# Unit II – Dynamics

**Topics covered:**

- Newton's $2^{nd}$ Law
- Newton's First Law
- Newton's Third Law
- 4 Fundamental Forces
- Universal Gravitation
- Electrostatic Forces
- FBD's, Summing Forces
- Friction

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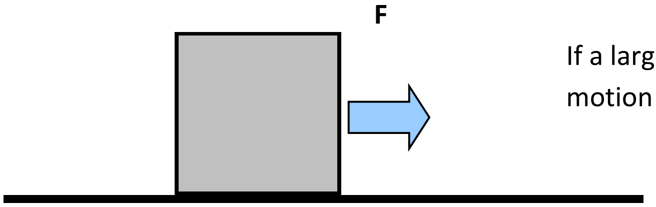
**Dynamics** – The study of the causes of motion (i.e. forces)
**Force** – Push or Pull

## Newton's Second Law

An example: a Mass on a Desk:



If a large enough force is applied to the mass, what kind of motion results? *Acceleration!*

**Newton's Second Law of Motion:**

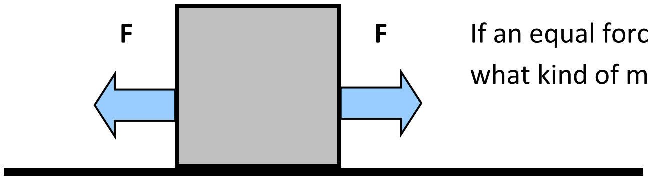
When a non-zero net force acts on an object, the object will accelerate.

i.e. $\vec{F}_{NET} = m\vec{a}$

Why *net* force?

Net Force (Resultant force) – the total (vector sum) of all the forces acting on an object

example: a Mass on a Desk:



If an equal force pushes in the opposite direction ($\vec{F}_{NET} = 0$), what kind of motion results? *No Acceleration! (*$\vec{a} = 0$*)*

According to $\vec{F}_{NET} = m\vec{a}$,

if the mass of an object (m) is constant:

As $\vec{F}\uparrow$, $\vec{a}\uparrow$
As $\vec{F}\downarrow$, $\vec{a}\downarrow$

if the motion ($\vec{a}$) of an object is constant:

As $\vec{F}\uparrow$, m$\uparrow$
As $\vec{F}\downarrow$, m$\downarrow$

**Units of Force:**

The unit of force is the *Newton, N*.

$1\ \text{N} = 1\ \text{kg}\ ^{m}/_{s}\ 2$ (from Newton's Second Law)

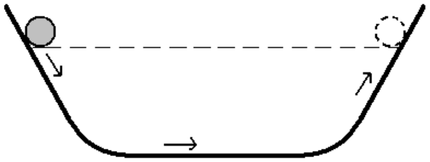
Since forces are vectors, they require directions

e.g. $\vec{F} = 55.5\ N\ [E]$ the force in the box was 55.5 N [E]

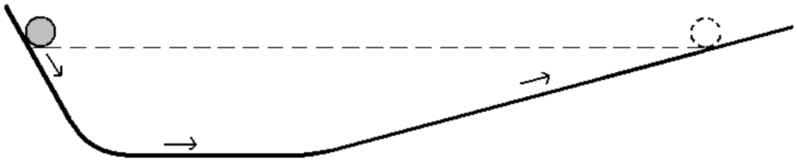
## Newton's First Law of Motion: The Law of Inertia

Galileo's Thought Experiment:

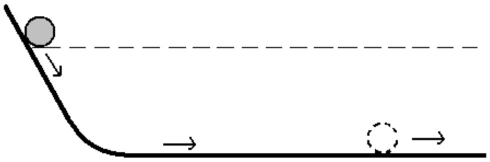
Ignoring friction, a ball rolling down one side of the ramp will roll up the other side of the ramp to the same height.



If the second ramp were extended and its slope reduced, the ball will still reach the same height, but travel further to do so (since the ramp is easier to ascend).



If the second ramp were lowered such that it became horizontal, the ball should move forever, forever trying to get back to its original height.



