# Introduction to Physics I

For Biologists, Geoscientists, & Pharmaceutical Scientists


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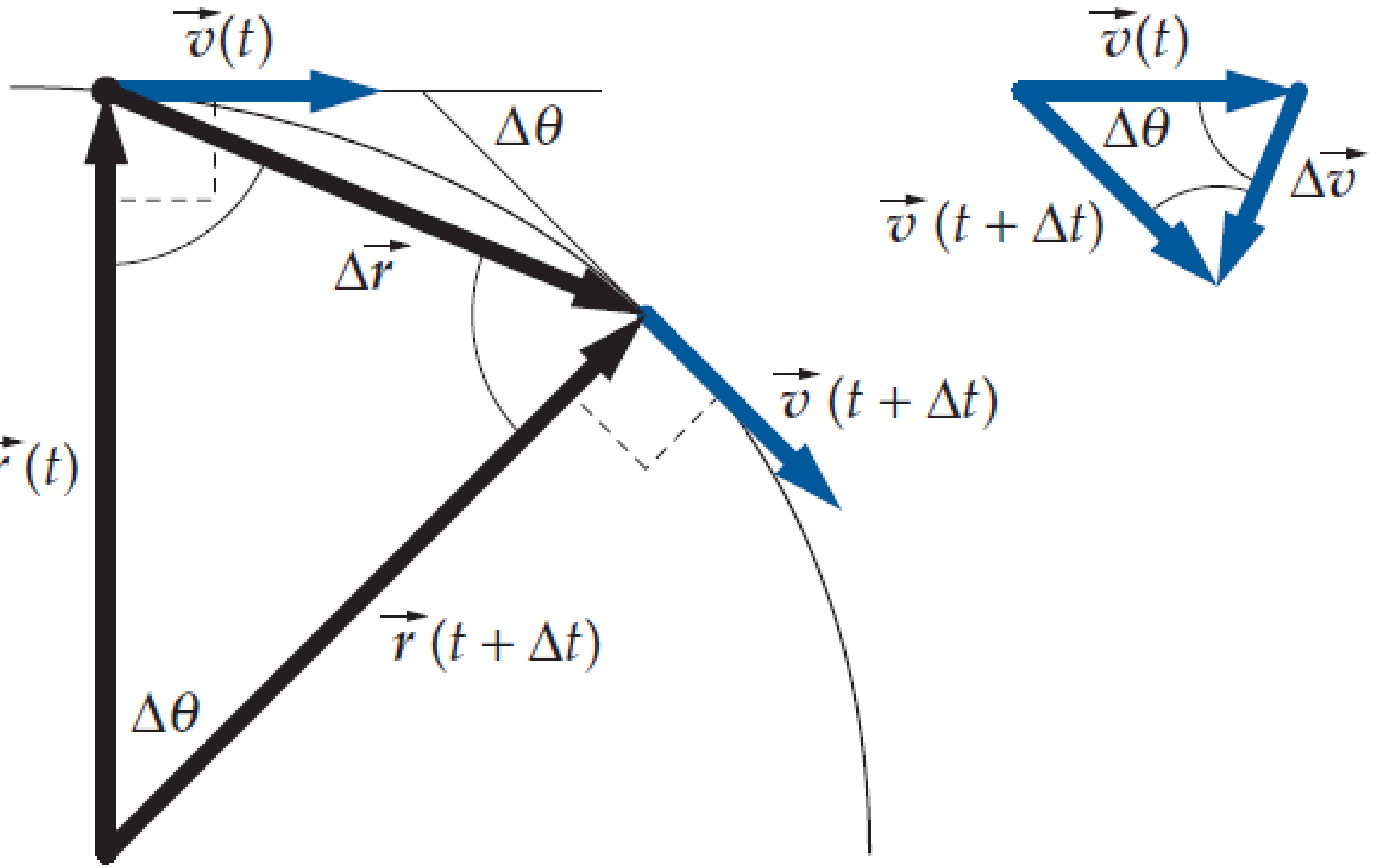
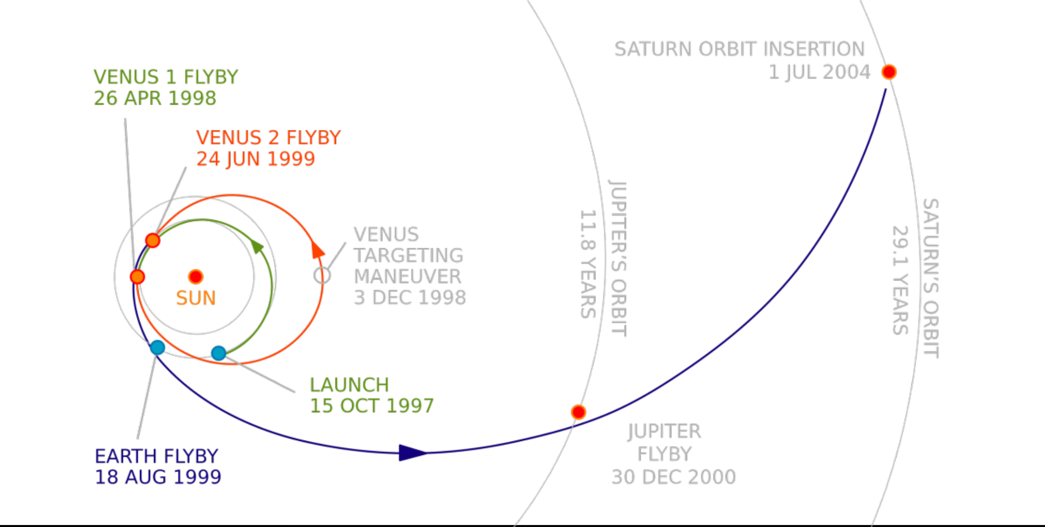
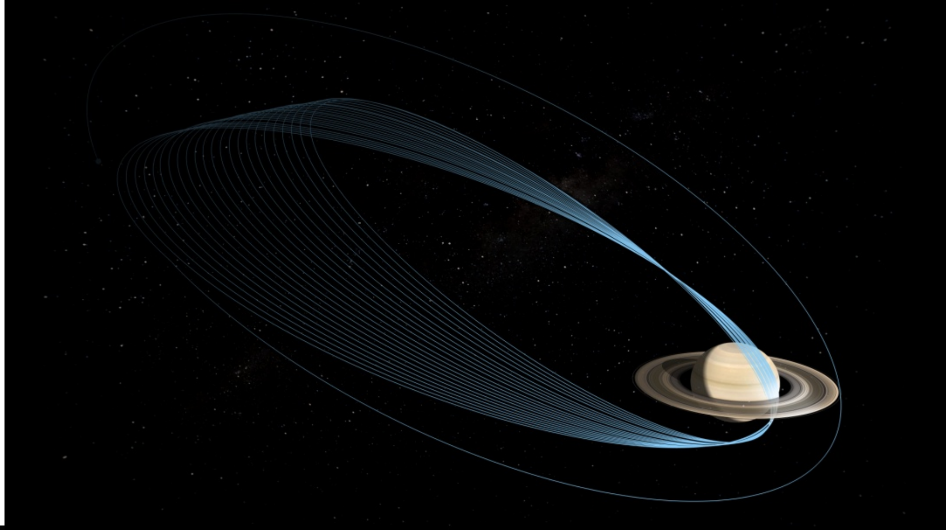


