Chapter 4

Newton's Laws of Motion

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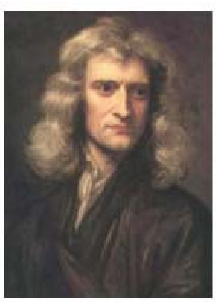
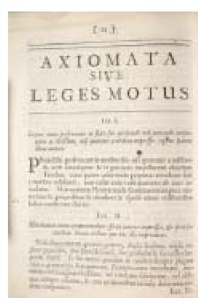
Newton's Law of Motion



Sir Isaac Newton
(1642 – 1727)



AXIOMATA
SIVE
LEGES MOTUS

published in 1687

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Kinematics vs. Dynamics

So far, we discussed kinematics (chapters 2 and 3)

The discussion, was essentially mathematical

No principles of physics were introduced.

Dynamics – the relationship of motion to forces that cause it.

Dynamics is built on three principles, called Newton's laws of motion.

Newton's laws are the foundation of classical mechanics

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new concepts

Two new concepts: FORCE and MASS

Force:

In everyday language: push or pull

In physics: quantitative description of interaction between a body and its environment

Types of forces

Contact force involves direct contact between bodies

Long-range forces act even when bodies are separated by "empty" space.

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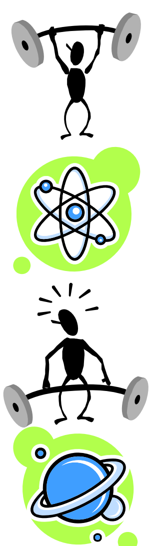
What forces do we know from our experience?

Gravitational Force
Frictional Force
Electromagnetic force
Spring Force
Aerodynamic Drag Force
Tension force
……

Note: all forces originate from long-distance interactions at microscopical level

How about love, hate, curiosity…?

There are ONLY four fundamental forces of nature



Force	Description	Strength	Range (m)
Strong	Force which holds nucleus togeher	1	10^{-15} (diameter of a medium sized nucleus)
Electro-magnetic		$\frac{1}{137}$	Infinite
Weak	neutrino interaction induces beta decay	10^{-6}	10^{-18} (0.1% of the diameter of a proton)
Gravity		6×10^{-39}	Infinite

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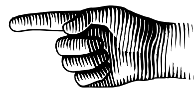
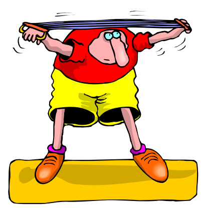
FOUR or ONE?



Many scientists think that all four of the fundamental forces are, the manifestations of a single force which has yet to be discovered.



Force is a vector quantity

Force has a direction!

Notation: $\vec{F}$

Units: Newton (N)

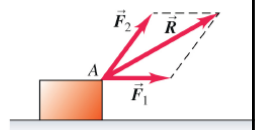
(British unit of force: pound (lb), 1 lb ≈ 4.45 N)

Superposition of forces

Any number of forces applied at a point on a body have the same effect as a single force equal to the vector sum of the forces

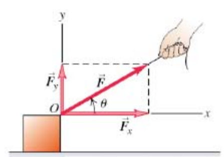
Equation:

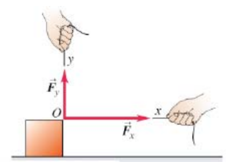
$$\vec{F} = \vec{F}_1 + \vec{F}_2 + \ldots \vec{F}_n = \sum_i^n \vec{F}_i$$



or using components

$$F_x = F_{x1} + F_{x2} + \ldots + F_{xn}$$
$$F_y = F_{y1} + F_{y2} + \ldots + F_{yn}$$
$$F_z = F_{z1} + F_{z2} + \ldots + F_{zn}$$





see also PhEt Colorado

Superposition of forces

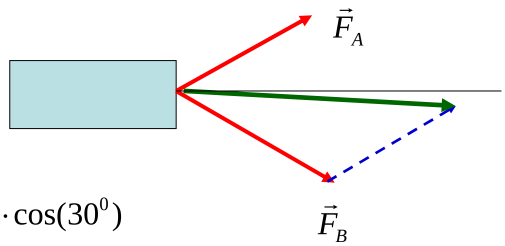
Important: forces act independently of each other: neither of them is modified by being applied at the same time as the other

Superposition works for any number of forces example

Two dogs

Two dogs pull horizontally on ropes attached to a sledge; the angle between the ropes is 60^0. Dog A exerts a force of 270 N and dog B exerts a force of 300 N.