**Newton's First Law of Motion:**

If the net force acting on an object is zero, the object will maintain its current state of motion (at rest or with a constant velocity).

What does this mean?

- objects at rest tend to remain at rest
- objects in motion tend to remain in motion
- if the velocity of an object is constant, the net external force must be zero
- if the object is accelerating, it must be caused by a non-zero net external force

**Inertia** - the 'tendency' of objects to remain in their current state of motion was called *inertia* by Sir Isaac Newton. The more *inertia* an object has, the more likely it will remain in its current state of motion (and, by extension, the more force will be required to change its current state of motion).

e.g. while riding in a moving car with no seatbelt, if the car stops (i.e. crashes) you continue to move forward (i.e. through the windshield).

## Newton’s Third Law of Motion - The Action-Reaction Law

**Newton's Third Law of Motion:**

For every action force there exists is a reaction force equal in magnitude and opposite in direction.

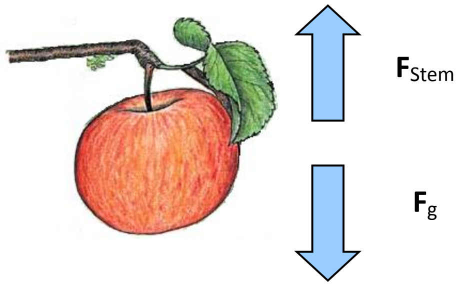
** Action / reaction forces act on **different objects****

### Action-Reaction Pairs:

For every force that is exerted, two separate objects experience it. Action-reaction pairs identify the relationship between the force and each object.

Example: Apple hanging on tree

Forces acting on apple: gravity (**$F_g$**), applied force from stem (**$F_{Stem}$**)



| Forces Acting on Apple | Action-Reaction Pairs |
|---|---|
| **$F_{Stem}$** | • stem pulls *upwards* on apple<br>• apple pulls *downwards* on stem |
| **$F_g$** | • earth pulls *down* on apple<br>• apple pulls *up* on earth! |

## Fundamental Forces of Nature

| Force | Relative Strength (approx.) | Range | Effect |
|---|---|---|---|
| strong nuclear | $10^{38}$ | less than $10^{-15}$ m | attraction and repulsion |
| weak nuclear | $10^{25}$ | less than $10^{-18}$ m | attraction and repulsion |
| gravitation | 1 | $\infty$ | attraction only |
| electromagnetic | $10^{36}$ | $\infty$ | attraction and repulsion |

### Strong Nuclear Force

The force that holds protons and neutrons together in the nucleus (protons repel!). This force is stronger than the electromagnetic force, but it is extremely short-ranged.

### Weak Nuclear Force

The force responsible for elementary particle (protons, neutrons, etc) interactions, such as radioactivity.

**(Universal) Gravitation**

The mutual force of attraction between any two objects that have mass. The magnitude of this force depends only on the masses of the two objects and the distance between them.

**Electromagnetic Force**

The force caused by charged particles, which includes both electric and magnetic forces. Most common forces are actually electromagnetic forces, when sufficiently analysed.

## Universal Gravitation

### Newton's Law of Universal Gravitation:

The force of gravitational attraction between any two objects is directly proportional to the product of the masses of the objects, and inversely proportional to the square of the distance between the objects. *OR*,

$$\vec{F}_g = \frac{Gm_1m_2}{r^2}$$

A gravitational force exists between all objects in the universe, no matter their mass or how far away they might be.

- The force with which one object pulls on a second object is the same in magnitude but opposite in direction to the force of the second object on the first (Newton's 3rd Law).
- Gravitational forces are extremely weak, since the gravitational constant, *G*, is so tiny.

### Universal Gravitational Constant (big 'G'*)*

- Universal gravitational constant, $G = 6.67\text{x}10^{-11}\ \text{Nm}^2/\text{kg}^2$
- *G* was calculated by Newton, but verified experimentally over 100 years later by Henry Cavendish.
- Knowing *G* enabled us to accurately determine the mass of the earth and other heavenly bodies.

