
Experimental Physics I in English
Classical mechanics, Waves and Fluids
Special Relativity
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Office 2013

Some information to the lecture...

- **Who am I ?**

  Prof Shawn Bishop
  Office **2013** Physics Building,
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  Office Hours for Course → When my office door is open.

- **Web content to the course**

  All the slides I use and examples we make in class will be made available on the web, every Wednesday before class

  – Navigate to → www.nucastro.ph.tum.de
  – Click “Lehre” → “Experimental physics in English I”

- **Timetable and course outline**
  – Subject to changes based on my travel (announcements will be made)

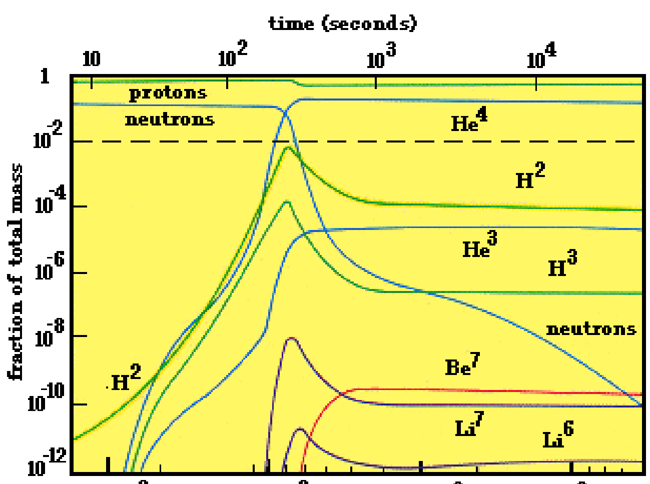
TUM Nukleare Astrophysik

Experimental Nuclear Astrophysics at TUM

The nuclear astrophysics group at the Technische Universität München welcomes you to our web portal.

Nuclear Astrophysics

Experimental nuclear astrophysics is largely concerned with the business of element production; that is, Nucleosynthesis. What we know of our Universe is that, within the first few minutes of its popping into being, only the lightest elements, ranging from simple hydrogen up to beryllium, were produced. You can see this in the plot below which shows, as a function of time since the beginning of the Universe (along the top horizontal axis) and temperature of the nascent Universe (along the bottom horizontal axis) the mass-abundance fractions of these light elements. After some few thousand seconds, the abundance fractions no longer change with time (or temperature), signalling the end of element production. (The ongoing decrease in neutrons is due to their **beta-decays** into protons. This process is **not** nucleosynthesis). The production of these light elements within the first few minutes of cosmic history is called Big Bang Nucleosynthesis (BBN).



Lehrstuhl E12

Lehrstuhl E12 für Experimentalphysik: Physik der Hadronen und Kerne

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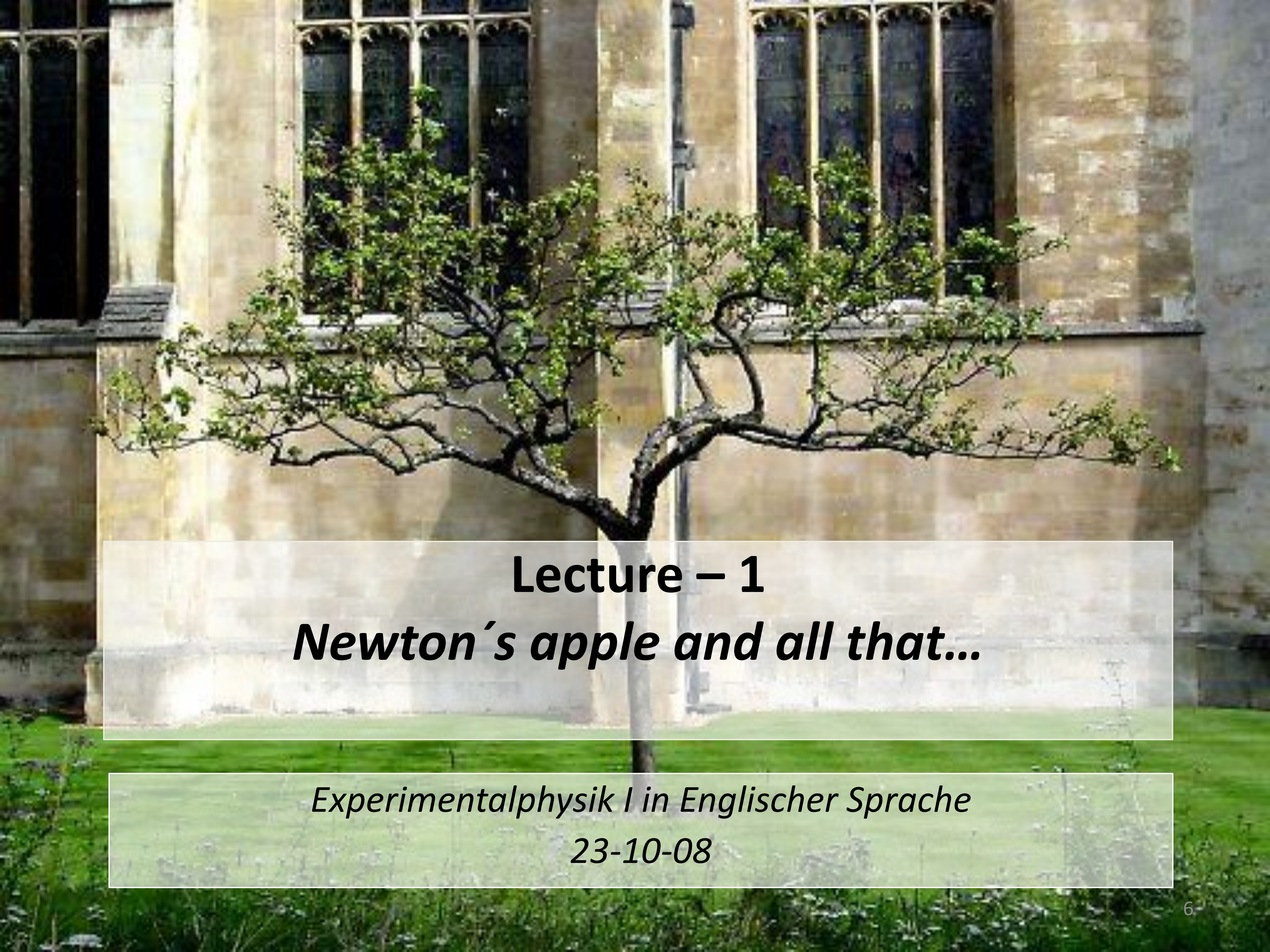


Lecture – 1
Newton´s apple and all that…

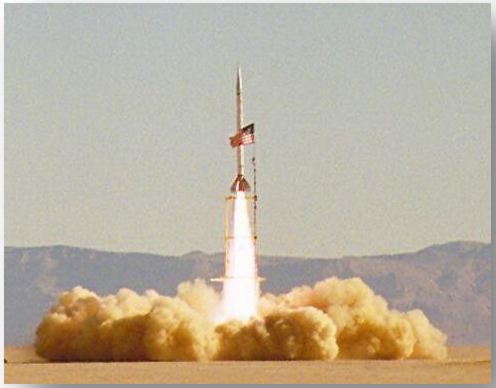
Experimentalphysik I in Englischer Sprache

23-10-08

Lecture 1 - Contents

M1.1 Fundamentals

- *Historical motivation...*
- ***Purpose** of classical mechanics*
- *Coordinates and vectors...*



M1.2 Motion in Space

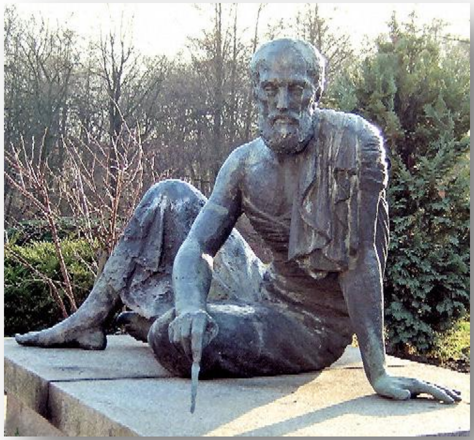
- ***Velocity** and **acceleration***
- *Motion in **two** or **three dimensions***
- *Projectiles and circular motion*

M1.3 Newton's laws of motion

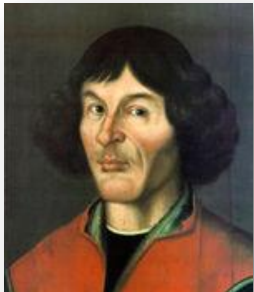
- *The origins of the **three little "laws"***
- *Examples of applying Newton's laws*

1.1 Historical Background

- **Aristotle** (384 BC – 322 BC) - physics and metaphysics
  – *Made distinction between natural motion and enforced motion.*
  – *"every body has a* ***heaviness*** *and so tends to fall to its natural place"*
  – *"A body in a vacuum will either stay at rest or move indefinitely if put in motion (law of inertia)"*



- **Archimedes** (287 BC – c. 212 BC)
  – laid the foundations of **hydrostatics**
  – Explained the principle of the **lever**
  – Invented many machines (Archimedes screw ...)



