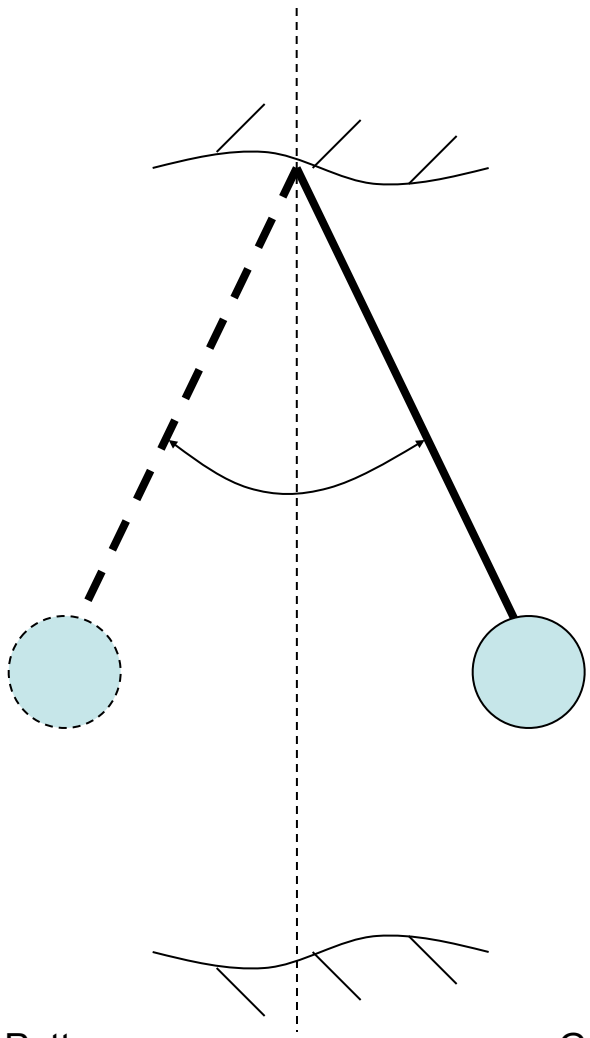
# Swing period by dimensional analysis



$[P]$ = seconds

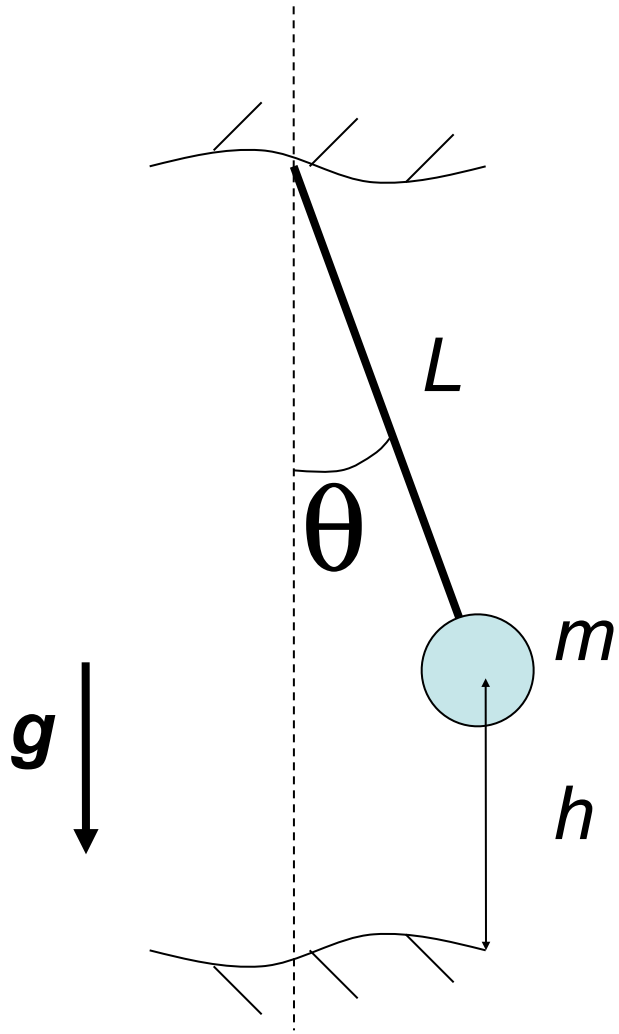
Consider various dimensionful quantities