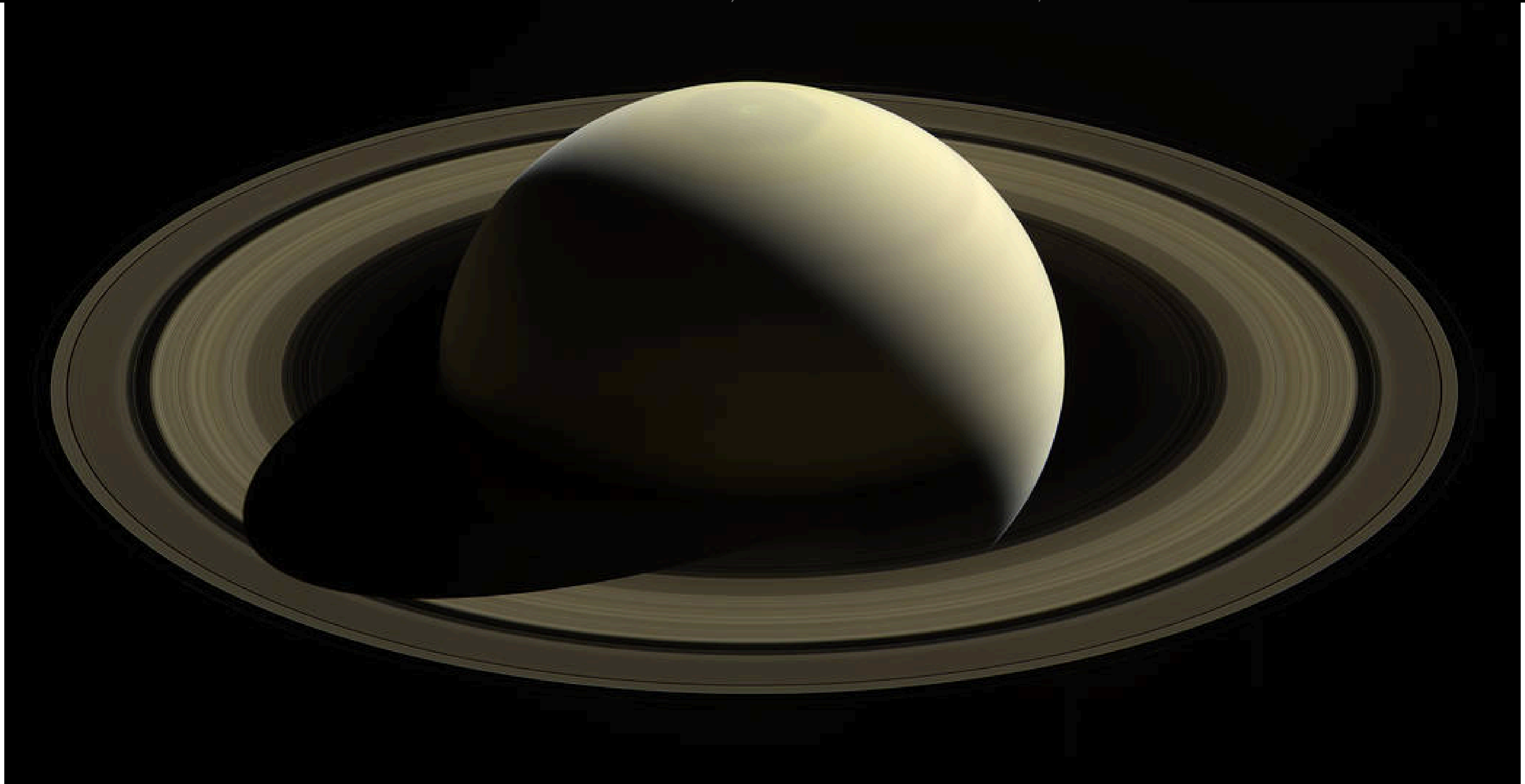

**FIGURE 3-24**

Tipler, Mosca, 6$^{th}$ ed.