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…

NICOLAI COPERNICI TORINENSIS DE REVOLVTIONIbus orbium cœlestium, Libri VI.

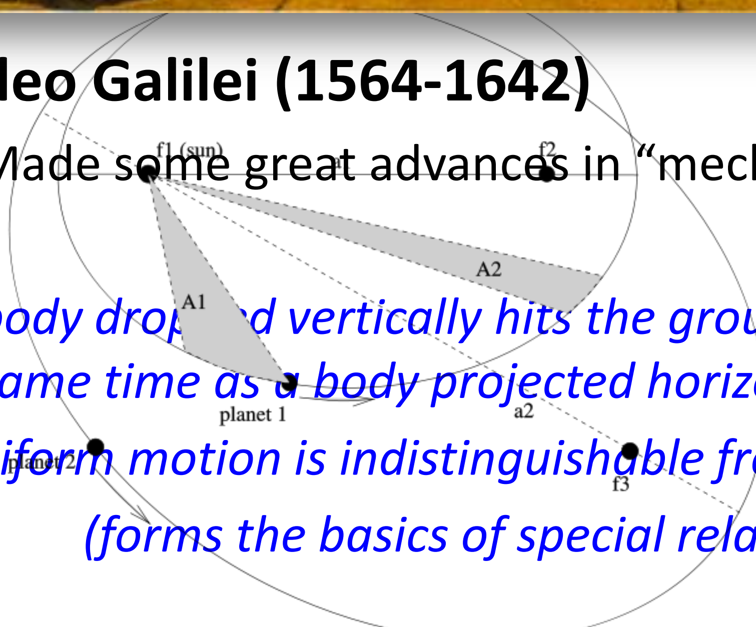
IN QVIBVS STELLARVM ET FIXARVM ET ERRATICARVM MOTVS, EX VETEribus atq; recentibus obseruationibus, restituit hic autor. Præterea tabulas expeditas luculentasq; addidit, ex quibus eosdem motus ad quoduis tempus Mathematum studiosus facillime calculare poterit.

ITEM, DE LIBRIS REVOLVTIONVM NICOLAI Copernici Narratio prima, per M. Georgium Ioachimum Rheticum ad D. Ioan. Schonerum scripta.

Cum Gratia & Priuilegio Cæs. Maiest.

BASILEAE, EX OFFICINA HENRICPETRINA.

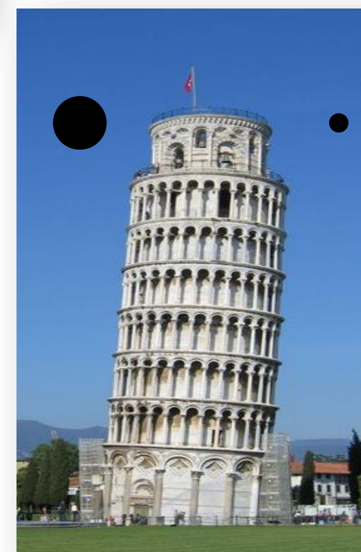
- **Galileo Galilei (1564-1642)**
  - Made some great advances in "mechanics"



"A body dropped vertically hits the ground at the same time as a body projected horizontally"

"Uniform motion is indistinguishable from rest"

(forms the basics of special relativity)



Hail the king !

- **Sir Isaac Newton FRS (1642-1727)**
  - Made giant advances in mechanics, optics, mathematics

Conservation of linear and angular momentum

Formulated first "laws" of motion

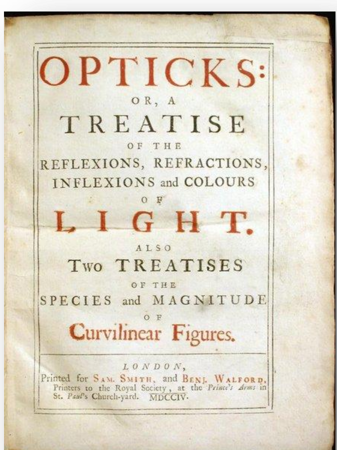
Formulated theory of gravitation

Invented reflecting telescope

Developed a theory of colour

Photons !

Shares credit with Leibniz for the development of the calculus



OPTICKS:
OR, A
TREATISE
OF THE
REFLEXIONS, REFRACTIONS, INFLEXIONS and COLOURS
OF
LIGHT.
ALSO
Two TREATISES
OF THE
SPECIES and MAGNITUDE
OF
Curvilinear Figures.

LONDON,
Printed for SAM. SMITH, and BENJ. WALFORD, Printers to the Royal Society, at the Prince's Arms in St. Paul's Church-yard. MDCCIV.

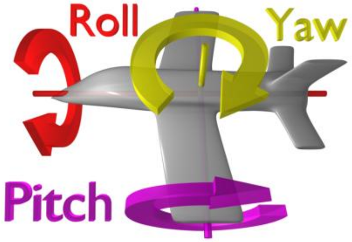
Fundamentals

What does “classical mechanics” aim to do?

→ Provide a physical basis to describe the behaviour of bodies (point masses or extended systems) subject to external forces...

Increasing level of complexity

- **Kinematics** of **point masses**
  (motion as a function of time)
- **Dynamics** of the **point masses**
  (why is the motion like it is ? – influences of forces etc...)

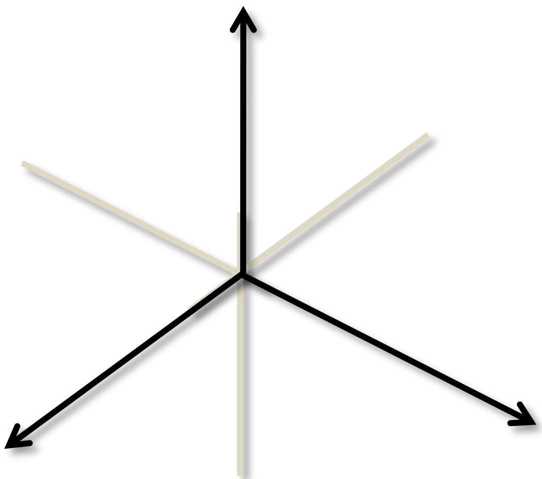


- **Extended rigid bodies**
  (Finite size effects?, Inertia etc.)
- **Extended <u>non-rigid</u> bodies** : Elastic bodies (*reversible* deformation)
  Hydrostatic, Aerostatic...
  Hydrodynamic, Aerodynamic...

- **Non-linear dynamics** (Chaotic dynamics)

1.2 coordinates and position

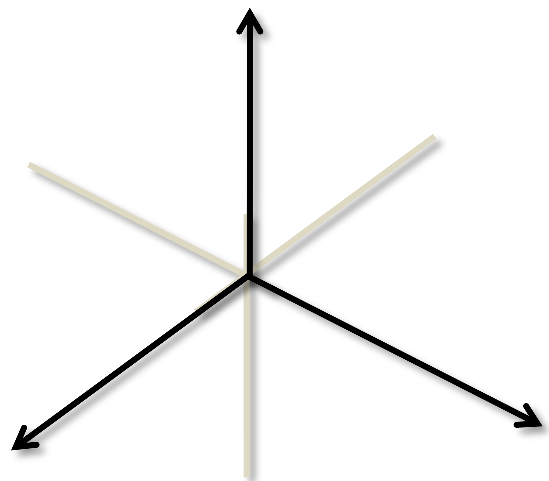
- The **position** of a “body” in any space is defined by specifying its **co-ordinates**...



$$\vec{r} = \{x, y, z\}$$

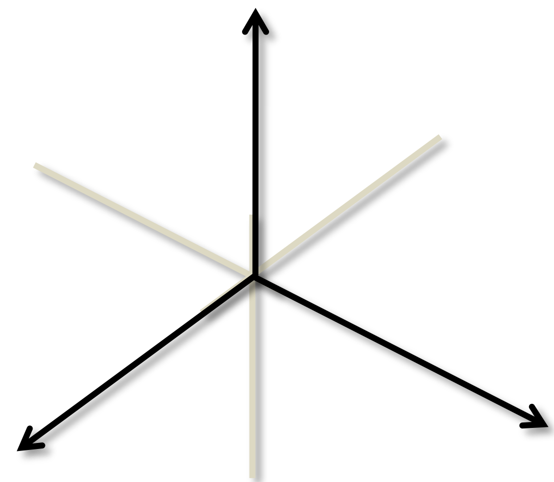
$$\vec{r} = x\vec{e}_x + y\vec{e}_y + z\vec{e}_z$$