Find the resultant force.



$$F_x = 270N \cdot \cos(30^0) + 300N \cdot \cos(30^0)$$

$$F_y = 270N \cdot \sin(30^0) - 300N \cdot \sin(30^0)$$

$$\tan(\alpha) = F_y / F_y$$

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Law 1

First Law of Motion

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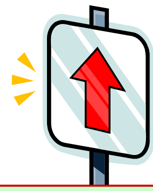
First Law of Motion: Formulation

An object at rest or traveling in uniform motion will remain at rest or traveling in uniform motion unless and until an external force is applied

Uniform motion is defined as motion with constant velocity: constant speed in an unchanging direction (a linear path)



$$\vec{F} = \sum_{i}^{n} \vec{F}_i = 0$$

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Inertial frames

Newton's formulation has two important implications:

1. Reference frames that move with constant velocities relative to each other are equivalent.
   These are called inertial frames of reference
2. Forces are the same in all inertial frames

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Forces and inertial frames

State of rest from point-of-view of one observer is a state of constant velocity from point-of-view of another

It isn't mere motion that we need to explain – it is the change in state of motion (acceleration)

RE: If non-zero net force is applied to a particle - all inertial observers see the same effect, viz. force is parallel to acceleration

Acceleration is the same in all inertial frames # force will be the same in all inertial frames

All forces behave in the same way: they all produce accelerations parallel to their directions

Some History

Aristotle (384 BC – 322 BC, a Greek philosopher)
"a thing will either be at rest or must be moving ad infinitum, unless something more powerful gets in its way"

But Galileo Galilei (1564 – 1642, an Italian physicist, mathematician, and philosopher) realized that force acting on a body determines acceleration, not velocity

…

"because I stood on the shoulders of giants…."
Newton

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Cars, cars, …

When a car stops suddenly, the passengers tend to move forward relative to their seats. Why?

When a car makes a sharp turn, the passengers tend to slide to one side of the car. Why?

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On a bus …

You may play catch with a softball (or a tennis ball) in a bus moving with constant speed on a straight road, just as though the bus were at rest.

Is it still possible when the bus is making a turn at constant speed on a level road? Why or why not?

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Law 2

Second Law of Motion

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Second Law of Motion: Formulation

The rate of change of the momentum of a body is directly proportional to the net force acting on it, and the direction of the change in momentum takes place in the direction of the net force

Momentum: $\vec{p} = m\vec{v}$

Second Law:

$\vec{F}_{net} = m\vec{a}$ or in the component form

$$F_{net,x} = ma_x$$
$$F_{net,y} = ma_y$$
$$F_{net,z} = ma_z$$

where $\vec{F}$ is the net or resultant force that acts on the particle and m is the mass of the particle

1 N = 1 kg m/s^2

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Mass

Second Law effectively defines mass:
acceleration and force can be measured independently
mass is then determined from $\vec{F} = m\vec{a}$

Mass in the second Newton's law is a measure of inertia.
It is a scalar quantity called inertial mass.

Notation: m

Units: kg

One more mass?

Gravitational mass m_g characterizes property of a particle to be attracted by any other particle with gravitational mass.
It is the source of the gravitational force
(see Newton's Law of Gravitation)

Inertial vs. gravitational mass

- ✓ Mass m in the 2nd Law measures inertia of a particle when a force, not necessarily a gravitational force, is applied to it.
- ✓ For this reason, we call that mass m_I the inertial mass
- ✓ It is not clear a priori that m_g and m_I should be the same
- ✓ Experimentally, no difference has been detected: $m_g = m_I = m$
- ✓ Equality between inertial mass and gravitational mass is in the foundations of Einstein's general theory of relativity

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Mass and Weight

Mass and weight are not the same entity:

Gravitational mass m_g is a scalar property of a particle
Its unit is kilogram (kg).

Weight of a particle is the force $\vec{W}$ on it by the earth's gravity. $\vec{W} = m\vec{g}$

Weight is a vector. Its unit is Newton (N)

Good to know: On Earth, g depends on your altitude. On other planets, gravity will likely have an entirely new value.
Example: on the moon 1.62 m/s^2, or 0.165g.

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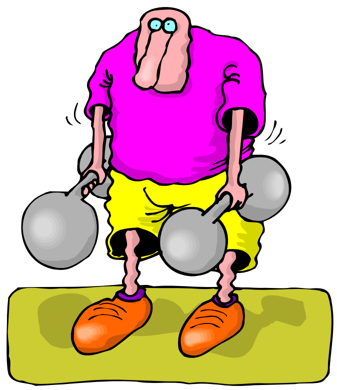
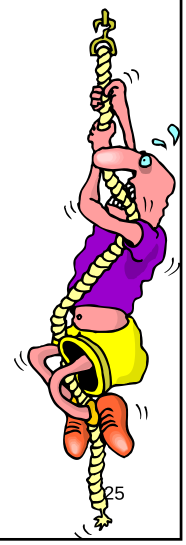
Gym on the Moon?

What gym equipment can be efficient on the Moon

free weights? fitness machines? treadmills?



$$\vec{W} = m\vec{g}$$



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What is wrong with Hollywood movies?