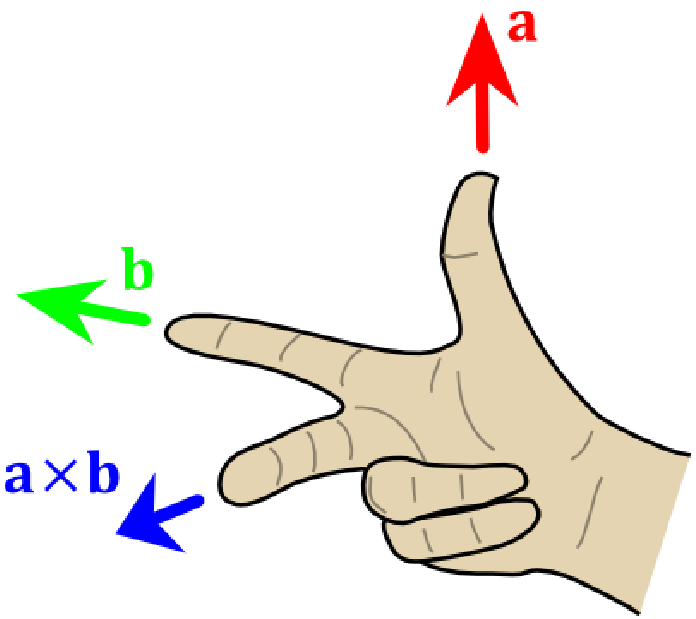


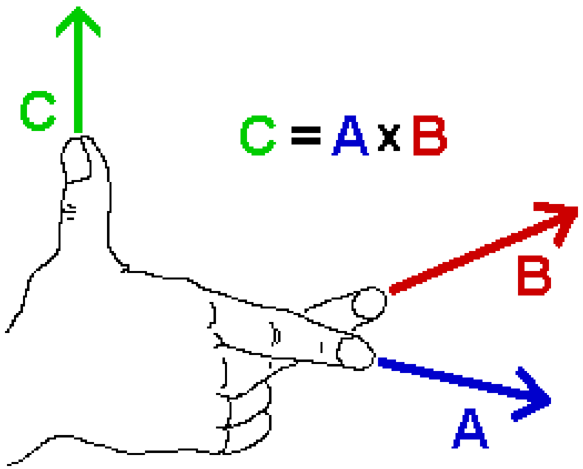



*Final orbits (Artist's view)*



**Cassini mission, NASA**


a
b
a×b


C
C = A x B
B
A

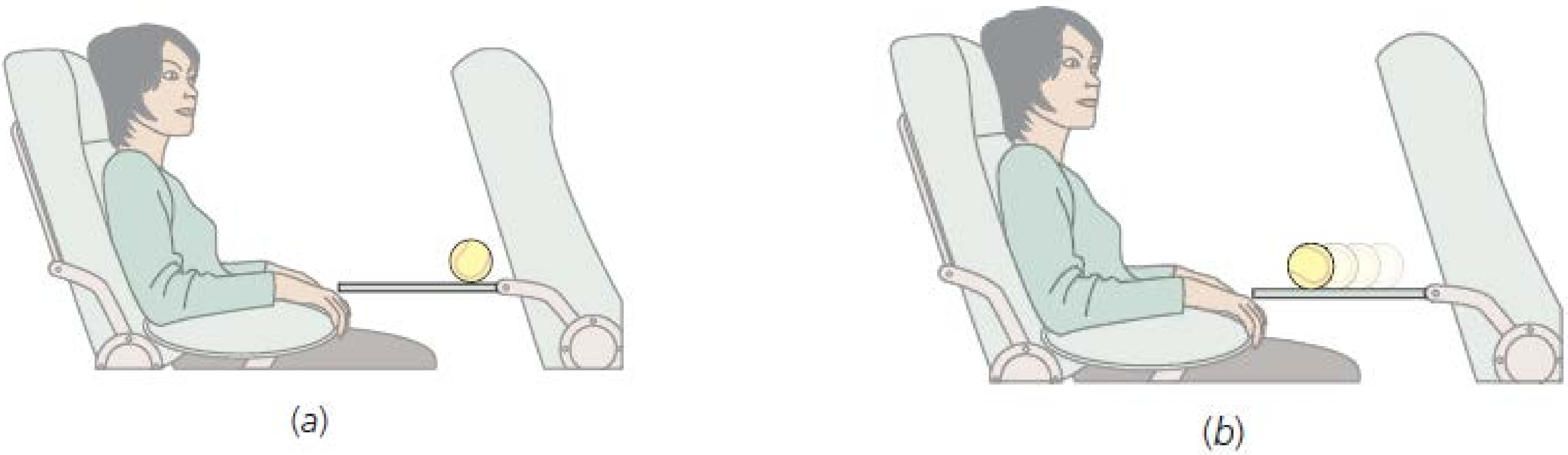



**FIGURE 4-1** The plane is flying horizontally in a straight path at constant speed when you place a tennis ball on the tray. (*a*) The plane continues to fly at constant velocity (relative to the ground) and the ball remains at rest on the tray. (*b*) The pilot suddenly opens the throttle and plane rapidly gains speed (relative to the ground). The ball does not gain speed as quickly as the plane, so it accelerates (relative to the plane) toward the back of the plane.