CARTESIAN COORDINATES



$$\vec{r} = \{\rho, \varphi, z\}$$

CYLINDRICAL COORDINATES

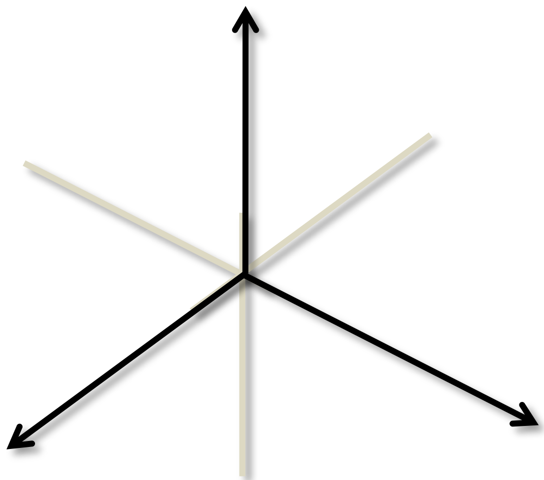


$$\vec{r} = \{r, \theta, \varphi\}$$

SPHERICAL COORDINATES

1.2.1 Trajectory, position and the nature of space

***Positions** are specified by vector quantities*



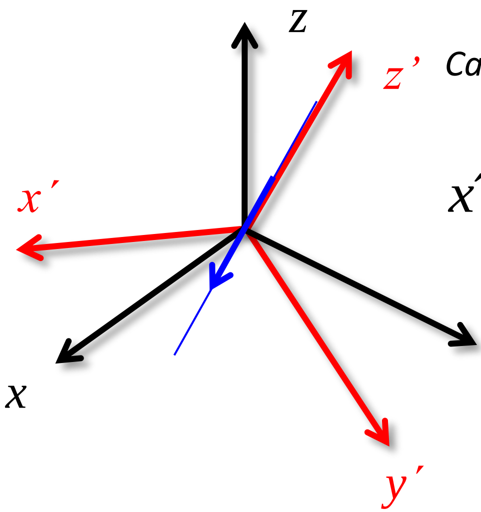
$$\vec{r}(t) = \{x(t), y(t), z(t)\}$$

Position co-ordinates are generally a <u>function of time</u>

since the particle moves along the trajectory subject to forces

(i) Linear Motion (e.g. Free fall)

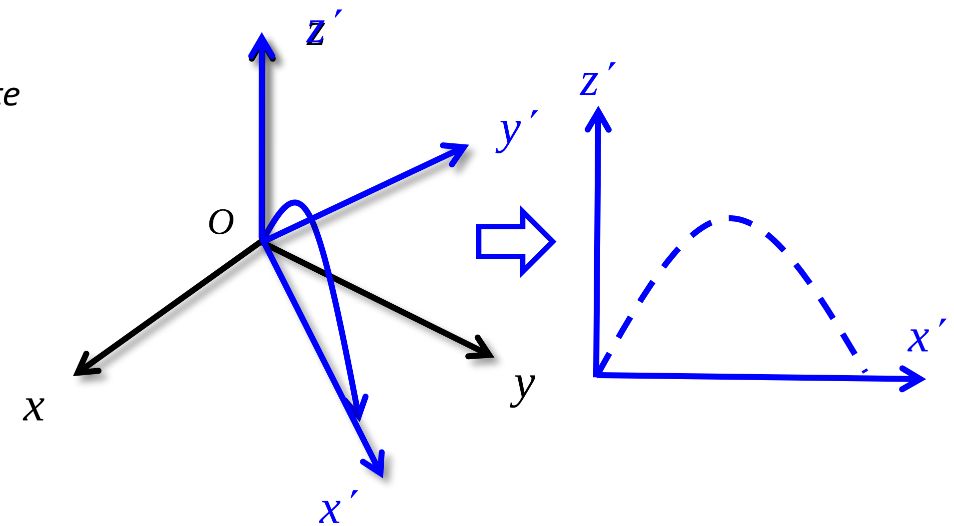
(ii) Motion in a Plane (e.g. Throw of a Ball)



Can always define a co-ordinate system such that :

$$x'(t) = y'(t) = 0 \quad \forall t$$

$$z'(t) \neq 0$$

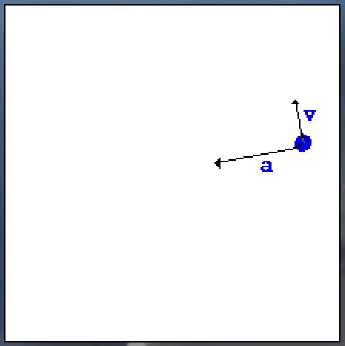


- **Translation** and **Rotation** of the coordinate system is allowed, when the trajectory is defined only by some universal physical laws

- Requires that these **“Laws of Motion” are independent** of
  - **Position**
    - space is homogeneous
  - **Direction**
    - space is isotropic
  - **Time**
    - time invariance

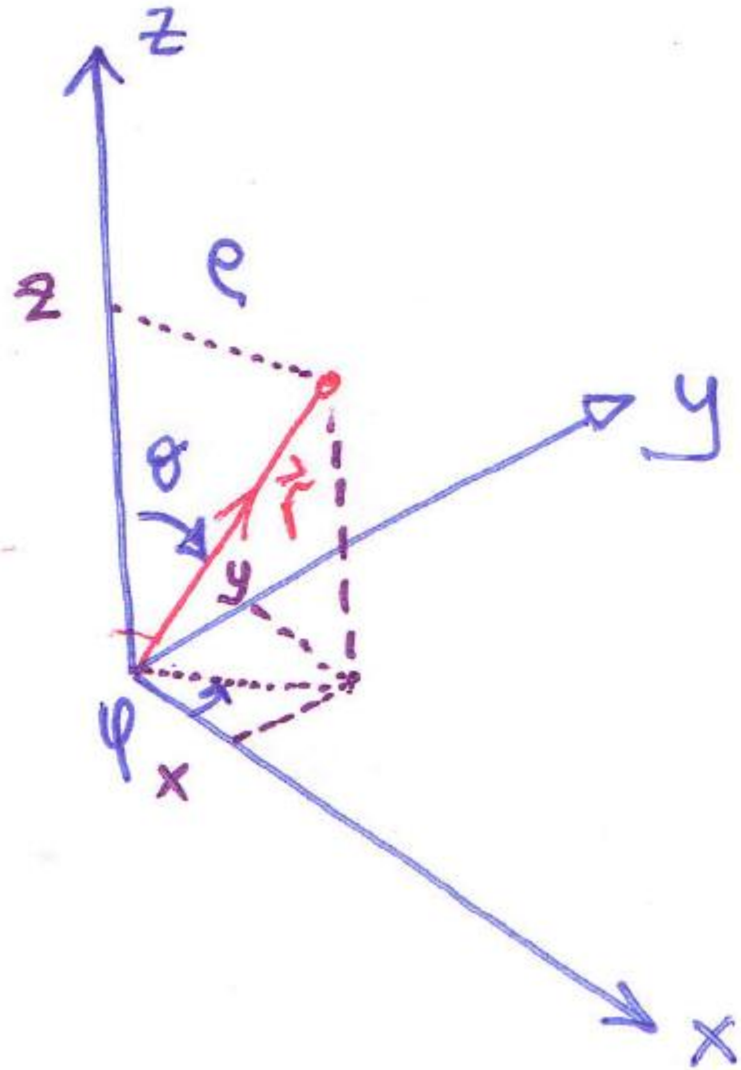
- These properties must be experimentally verified and will lead later in the lectures to very important **conservation laws** (energy and momentum)

The chosen co-ordinate system *can* then be “chosen” to match the symmetry of the trajectory



1.2.2 Converting between co-ordinate systems

$\vec{r} = \{r, \theta, \varphi\}$ ⟺ $\vec{r} = \{x, y, z\}$ ⟺ $\vec{r} = \{\rho, \varphi, z\}$



Cartesian ←→ Spherical

$x = r \sin\theta \cos\varphi$

$y = r \sin\theta \sin\varphi$

$z = r \cos\theta$

$r = \sqrt{x^2 + y^2 + z^2}$

$\theta = \arccos\left(\frac{z}{r}\right)$

$\varphi = \arctan\left(\frac{y}{x}\right)$

Cartesian ←→ Cylindrical

$x = \rho \cos\varphi$

$y = \rho \sin\varphi$

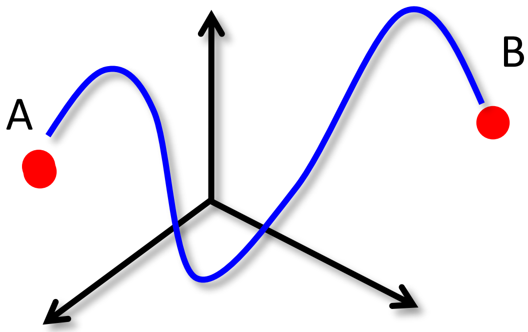
$z = z$

$\rho = \sqrt{x^2 + y^2}$

$\varphi = \arccos\left(\frac{x}{\rho}\right)$

1.2.3 Velocity and Acceleration

- The time dependence of the position vector leads to other kinematic quantities
  → **velocity** and **acceleration**