# Swing period by dimensional analysis



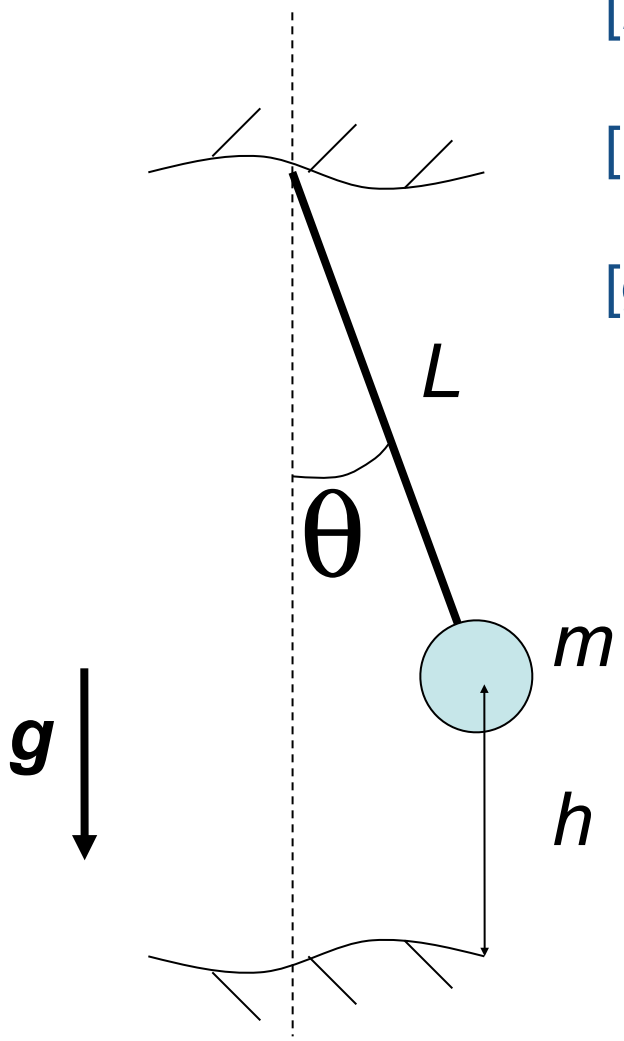
$$\begin{cases} [L] = \text{cm} \\ [m] = \text{g} \\ [g] = \text{cm s}^{-2} \end{cases}$$

# Dynamical variables




$$\begin{cases} [\theta(t)] = 1 \\ [h(t)] = \mathrm{cm} \end{cases}$$

# Formulate *P*




[*L*] = cm

[m] = g

[g] = cm s$^{-2}$

$$\left[\frac{L}{g}\right] = \mathrm{s}^2 \;\text{®}\; \left[\sqrt{\frac{L}{g}}\right] = \mathrm{s}$$

$$P = c_1\sqrt{\frac{L}{g}}$$

$c_1$ dimensionless constant

$c_1 = 2\pi$ from exact analysis

# SI units

SI = Système International d'Unités

Legacy of the French Revolution (1789)

Unify regional variations in weights and measures

MKS = meter, kilogram and seconds

popular with engineers, household appliances and trade

cgs = centimeter, gram and seconds

popular with astrophysics and physics

(electric and magnetic field have same units)

# SI units

Mass:

kg (“kilogram”) and g (“gram”)

Length:

m (“meter”) and cm (“centimeter”)

Time:

s, 1/60$^{th}$ of a minute, defined by periodicity radiation Cesium-133

*Also the following dimensionless quantities (not part of SI system)*

Angle: degree or radians (360$^{o}$ or 2$\pi$ rad in a circle)
arc second (second of arc), 1/60$^{th}$ of minute of **arc** (’’)
one degree is 3600 arc seconds

Bits or bytes: unit of information

# Metric prefixes

femto (f) = 10-15 = 0.000 000 000 000 001
pico (p) = 10-12 = 0.000 000 000 001
nano (n) = 10-9 = 0.000 000 001
micro (μ) = 10-6 = 0.000 001
centi (c ) = 10-2 = 0.01
milli (m) = 10-3 = 0.001

kilo (k) = 103 1,000
mega (M) = 106 1,000,000
giga (G) = 106 1,000,000,000
tera (T) = 1012 1,000,000,000,000
peta (P) = 1015
1,000,000,000,000,000
exa (E) = 1018 1,000,000,000,000,000,000

Google = $10^{100}$ (NOT a metric prefix!)

# Conversions

| | | | |
|---|---|---|---|
| 1 nautical mile | = | 2025 yards | = 1852 m |
| 1 foot (1’) | = | 12 inch (12”) = 30.48 cm | |
| 1 yard | = | 3 feet | |
| 1 meter | = | 39.4 inches | |
| 1 uncia | | = | 0.0272775 kg |
| 1 kg | = | 36.646816 uncia | |
| 1 marathon | = | 26 miles + 385 yards | |
| 1 gallon (US) | = | 3.79 liters | |

# Conversions: energy

***Energy* [MKS]** **1 Joule** = 1 Newton x 1 meter = 1 Nm

1 Newton = 1 kg m / $s^2$

= 1000 g * 100 cm / $s^2$

= $10^5$ g cm / $s^2$

1 Joule = $10^5$ g cm / $s^2$ x 100 cm = $10^7$ erg

***Energy* [cgs]** **1 erg** = 1 g $cm^2$ / $s^2$