Tipler, Mosca, 6th ed.

# Newton’s First Law

- An object at rest remains at rest *unless* acted on by an external force.

- An object in motion continues to travel with constant velocity *unless* acted on by an external force.

*This is also known as the ‘Law of Inertia’.*

# Newton’s Second Law

- The force acting on an object is equal to its acceleration times its mass.

- Mathematically:
  - $\vec{F} = m\vec{a}$

- Furthermore:
  - $\vec{F} = m\vec{a} = m\frac{d\vec{v}}{dt} = \frac{d}{dt}(m\vec{v})$, where $m\vec{v}$ is the momentum.

# Newton’s Third Law

- When two objects A and B interact, the force $\vec{F}_{BA}$ exerted by B on A is equal in magnitude and opposite in direction to the force $\vec{F}_{AB}$ exerted by A on B.

- Mathematically:
  - $\vec{F}_{BA} = -\vec{F}_{AB}$

Man hat einen Ball der Masse $m$. Man nimmt drei verschiedene Situationen an:

- (i) Der Ball bewegt sich mit der Geschwindigkeit $v$, und wird zur Ruhe gebracht.
- (ii) Der Ball wird aus der Ruhe auf die Geschwindigkeit $v$ gebracht.
- (iii) Der Ball bewegt sich mit der Geschwindigkeit $v$, und wird zur Ruhe gebracht. Gleich darauf wird er wieder auf die Geschwindigkeit $v$, in umgekehrter Richtung gebracht.

In welcher Situation erfährt der Ball die grösste Impulsänderung?

1. (i)
2. (ii)
3. (iii)
4. (i) und (ii)
5. Die Impulsänderung ist in allen Fällen gleich.

**Antwort: 3.**

Die Impulsänderung beträgt im ersten Fall:

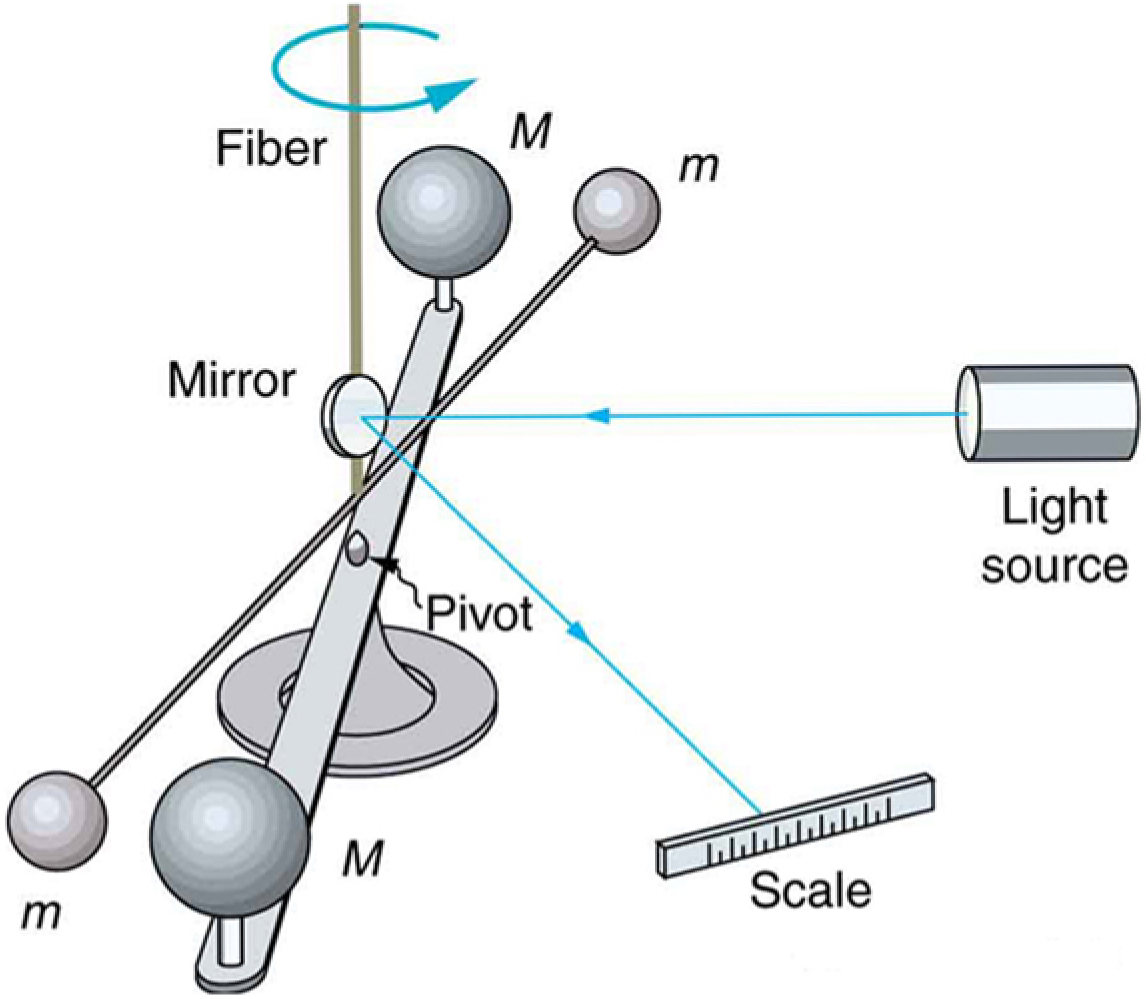
$$\Delta p = 0 - mv = -mv$$

, im zweiten Fall:

$$\Delta p = mv - 0 = mv$$

, und im dritten Fall:

$$\Delta p = m(-v) - mv = -2mv$$




Cavendish pendulum

Exp Freier Fall quantitativ: • ball falling from ceiling, meas. g

$$x(t) = \frac{1}{2}at^2 + v_0 t + x_0$$

$v_0 = 0 \qquad x_0 = 4.92\,m$

$$-4.92 = \frac{1}{2}\cdot(+a)\cdot t^2 \qquad , \quad t \sim 1s$$

$$\Rightarrow a \cong -9.84 \frac{m}{s^2} \qquad , \quad \text{gravitation}$$

Exp freier fall, qualitativ

plume and ball in tube a) air

b) no air

# Phys I: Mass and force — Dynamics of motion

So far: motion / kinematics considered, but not the causes of motion

why do objects start to move?
what causes a moving object to change speed and/or direction?

→ Newton (Galileo) → 3 basic laws of motion
(classical mechanics)

(Slide) Tipler Fig 4-1: Tennis ball on table in plane

a) const speed (plane): ball remains at its position

b) plane accelerates ($a \neq 0$): ball does not gain speed as quickly as plane ... accelerates towards back of plane (relative to plane)

for object to move: needs "action"; this force ... to a ch...
force ↗

Exp LKB
(1) Luftkissenbahn
(3)

(slide) Law of inertia, Newton's 1st law

force: external influence (action) acting on an object

$\vec{F}$: vector quantity

- contact forces (hitting a ball, shoes on ground)
- action at a distance (gravitation, electrical forces) forces em ↗

Principle of superposition: $\vec{F}_{total} = \vec{F}_1 + \vec{F}_2 + \ldots$
$= \sum_i \vec{F}_i$

net force

$[F] = N$
Newton

Exp. <u>LKB (Luftkissen Bahn) for 1st law (inertia)</u>

cart moving on air cushion (no friction)

→ will not stop or change direction without a force acting on it

## Mass

observation: objects resist being accelerated

mass = measure of an object's inertia; property of matter

$[m] = kg$

density: $\rho = \frac{m}{V}$, $[\rho] = \frac{kg}{m^3}$

→ relation between force, mass and acceleration?

Slides Newton 2nd law

Newton 3rd law

Exp. Flasche, Kraftzerlegung (2)

(3) Seilziehen

Second law, Newton:

$$\vec{F} = \frac{d}{dt}(m \cdot \vec{v}) \overset{m = const}{=} m \cdot \vec{a}$$

net force acting on an object

~~momentum is a vector~~ -- (Hockey!)

units: $N = kg \cdot \frac{m}{s^2}$

· Note: momentum $\vec{p} = m \cdot \vec{v}$, $[\vec{p}] = kg \cdot m/s$

and $\vec{F} = \frac{d\vec{p}}{dt}$, change of momentum, vector quantity

velocity change

or mass change ...

$\sum \vec{F} = 0 \Rightarrow \sum \dot{\vec{p}} = 0$ and $\sum \vec{p} = const$ || in a closed system (no external force), the total momentum is constant

◦ from Object perspective : $\vec{F}$ : net force on an object $\vec{F} = \sum \vec{F}_i$

$\vec{a} \propto \vec{F}$ (prop. to) $\qquad |\vec{F}| \nearrow \Rightarrow |\vec{a}| \nearrow$

mass effect ? if $m$ large $\nearrow$ (for given $|\vec{F}|$), $|\vec{a}|$ small $\searrow$

$\Rightarrow |\vec{a}| \propto \frac{1}{m}$

$\Rightarrow \quad \vec{a} \overset{?}{=} \frac{\vec{F}}{m}$ , vectors, $\vec{a}$ along $\vec{F}$ direction, same sign.

◦ example of masses : bike ~ 10 kg
car ~ $10^3$ kg
train ~ $10^6$ kg
earth $\gtrsim 10^{24}$ kg
red blood cell ~ $10^{-12}$ kg
(small) atom ~ $10^{-26}$ kg

densities : air (20°C) ~ 1.3 kg/m³
water (20°C) ~ $10^3$ kg/m³
wood 400 - 800 kg/m³
steel ~ $8 \cdot 10^3$ kg/m³
Pt ~ $21 \cdot 10^3$ kg/m³

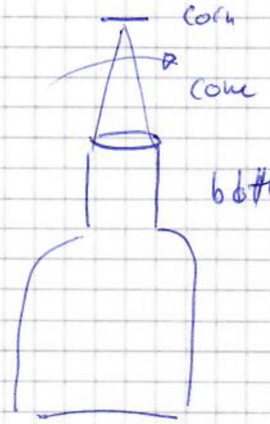
atom nucleus ~ $10^{17}$ kg/m³

best vacuum on earth / lab ~ $10^{-16}$ kg/m³

matter in interstellar space ~ $10^{-21}$ kg/m³

◦ unified atomic mass unit $\qquad 1\,u = 1.66 \; 10^{-27}$ kg
$= \frac{1}{12}$ Carbon atom mass