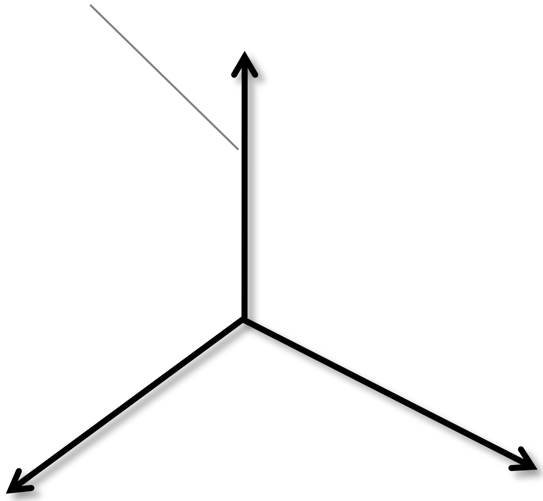
*1) The **average velocity** is defined by*

$$\langle \vec{v} \rangle (t_1, t_2) = \frac{\vec{r}(t_2) - \vec{r}(t_1)}{(t_2 - t_1)} \qquad \langle \ldots \rangle \quad \text{average}$$

Dependent on the time interval (t_2-t_1) and trajectory

*2) The **instantaneous velocity** is the time derivative of the position*

*d**r** = displacement*

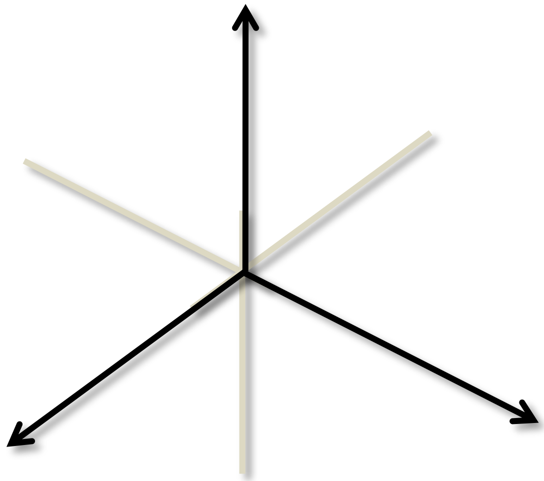


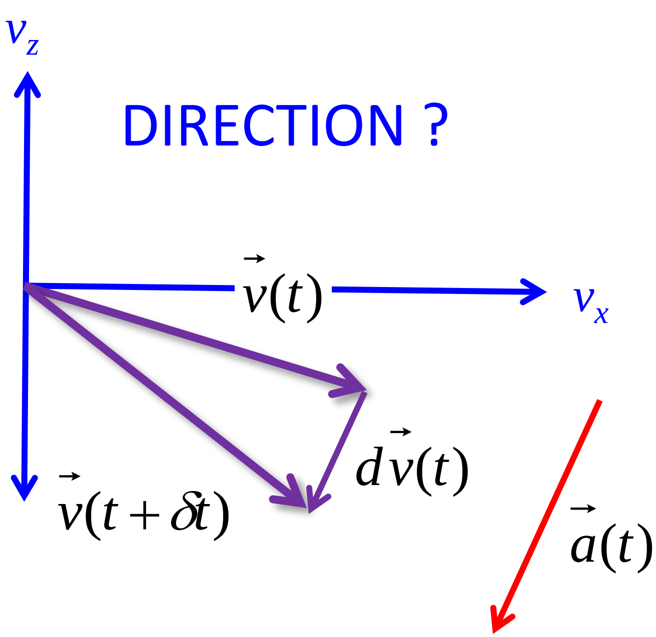
Consider an infinitesimal displacement of the position vector
***dr** over an infinitesimal time dt*

$$\vec{v}(t) = \{\dot{x}(t), \dot{y}(t), \dot{z}(t)\} = \{v_x(t), v_y(t), v_z(t)\}$$

***Velocity** is always parallel to the trajectory*

The **instantaneous acceleration** is the time derivative of the **velocity**

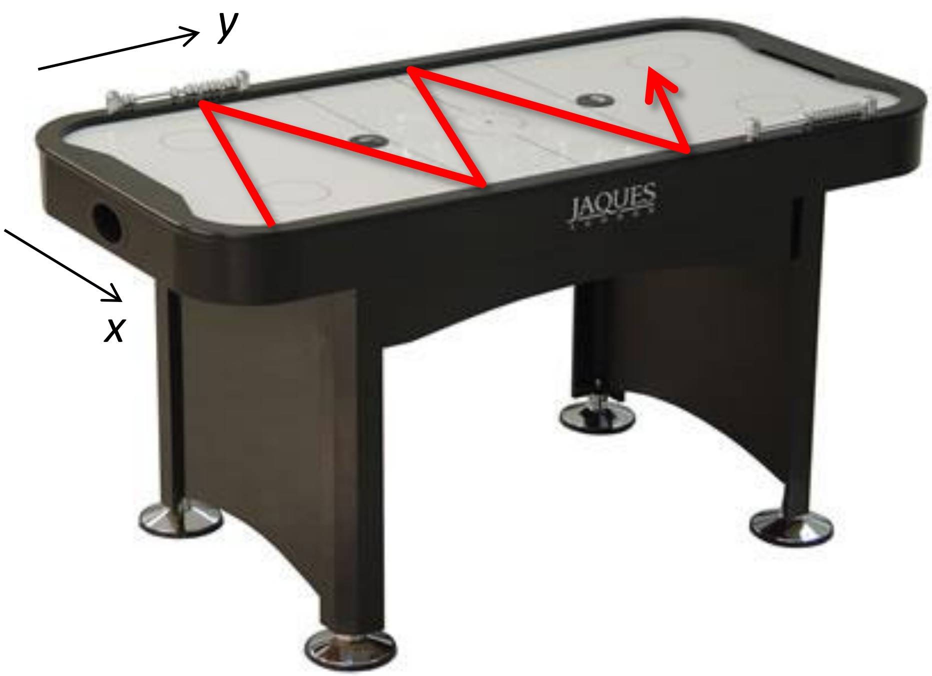


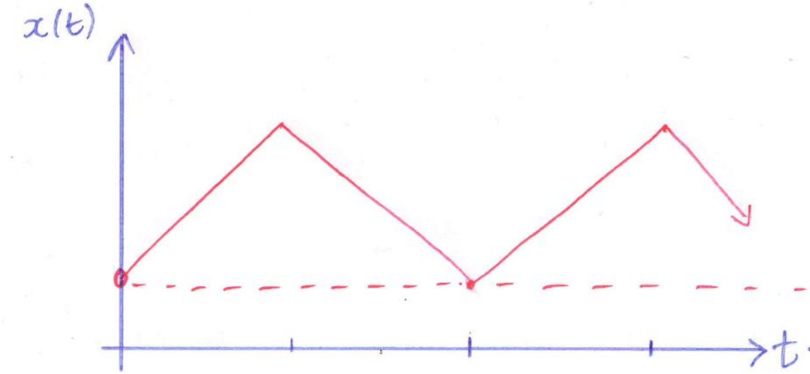


The instantaneous acceleration (*Beschleunigung*) is a vector orientated parallel to d**v**(t)

It´s magnitude is:

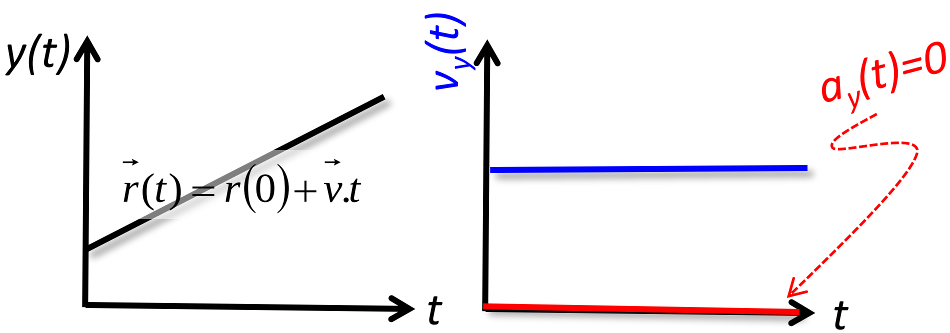
$$\vec{a}(t) = \{\dot{v}_x(t), \dot{v}_y(t), \dot{v}_z(t)\} = \{\ddot{x}(t), \ddot{y}(t), \ddot{z}(t)\}$$