Armageddon (1994): A Texas-sized asteroid is headed toward Earth at 22,000 mph and the only way to save humanity is to to land a ragtag oil rig crew on its surface, drill an 800-foot-deep hole, plant a nuclear bomb on a convenient fault line, and split the asteroid in half

"Our heroes have no problems walking or standing in an Earthlike way even though the gravity force would have been about a tenth of the gravity force on Earth. The low gravity cannot support an atmosphere and yet we see flames at the crash site of one of the space shuttles."
http://www.intuitor.com/moviephysics/armageddon.html

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example

Stopping a car

What average net force is required to stop a 1500 kg car moving with a speed of 55 mph (88 km/h) within a distance of 200 ft (61 m)?

$$v^2 = v_0^2 + 2a(x - x_0)$$

$$a = \frac{v^2 - v_0^2}{2(x - x_0)} = -4.95\, m/s^2$$

$$F = ma = 7430\ N$$

since 1 lb ≈ 4.45 N, then F = 1670 lb

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Law 3

Third Law of Motion

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Third Law of Motion: Formulation

For every Action, there is an equal but opposite Reaction

- ✓ Note: "Action" and "Reaction" both mean "Force"
- ✓ This law means that forces always occur in pairs
- ✓ Forces arise fundamentally from interaction between two particles that exert forces on each other
- ✓ Such forces are called action-reaction pairs of forces
- ✓ If one of them is called "the action", the other is called "the reaction"

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Action-reaction pairs

Action-Reaction pairs (call them $\vec{A}$ and $\vec{R}$) have the following characteristics:

1. $\vec{A}$ and $\vec{R}$ are equal in magnitude
2. $\vec{A}$ and $\vec{R}$ are opposite in direction
3. $\vec{A}$ and $\vec{R}$ are of the same physical origin (If $\vec{A}$ is gravitational, $\vec{R}$ must also be, etc.)
4. $\vec{A}$ and $\vec{R}$ act on different objects

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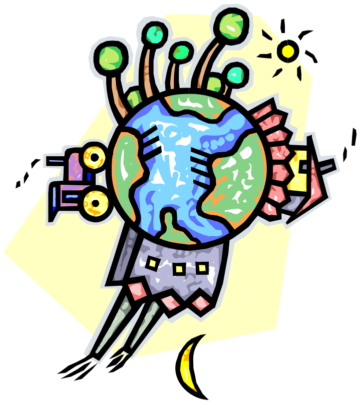
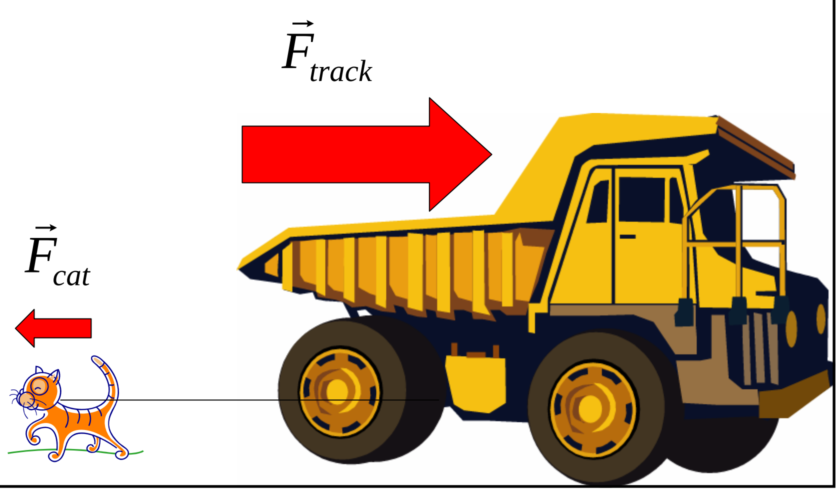
Example: gravitational force



Example: Can it be true?

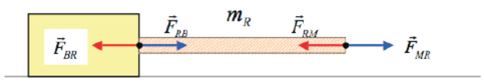
$$\vec{a} = \frac{\vec{F}_{net}}{m}$$

Which force has a larger amplitude, or are they the same?



Example

EXAMPLE: A man pulls on a rope attached to a block



1. $\vec{F}_{BR}$ and $\vec{F}_{RB}$ are an A–R pair.
2. $\vec{F}_{MR}$ and $\vec{F}_{RM}$ are an A–R pair.
3. However, $\vec{F}_{RB}$ and $\vec{F}_{RM}$ are not an A–R pair.

- NOTICE: both $\vec{F}_{RB}$ and $\vec{F}_{RM}$ act on the same body
  $\Rightarrow$ enough to disqualify them
- They are not necessarily equal in magnitude:
  apply the 2nd Law to the rope:
  $$m_R\vec{a}_R = \vec{F}_{RB} + \vec{F}_{RM} = (F_{RB} - F_{RM})\,\hat{\imath}$$
  $\Rightarrow$ Two forces have the same magnitude only if $m_R = 0$

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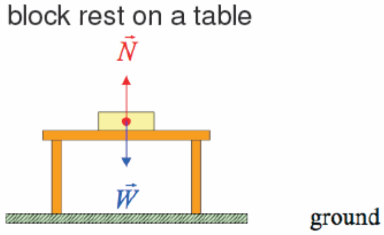
Example

- Identification of action-reaction pairs can be tricky unless you learn to verify these characteristics carefully
  EXAMPLE: Let a block rest on a table



- Since the block is at rest, $\vec{N} = -\vec{W}$
- Do these forces form an action-reaction pair?
- They do not
- Can you identify the action-reaction pairs?

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