Exp: Flasche, Kegel, Münze

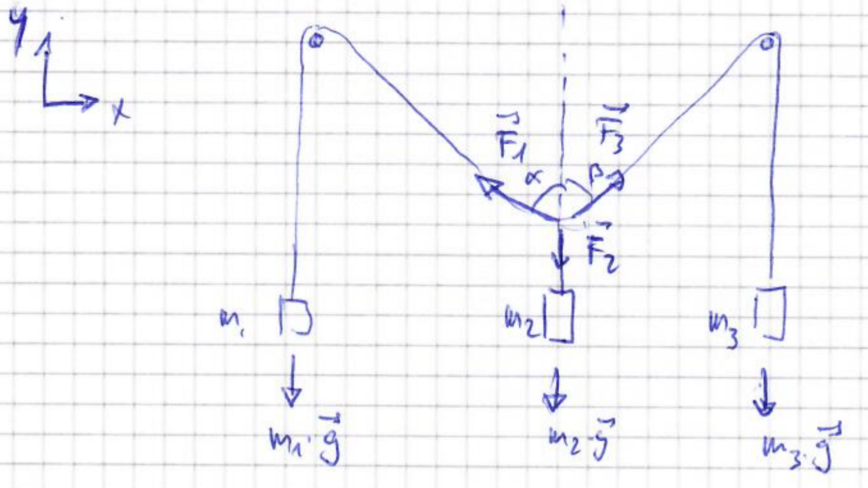



remove cone fast (push at top)

only $\vec{F}_G$, no additional force,

=> coin falls in bottle

Exp. zero net force, suspended masses, with ~~wire~~ wire




masses chosen

$m_1 = 5N$

$m_2 = 10N$

$m_3 = 8.7N$

Equilibrium ...?

- angles
- masses

Superposition of vectors : $\sum \vec{F_i} = 0$ at rest (equilibrium)

$$\vec{F_1} + \vec{F_2} + \vec{F_3} = 0$$

along x : $F_1 \cdot \sin\alpha = F_3 \cdot \sin\beta$

" y : $F_2 = F_1 \cdot \cos\alpha + F_3 \cdot \cos\beta$

$$\Rightarrow \left\| \; \frac{F_3}{F_1} = \tan(\alpha) = \frac{m_3}{m_1} \right. \quad \text{(angle found)}$$

$$\uparrow \; F_i = m_i \cdot g$$

Observe : $\alpha + \beta = 90°$

for this choice of masses

$\beta = 90 - \alpha$

$\sin\beta = \sin(90 - \alpha) = \cos\alpha$

$\cos\beta = \cos(90 - \alpha) = \sin\alpha$

Exp suspended mass, continued

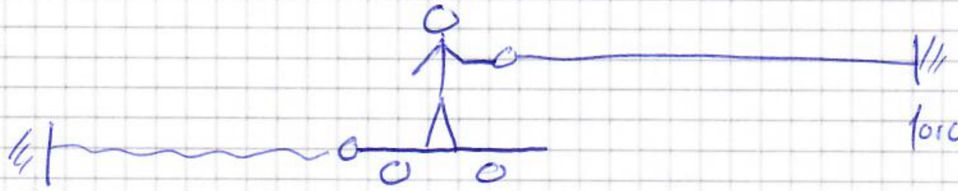

also vector addition ($\Sigma \vec{F} = 0$):

and $F_1^2 + F_2^2 = F_3^2$

$\| \; m_1^2 + m_2^2 = m_3^2$ relation between masses for equilibrium

(with $\tan \alpha = \frac{m_3}{m_1}$)

Exp. Seilziehe, car and pulling on cords




a) show force sensors separately
b) at rest, no force (on cord, no pulling)
c) pull on rope: show both forces ~~idem~~ identical

Note: we measure the module/amplitude of the force.

So in summary:

- net force = $\sum \vec{F_i}$, addition of vectors
- that means also: a force acting on an object can be compensated by counteracting forces

→ levitation, for instance: magnetic cf Phys II, levitating frog
- in space: why astronauts "float"?

(ask) Fundamental interactions in nature

- gravitational interaction : long range
  due to mass
  (exchange of hypothetical particles : graviton?)

Note: detection of gravitational waves, Kavli prize 2016, R. Drever, K. Thorne, R. Weiss
$\frac{\Delta L}{L} = 10^{-21}$; 1 atom size difference over $10^8$ km (Sun-Venus; Sun earth: $150 \cdot 10^6$ km)

electro-weak interaction (unified interaction):

- electromagnetic interaction : long range
  due to charges (and charges in motion)
  (exchange of photons)

- weak interaction : very short range
  between sub-nuclear particles
  exchange/production of (W and Z) bosons
  (Nobel 2013 P. Higgs, F. Englert : origin of mass of subatomic particles / CERN experiments Atlas & CMS)

( • strong interaction : long-range
  between hadrons* (made of quarks), binding together protons & neutrons to form atomic nuclei
  (exchange of mesons between hadrons, gluons a quarks) )

* mesons : quark/anti-quark
baryons : 3 quarks

Note: • inertial forces are apparent forces ~~arising due to~~ acting on masses whose motion is described in a non-inertial frame of reference (e.g. rotating frame of ref.)
• not due to physical interaction between objects (like gravitation, electrostatics) but due to acceleration of ref. frame

mass & force
(4

## Force due to gravity : weight

- gravitational force : $\vec{F}_g = m \cdot \vec{g}$ , $g = |\vec{g}| = 9.81 \frac{m}{s^2}$

weight of m := $|\vec{F}_g|$ acting on m

- distinction mass and weight
  mass ↑ inertia; weight ↑ force due to gravity

e.g. a) inertia of ball thrown on moon or earth, idem
momentum : $m \cdot \vec{v}$ , depends on v and m
force to launch m horizontally and reach v will be the same