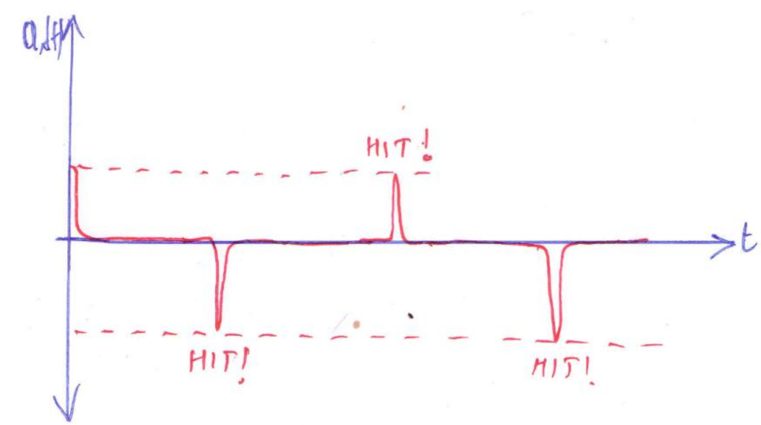




Important special cases

(i) Uniform linear motion (like *y* in above example)





$$\vec{v}(t) = \frac{d\vec{r}(t)}{dt} = \vec{v} = const$$

$$\vec{a}(t) = \frac{d\vec{v}(t)}{dt} = 0$$

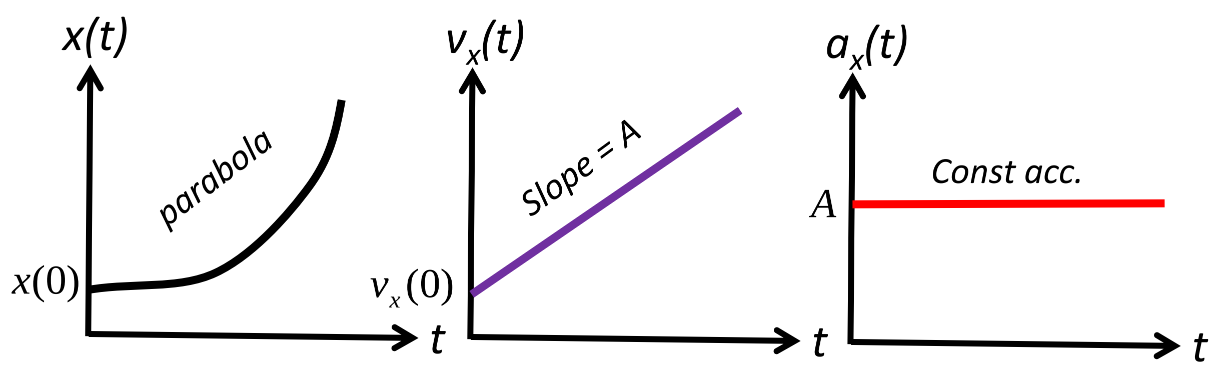
1.2.4 Integrating Trajectories

Example 2) Constant acc (A) along $\mathbf{e}_x$.

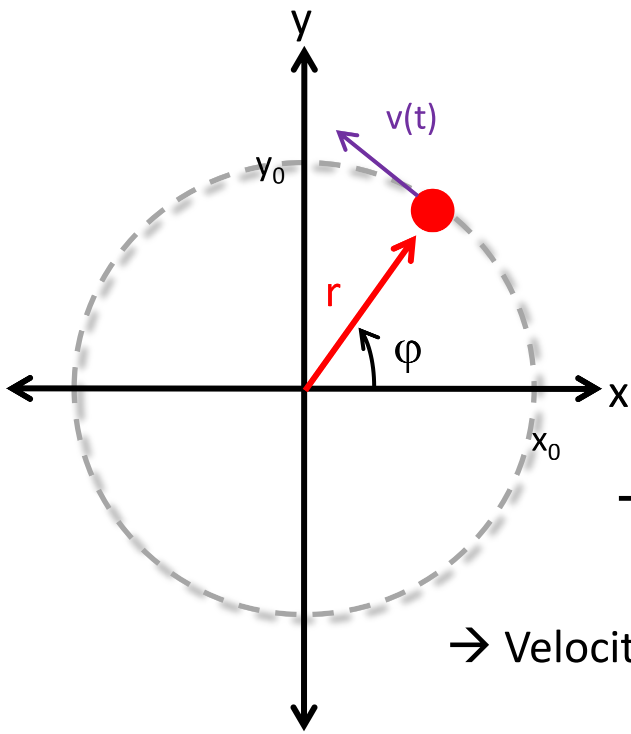
$$\vec{a}(t) = \frac{d\vec{v}}{dt} = \{A, 0, 0\}$$

$$\vec{v}(t) = \{At + v_x(0), 0, 0\} = \frac{d\vec{r}}{dt}$$

$$\vec{r}(t) = \left\{\frac{At^2}{2} + v_x(0)t + x(0), 0, 0\right\}$$



Example (iii) Constant circular motion (HARMONIC MOTION)



→ circular co-ordinates match the symmetry of the problem

$$r = \left|\vec{r}(t)\right| = \sqrt{x^2 + y^2} = const = x_0 = y_0$$ AMPLITUDE

$$\varphi = \omega t + \varphi(0)$$ PHASE

$$\omega = \frac{d\varphi}{dt} = \dot{\varphi}$$ Angular velocity $\omega = const$

→ Ansatz $x(t) = x_0 \cos(\omega t + \varphi(0))$ $y(t) = y_0 \sin(\omega t + \varphi(0))$

→ Velocity $v_x(t) = \dot{x}(t) = -\omega x_0 \sin(\omega t + \varphi(0))$ $v_x(t) = \omega y_0 \cos(\omega t + \varphi(0))$

$$\vec{v}(t) = (v_x(t), v_y(t), 0) \Rightarrow \left|\vec{v}\right| = \sqrt{v_x{}^2 + v_y{}^2} = \sqrt{\omega^2 x_0^2 + \omega^2 y_0^2} = \omega r$$

$$v = \omega r$$

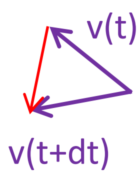
Magnitude of velocity stays constant, but direction constantly changing (acceleration always non zero)

$$\vec{a}(t) = \frac{d\vec{v}}{dt} = \left\{-\omega^2 x_0 \cos(\omega t + \varphi(0)), -\omega^2 y_0 \sin(\omega t + \varphi(0)), 0\right\}$$

Towards orbit center

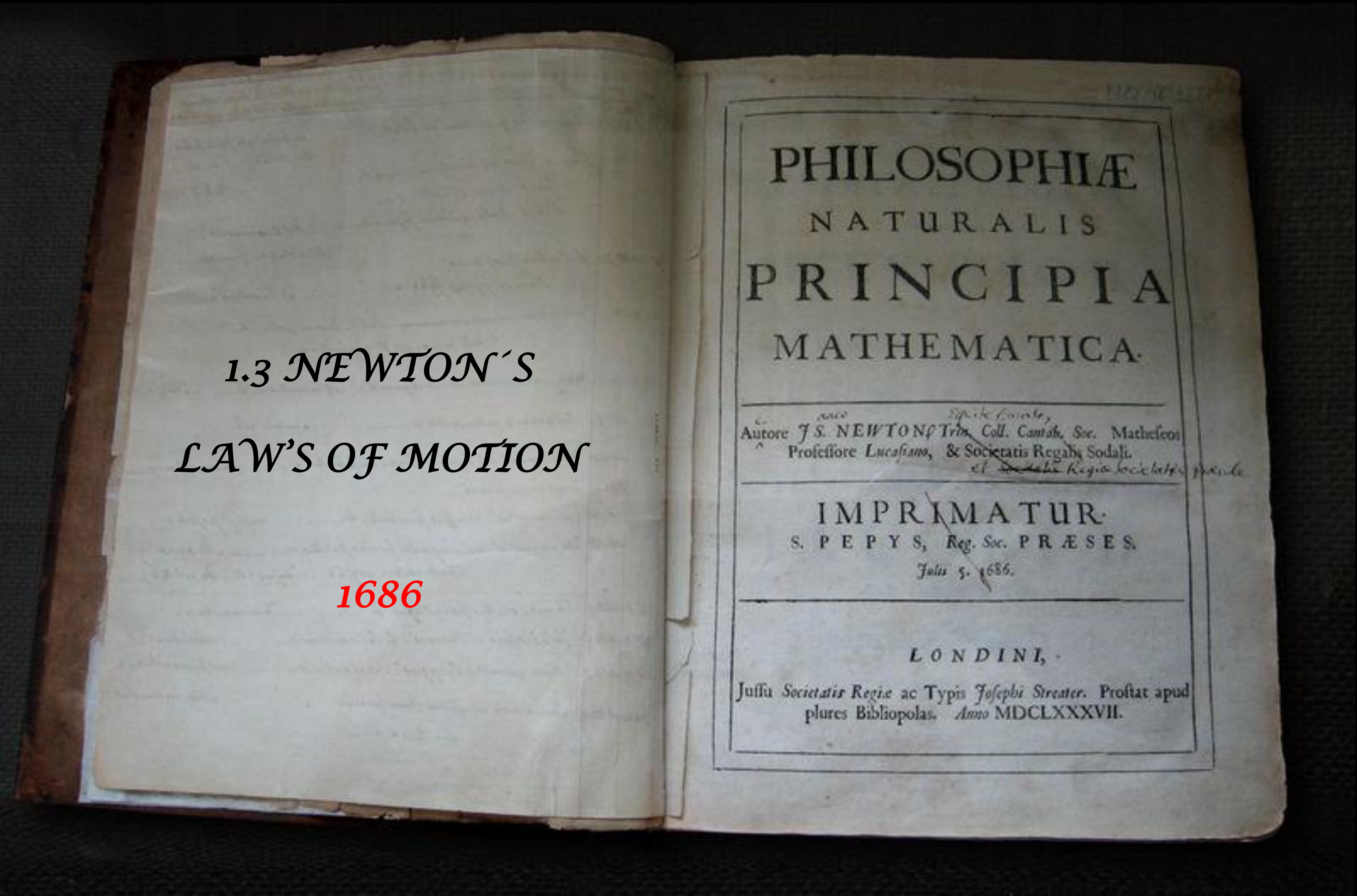
$$\left|a(t)\right| = -\omega^2 r$$

dv(t) || a(t)