### Gravitational Field Strength

Force Field: space surrounding an object in which the object exerts a force on other objects in that space

Gravitational field strength: force per unit mass

$\vec{F}_g = \boxed{\frac{Gm_1}{r^2}} \cdot \frac{m_2}{1}$ gravitational field strength of mass $m_1$.

The symbol we give for the gravitational field strength of an object is $\vec{g}$ (little 'g'). We can now simplify the equation of universal gravitation if we know the gravitational field strength of an object:

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

Every object in the universe has a gravitational field, and its strength only depends on its mass and how far *another* object is from it (i.e. the further away a 'test' object from the object producing the field is, the weaker the force of attraction. Due to the $\frac{1}{r^2}$ relationship, this gravitational force quickly diminishes with distance).

## Gravity and Outer Space

- Sometimes astronauts are said to experience 'weightlessness' or 'microgravity'. Both of these terms can be misleading: **The force of gravity still exists in outer space**, and of course only depends on the astronauts' mass and how far from the earth they are, and so therefore astronauts still have weight (though, when in orbit, if a scale is placed under an astronaut, it would read 0 N, since both the astronaut and scale are in free fall - more on this in grade 12).

- Gravity is never zero - according to the equation above, the only time the force of gravity is zero is when you are infinitely far away. It can be extremely small, but never zero.

## Weight

When we ask someone how, much they weigh, the answers we get do not match what we are really asking for:

> "How much do you weigh?"
> "Oh, about 65 kg (145 lbs)"

In physics, weight is the total force an object exerts on the ground due to gravity. If you ask for a person's weight, they should respond in *Newtons*, not *kilograms* (which is mass)

| | |
|---|---|
| mass: quantity of matter in an object. | (measured in kilograms, *kg*) |
| weight: the force of gravity on an object. | (measured in Newtons, *N*) |

## Force of Gravity, Due to the Earth, Near the Earth's Surface

If we use the mass and radius of the earth, we can determine the gravitational field strength of the earth at its surface:

$$\vec{F}_g = \frac{Gm_{earth}}{r^2} \cdot \frac{m_2}{1}$$

$$\vec{g} = \frac{\left(6.67\times10^{-11}\, {Nm^2}/{kg^2}\right)(5.98\times10^{24} kg)}{(6.3810^6 m)^2}$$

$$\vec{g}_{earth} = 9.8\ {m}/{s^2}\ !!!!!$$

Of course!! Our theory of gravity must match reality, and indeed the value for the acceleration of any object falling near the surface of the earth measured by Galilieo, many years previous, matched that which was predicted in Newton's mathematics! Galileo had only discovered a special case for general (universal) law of gravity: near the surface of the earth, whereas Newton's description whorls every where and for everything!

## Types of (macroscopic) Electromagnetic Forces

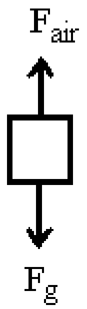
| Type of Force | Symbol | Description | Useful Info | Example |
|---|---|---|---|---|
| Applied Force | $F_{app}$ | Any general contact force | its symbol can depend on the object providing the force (i.e. $\mathbf{F}_{engine}$, $\mathbf{F}_{girl}$, $\mathbf{F}_{finger}$, etc.) | A human pushing a refrigerator |
| Normal | $F_N$ | Forces applied by surfaces | The direction of this force is always perpendicular to the surface | A refrigerator on the floor |
| Tension | $F_T$ | Forces applied by ropes, strings, etc | Only *pull*s<br>("Can't push a rope") | Pulling a refrigerator with a rope |
| Friction | $F_f^*$ | Any force that opposes motion | The direction of this force is always in opposite direction of motion | |
| Static Friction | | forces that prevent stationary objects from moving | $F_{kinetic} < F_{static}$ | the floor preventing the movement of a large refrigerator when an applied force is used |
| Kinetic friction | | forces that oppose the motion of moving objects | Static and kinetic friction do not have their own symbols, one must know which is appropriate for a given situation. | the floor resisting the motion of a refrigerator as it moves |