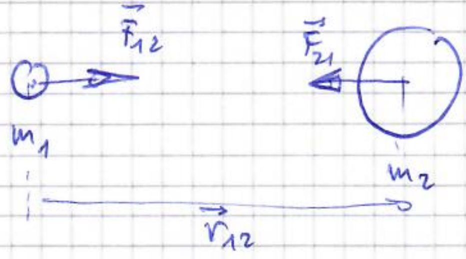
b) weight will be different , as $\vec{g}_{moon} \approx \frac{1}{6} \vec{g}_{earth}$

- origin of force : ~~mass~~ attractive interaction between masses

Gravitations waage
(Cavendish Pendulum)

Exp. Cavendish Pendulum
(Gravitations Waage)
Slide setup, explain

interaction (force) between masses: $\vec{F}_{12} = -\vec{F}_{21}$ (Newton's 3rd law)




- Newton's gravitation law:

$$F = G \cdot \frac{m_1 \cdot m_2}{r_{12}^2} \quad , \quad G = 6.67 \cdot 10^{-11} \frac{N \cdot m^2}{kg^2}$$

universal gravitation constant

NB: $m_i$ denote here gravitational masses (cf Tipler p 370)

equivalence of inertial mass (opposing acceleration) and gravitational mass demonstrated to ~ 1 part in $10^{12}$ ($5 \cdot 10^{13}$)

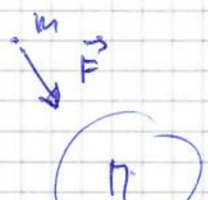
- gravitational field : def "field": associate to each point in space a value for a given physical quantity (scalar or vector)
e.g. Temperature (scalar)
air speed (wind) (vector)

$\vec{F} = m \cdot \vec{g}$

$\vec{g} = \frac{\vec{F}}{m} = \frac{\text{grav. force on test mass } m}{\text{test mass } m}$

gravitational field

with Newton's grav. law




$$|\vec{g}| = \frac{\frac{G \cdot M \cdot m}{r^2}}{m} = \frac{G \cdot M}{r^2}$$

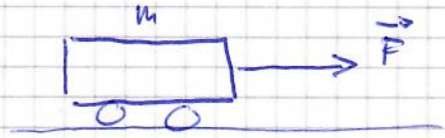
$\simeq 9.81 \frac{m}{s^2}$ , at Earth surface
$r$ = Radius Earth ~ 6'371 km

- Weight of a 1 kg mass

$\vec{F} = m \cdot \vec{g}$ , $F = 1 \cdot 9.81 = \underline{9.81}$ N

## inertial forces

Consider mass m,
accelerated by force $\vec{F}$




a) observer at rest (ref frame is ground):

we have $\vec{F} = \frac{d\vec{p}}{dt} = \frac{d(m\vec{v})}{dt} = m \cdot \vec{a}$, $m = \text{const.}$

$\vec{F} \uparrow\uparrow \vec{a}$

b) observer on car (ref frame is car)

observer feels a force (inertial force, or pseudo force) opposed to the direction of the acceleration

$\sum \vec{F} = 0 \Rightarrow$ inertial force = − force exerted on car

note: observer cannot differentiate the inertial force from a "true" gravitational force for instance

Exp.

. Schnur zerreißen

. Tischlein Deck

29.09

Summary : motion / kinematics : interdependance of quantities

$$\begin{tikzcd}
\text{position vector } \vec{r}(t) \arrow[d, bend right, "\frac{d\vec{r}(t)}{dt}"'] \\
\text{velocity vector } \vec{v}(t) \arrow[u, bend right, "\int \vec{v}(t)\cdot dt"'] \arrow[d, bend right, "\frac{d\vec{v}(t)}{dt}"'] \\
\text{acceleration vector } \vec{a}(t) \arrow[u, bend right, "\int \vec{a}(t)\cdot dt"']
\end{tikzcd}$$

e.g. : $\vec{v}(t) = \dfrac{d\vec{r}(t)}{dt}$     $d\vec{r}(t)$ : infinitesimal displacement vector

hence $d\vec{r}(t) = \vec{v}(t)\cdot dt$

and $\int d\vec{r}(t) = \vec{r}(t)$

$\| \quad \vec{r}(t) = \int \vec{v}(t)\cdot dt$

Similarly $\vec{v}(t) = \int \vec{a}(t)\cdot dt$

29.9.

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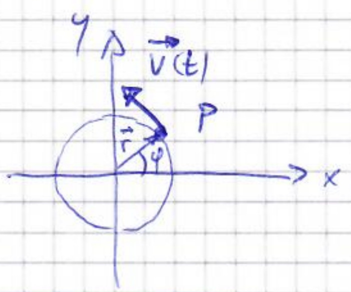
## Circular motion (and harmonic oscillation)

particular case, present in many situations

(Slide) carousel, centrifuge

Trajectory of a point following a circular motion (2D)




uniform: $v = \text{const}$

but circle trajectory $\Rightarrow$ acceleration

def: angular velocity $\omega = \frac{d\varphi}{dt}$

$[\omega] = \frac{\text{rad}}{s}$

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(Slide) Geometry of motion (Tipler Fig 3-24)

black triangle ($\vec{r}$ vectors)
is similar to blue triangle (velocities)
(homothetic)

hence we can compare lengths, e.g.:

$$\frac{|\Delta \vec{v}|}{|\Delta \vec{r}|} = \frac{|\vec{v}|}{|\vec{r}|} = \frac{v}{r}$$

multiply by $\frac{|\Delta \vec{r}|}{\Delta t}$:

$$\frac{|\Delta \vec{v}|}{\Delta t} = \frac{v}{r} \frac{|\Delta \vec{r}|}{\Delta t}$$

lim $\Delta t \to 0$, $\frac{|\Delta \vec{v}|}{\Delta t} \to a$; $\frac{|\Delta \vec{r}|}{\Delta t} \to v$

$$a_c = \frac{v^2}{r}$$

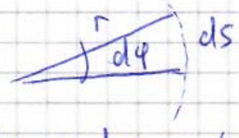
centripetal acceleration

acceleration $\perp$ to motion $v = \text{const}$, but circular trajectory

frequency of motion:

$\nu = \frac{\omega}{2\pi}$, $2\pi$: full circle in rad. ($= 360°$)

distance along circle: $ds$




$ds = r\, d\varphi$ (circle: perimeter $= 2\pi \cdot r$)

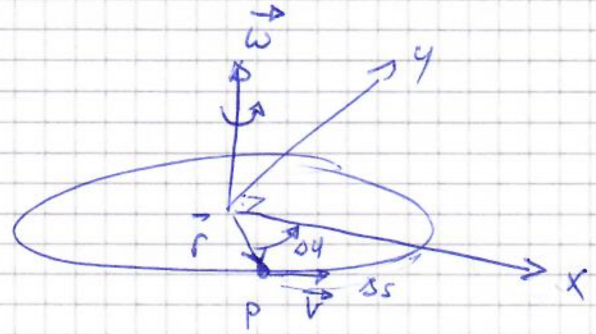
$$\frac{ds}{dt} = r \cdot \frac{d\varphi}{dt}$$

$$v = r \cdot \omega$$
$$= 2\pi \cdot \nu \cdot r$$
$$= \frac{2\pi \cdot r}{T}$$

T: period of rotation

$T = \frac{1}{\nu}$

in 3D:




- velocity

$v = \omega \cdot r$

$\vec{v} = \vec{\omega} \times \vec{r}$    vector product (Slide) thumb rule    ( show corkscrew, Finger for rule )

- acceleration

$$\vec{a} = \frac{d\vec{v}}{dt} = \frac{d}{dt}\left(\vec{\omega} \times \vec{r}\right)$$

$$\vec{a} = \vec{\omega} \times \frac{d\vec{r}}{dt} = -\omega^2 \cdot \vec{r} = -\frac{v^2}{r^2} \cdot \vec{r} \quad , \quad v = \omega \cdot r$$

$\omega = \text{const}$ , uniform circular motion

$$= \vec{\omega} \times \left(\vec{\omega} \times \vec{r}\right) \quad \left( = -\omega^2 \cdot \vec{r} \right)$$

$$\frac{d\vec{r}}{dt} = \vec{v} = \vec{\omega} \times \vec{r}$$

% demo. vector product

**Note:** projection of circular motion to x or y axis represents a <u>harmonic</u> motion

def harmonic oscillator

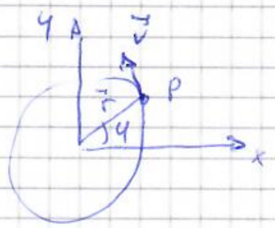
$$A(t) = A_0 \cdot \cos\left(\omega t + \varphi_0\right) \qquad \left( \text{or} \; = A_0 \cdot \sin\left(\omega t + \varphi_0\right) \right)$$

amplitude of motion

$$T = \frac{2\pi}{\omega} = \frac{1}{\nu}$$ period of ~~motion~~ oscillatory motion

Exp. rot. Scheibe,
Pendel

circular motion (continued)




Coordinates of moving point on trajectory $\vec{r}(t) = (x(t), y(t))$

$x(t) = r \cdot \cos(\varphi(t))$ $\quad$ ($r = |\vec{r}|$ = const ; circular motion)

$y(t) = r \cdot \sin(\varphi(t))$

$\uparrow$ time dependent $\quad \omega = \frac{d\varphi}{dt}$ , circular freq.

$$[\omega] = \frac{\text{rad}}{s}$$

frequency $\nu = \frac{\omega}{2\pi}$ , $[\nu] = \frac{1}{s} = Hz$, Hertz

period $T = \frac{1}{\nu} = \frac{2\pi}{\omega}$ , $[T] = s$

Velocity : $\vec{v}(t) = (\dot{x}(t), \dot{y}(t))$

$$v_x(t) = \frac{d}{dt}(r \cos \varphi(t)) \underset{\varphi = \omega \cdot t}{=} \frac{d}{dt}(r \cdot \cos(\omega t)) = -\omega r \cdot \sin(\omega t)$$

$$v_y(t) = \frac{d}{dt}(r \cdot \sin(\varphi(t))) = \frac{d}{dt}(r \cdot \sin(\omega t)) = \omega r \cdot \cos(\omega t)$$

$$|\vec{v}| = (v_x^2 + v_y^2)^{1/2} = (\omega^2 r^2 \cdot (\sin^2(\omega t) + \cos^2(\omega t)))^{1/2}$$

$$\| \; v = \omega \cdot r$$

acceleration

$$\vec{a}(t) = \dot{\vec{v}}(t) = (\ddot{x}(t); \ddot{y}(t))$$

$$= (-\omega^2 r \cdot \cos(\omega t); -\omega^2 r \cdot \sin(\omega t))$$

$$\| \; |\vec{a}(t)| = \omega^2 \cdot r$$

Note : $\vec{v}(t) \perp \vec{r}(t)$

$\vec{a}(t) \uparrow\downarrow \vec{r}(t)$

antiparallel