1.3 NEWTON´S LAW'S OF MOTION

1686



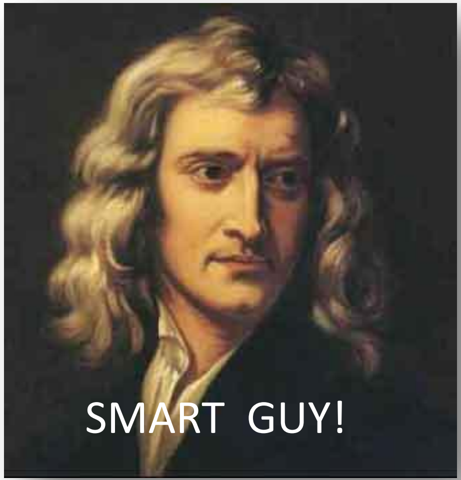
1.3.1 Let's do some "inductive reasoning"

- Q) When is the position of an object described by $\vec{r}(t) = (x_0, 0, 0)$?

- Q) When does an object move according to $\vec{r}(t) = (v_x t, 0, 0)$?

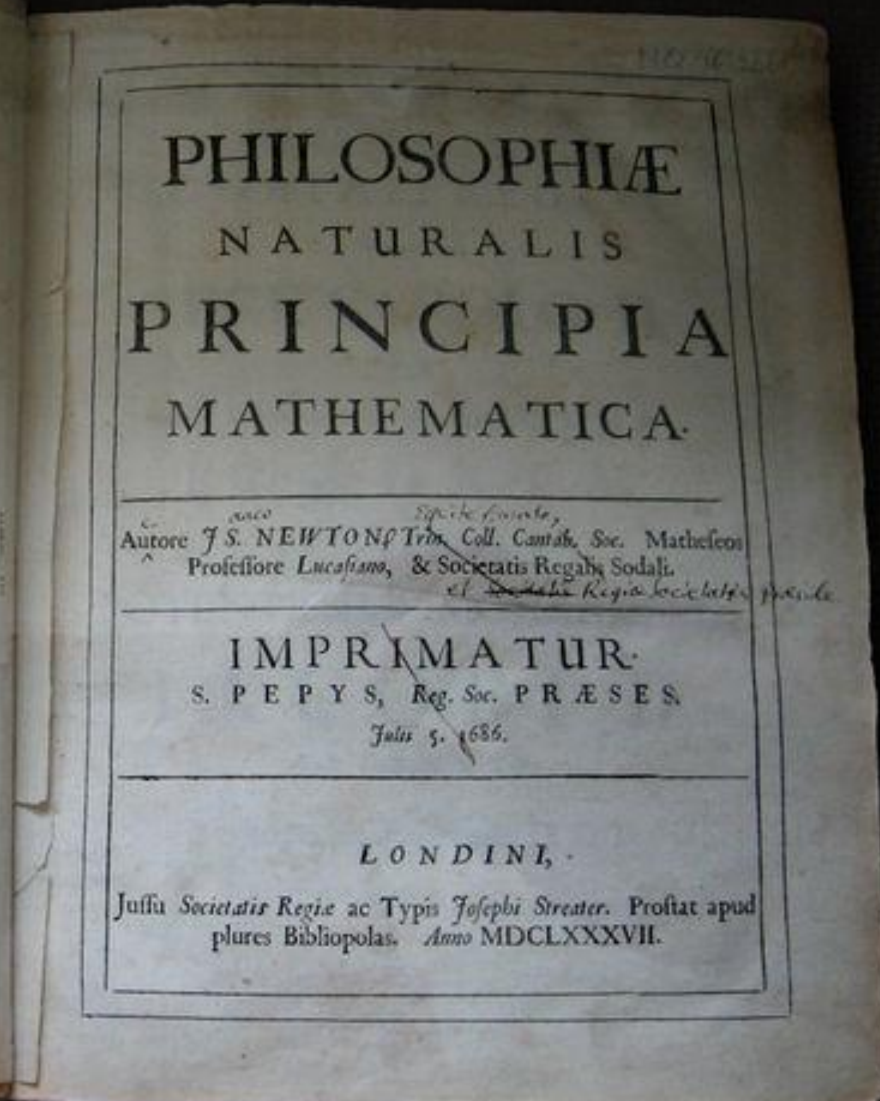
  A) When it is left by itself!

→ *Newton "genius" was that he postulated that "all objects behave this way"*



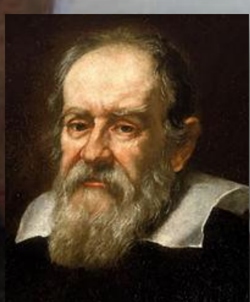
NEWTONS FIRST LAW

"An object at rest tends to stay at rest and an object in motion tends to stay in motion"



Law of inertia or momentum

$P_{initial} = P_{final}$



Also written down by Galileo 35 years earlier! ☺

1.3.2 Let's do some more "inductive reasoning"

- When is the position of an object described by $\vec{r}(t) = (x_0, 0, 0)$?
- When does an object move according to $\vec{r}(t) = (v_x t, 0, 0)$?
- Q) When does an object move according to $\vec{r}(t) = (\frac{a}{2} t^2, 0, 0)$?

To change the velocity of something, we have to "push" (our arms get's tired!)

Larger changes in velocity for the same object require larger pushes

Define the "amount of pushing" as FORCE
$F \sim \Delta v / \Delta t$

"amount of pushing needed to change v depends on body's to ***mass***
$F \sim m$

1.3.2
NEWTONS SECOND LAW

"The force required to change the velocity of an object is proportional to the mass of the object times the induced acceleration"

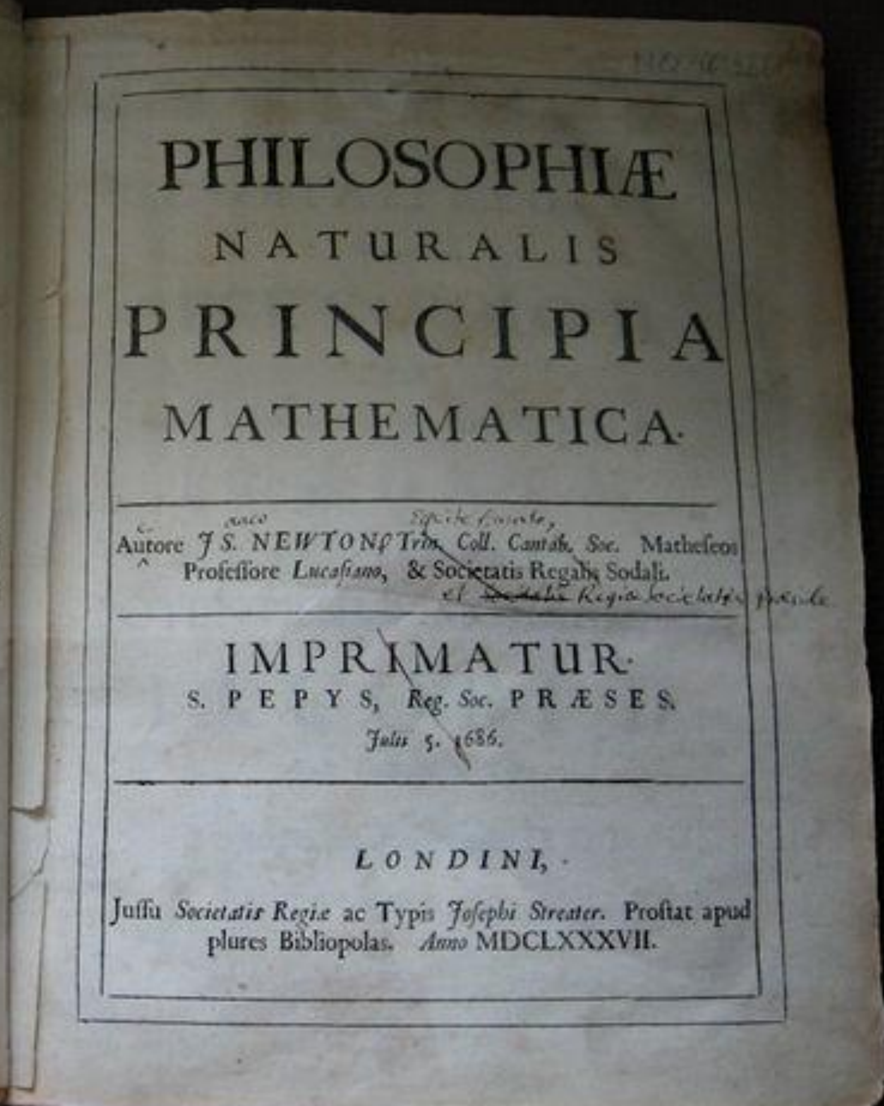
$$\vec{F} = m\frac{d\vec{v}}{dt} = m\vec{a}$$

$$\vec{F} = \begin{pmatrix} F_x \\ F_y \\ F_z \end{pmatrix} = m\begin{pmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{pmatrix}$$

3 laws in one !

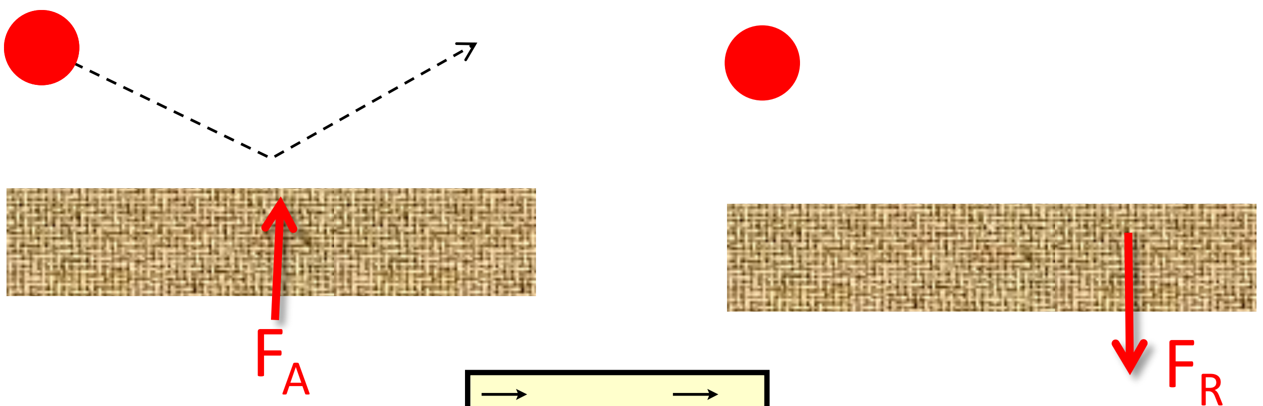
2nd order differential equation

→ Will require 2 initial conditions, i.e. $x(0)$ and $v_x(0)$ to solve



1.3.3 Yet more "inductive reasoning"

- When is the position of an object described by $\vec{r}(t) = (x_0, 0, 0)$?
- When does an object move according to $\vec{r}(t) = (v_x t, 0, 0)$?
- Q) When does an object move according to $\vec{r}(t) = (\frac{a}{2} t^2, 0, 0)$?



$$\vec{F}_A = -\vec{F}_R$$

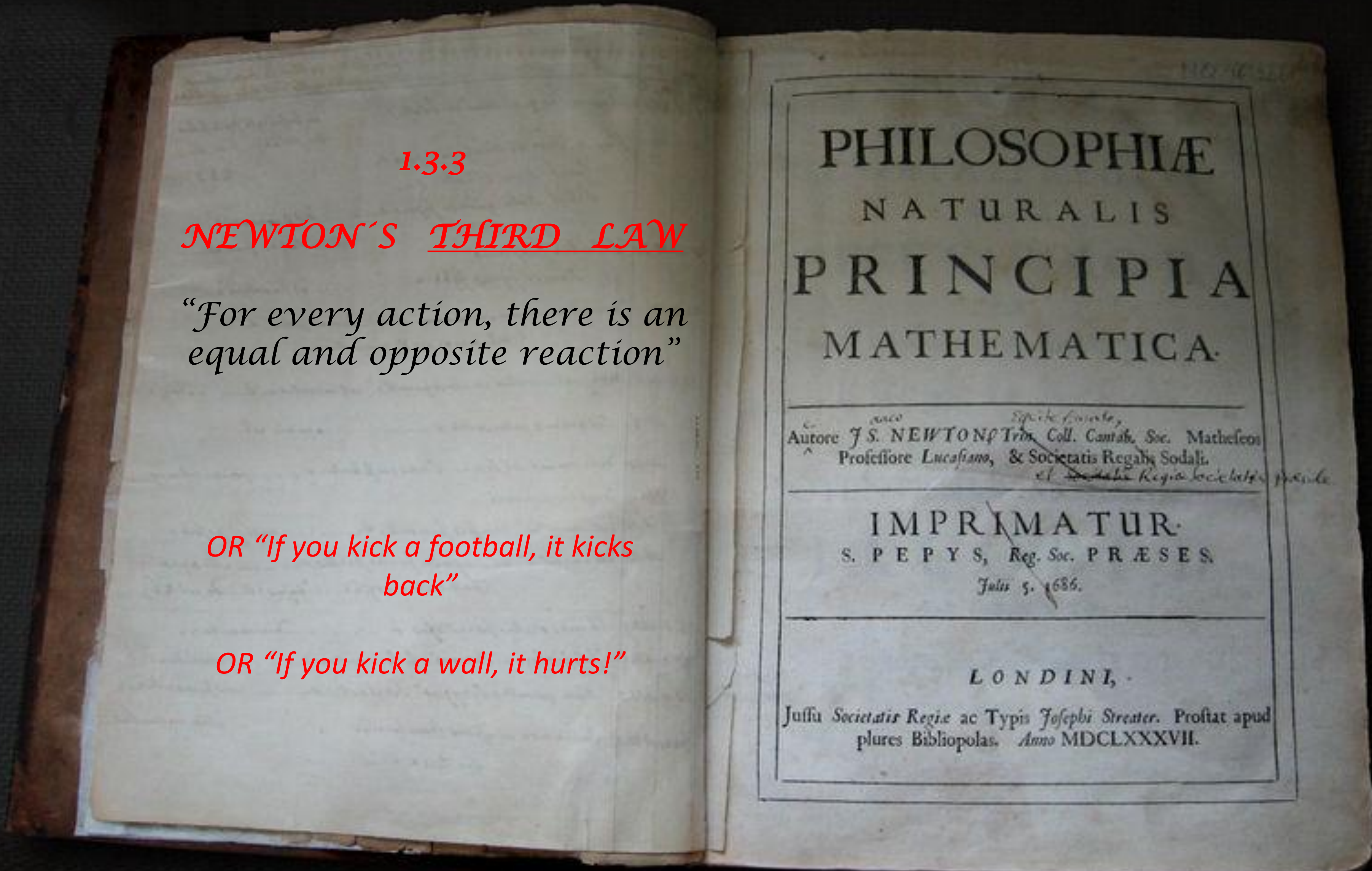
1.3.3

NEWTON´S THIRD LAW

"For every action, there is an equal and opposite reaction"

OR "If you kick a football, it kicks back"

OR "If you kick a wall, it hurts!"



THE MATHEMATICAL PRINCIPLES *OF* NATURAL PHILOSOPHY.

DEFINITIONS.

DEFINITION I.

THE QUANTITY OF MATTER IS THE MEASURE OF THE SAME, ARISING FROM ITS DENSITY AND BULK CONJUNCTLY.

Thus air of a double density, in a double space, is quadruple in quantity; in a triple space, sextuple in quantity. The same thing is to be understood of snow, and fine dust or powders, that are condensed by compression or liquefaction; and of all bodies that are by any causes whatever differently condensed. I have no regard in this place to a medium, if any such there is, that freely pervades the interstices between the parts of bodies. It is this quantity that I mean hereafter everywhere under the name of body or mass, And the same is known by the weight of each body; for it is proportional to the weight, as I have found by experiments on pendulums, very accurately made, which shall be shewn hereafter.

DEFINITION II.

THE QUANTITY OF MOTION IS THE MEASURE OF THE SAME, ARISING FROM THE VELOCITY AND QUANTITY OF MATTER CONJUNCTLY.

The motión of the whole is the sum of the motions of all the parts; and therefore in a body double in quantity, with equal velocity, the motion is double; with twice the velocity, it is quadruple.

DEFINITION III.

THE *VIS INSITA*, OR INNATE FORCE OF MATTER, IS A POWER OF RESISTING, BY WHICH EVERY BODY, AS MUCH AS IN IT LIES, ENDEAVOURS TO PERSEVERE IN ITS PRESENT STATE, WHETHER IT BE OF REST, OR OF MOVING UNIFORMLY FORWARD IN A RIGHT LINE.

This force is ever proportional to the body whose force it is: and differs nothing from the inactivity of the mass, but in our manner of conceiving it. A body, from the inactivity of matter, is not without difficulty put out of its state of rest or motion. Upon which account, this *vis insita*, may, by a most significant name, be called *vis inertiæ*, or force of inactivity. But a body exerts this force only when another force, impressed upon it, endeavours to change its condition; and the exercise of this force may be considered both as resistance and impulse; it is resistance, in so far as the body, for maintaining its present state, withstands the force impressed; it is impulse, in so far as the body, by not easily giving way to the impressed force of another, endeavours to change the state of that other. Resistance is usually ascribed to bodies at rest, and impulse to those in motion; but motion and rest, as commonly conceived, are only relatively distinguished; nor are those bodies always truly at rest, which commonly are taken to be so.

But how we are to collect the true motions from their causes, effects, and apparent differences; and, *vice versa*, how from the motions, either true or apparent, we may come to the knowledge of their causes and effects, shall be explained more at large in the following tract For to this end it was that I composed it.

THE LAW'S

1) An object at rest or uniform motion remains unchanged

2) Force = Mass x Acceleration

3) "For every action, there is an equal and opposite reaction"

Some notes...

1) Law 1 is just a special case of 2 when $|F|=0$

2) There is a defined linear relationship between **F** and **a** (cause and effect), the mass m is defined as the constant of proportionality – m_i the **inertial mass** (träger Masse)

3) From law 2, the unit of force is defined as [F]=kgm/s2=N – the Newton

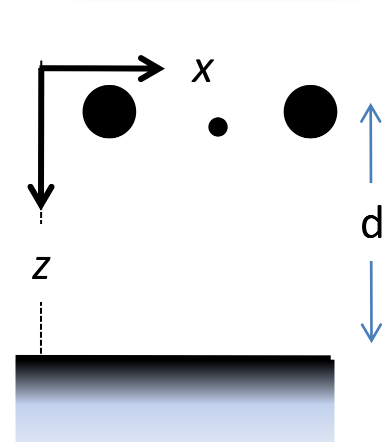
4) For m=const, we have:

$$\vec{F} = m\vec{a} = \frac{d}{dt}(m\vec{v}) = \frac{d\vec{p}}{dt}$$

5) If F=0, we have d**p**/dt=0 and linear momentum is a **conserved quantity**

Examples of applying Newton´s laws

Examples and applications of Newton´s Laws



Example 1) Free fall on earth

Galileo showed experimentally that all bodies fall to earth in the same time

→ Ratio's of the displacement from start over the same time interval = *1,3,5,7,9...*

because

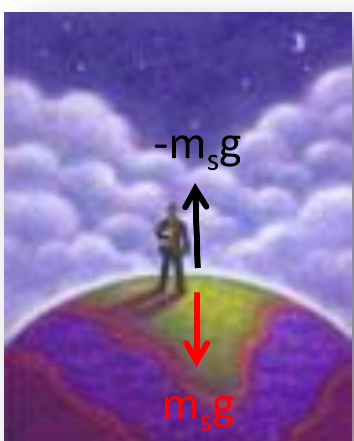
$$\sum_{n=1}^{N}(2n-1) = N\frac{1}{2}\left(1+(2N-1)\right) = N^2$$

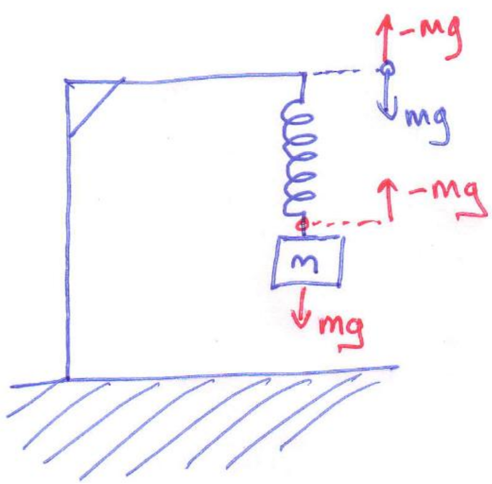
arithmetic series

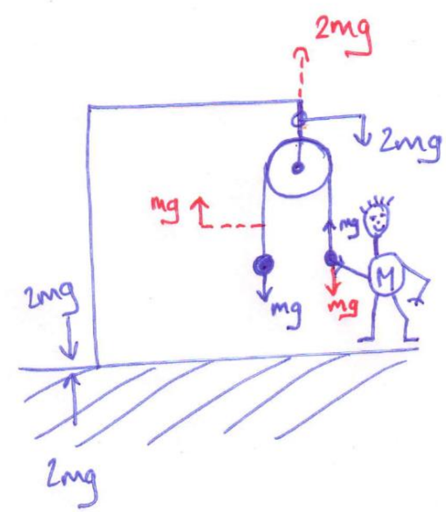
$$= 1 + 3 + 5 + 7 + \ldots\ldots$$

→ Acceleration due to gravity $g=9.80665\ m/s^2$ (varies on earth $\pm 0.01 m/s^2$, larger near poles)

→ One defines the **gravitational force $F_G=m_s g$**, where m_s is the **gravitational mass (weight)**, which can be very different to the **inertial mass** used in Newton´s 2nd law

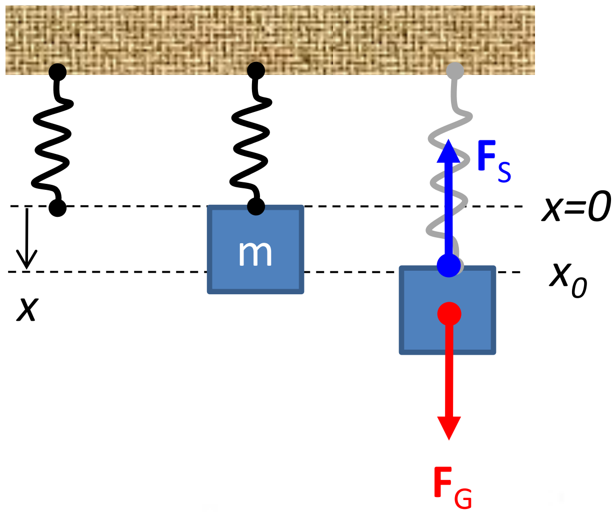






All physicists *love* masses on springs

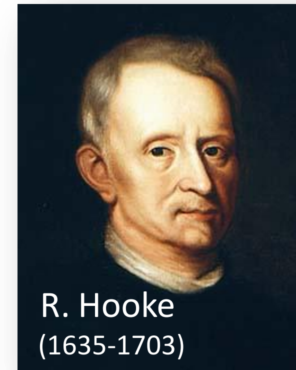
Springs are devices that are capable of storing mechanical energy



To a fairly good approximation, springs obey Hooke´s law

$$\vec{F}_s = -k\overrightarrow{\Delta s}$$

↑ Spring constant



"As the extension, so the force."

Spring

SPRING CONSTANT

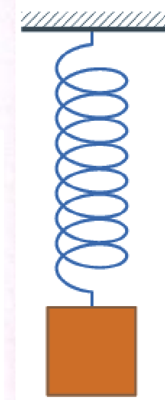
$\vec{F}_s = -k\vec{x}$

$x(t) = x_0$

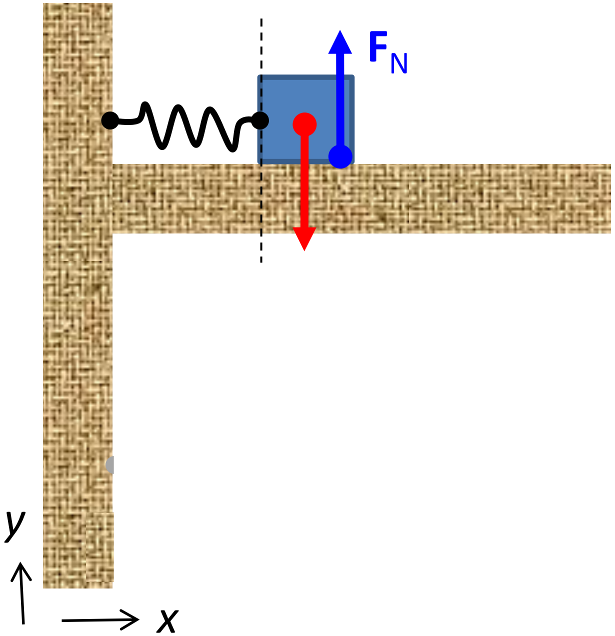
⇓

$a = \ddot{x}(t) = 0$

$\vec{F}_{TOT} = \vec{F}_s + \vec{F}_g = m\vec{a}$



This alternative "mode" of motion can be easily studied by looking at a mass attached to a spring on a frictionless surface (e.g. air hockey table)



Start mass at a distance x_d and then let go.

$$\vec{F}_{TOT} = \vec{F}_s + \vec{F}_g + \vec{F}_N = m\vec{a} \quad \text{(Newton II)}$$