* friction caused by air is usually written as $\boldsymbol{F}_{air}$

## Free Body Diagrams (FBD's), Summing Forces

- Draw a circle/box to represent the object.
- Draw forces as vectors (arrows) originating from the centre of the box/circle, pointing away.
- The direction of the vectors must match the direction of the forces

example:



### Mathematically Analyzing Motion

- Separate forces into those that exist in the 'y' direction and those that exist in the 'x' direction.
- Add the forces (remember they are vectors!) the find the net force in each the 'y' and 'x' directions, using the following format:

$$\Sigma \mathbf{F}_x = \mathbf{F}_{1x} + \mathbf{F}_{2x} + \mathbf{F}_{3x} + \ldots$$

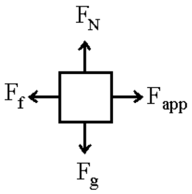
$$\Sigma \mathbf{F}_y = \mathbf{F}_{1y} + \mathbf{F}_{2y} + \mathbf{F}_{3y} + \ldots$$

- Apply these net forces to Newton's second law:

$$\Sigma \mathbf{F}_x = \mathbf{F}_{1x} + \mathbf{F}_{2x} + \mathbf{F}_{3x} + \ldots = m\mathbf{a_x}$$

$$\Sigma \mathbf{F}_y = \mathbf{F}_{1y} + \mathbf{F}_{2y} + \mathbf{F}_{3y} + \ldots = m\mathbf{a_y}$$

example:



$$\Sigma \mathbf{F}_x = \mathbf{F}_{app} + \mathbf{F}_f = m\mathbf{a}_x$$

$$\Sigma \mathbf{F}_y = \mathbf{F}_N + \mathbf{F}_g = m\mathbf{a}_y = \mathbf{0}$$

## Effects of Friction

Friction exists whenever two surfaces are in contact. The amount of friction depends on the characteristics of each surface, and so, is different for every combination of surfaces (i.e. rubber and dry asphalt, rubber and wet asphalt, etc). The measure of how much friction exists between two surfaces is the coefficient of friction, μ

### Coefficient of Friction ( μ )

- A number ratio between the **magnitude** of the frictional force, $F_f$, and the **magnitude** of the normal force $F_N$, such that:

$$\mu = \frac{F_f}{F_N} \qquad \text{or,} \qquad \mu = \frac{|\vec{F}_f|}{|\vec{F}_N|}$$

- Gives us an idea of the amount of friction present: the higher the value, the more friction exists
- Coefficients of friction can only be determined experimentally.
- Rearranging the equation, we can determine frictional forces: $F_f = \mu F_N$

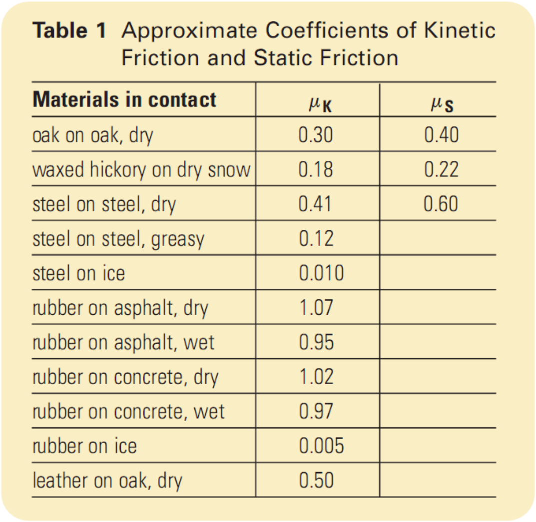


**Table 1** Approximate Coefficients of Kinetic Friction and Static Friction

| **Materials in contact** | $\mu_K$ | $\mu_S$ |
|---|---|---|
| oak on oak, dry | 0.30 | 0.40 |
| waxed hickory on dry snow | 0.18 | 0.22 |
| steel on steel, dry | 0.41 | 0.60 |
| steel on steel, greasy | 0.12 | |
| steel on ice | 0.010 | |
| rubber on asphalt, dry | 1.07 | |
| rubber on asphalt, wet | 0.95 | |
| rubber on concrete, dry | 1.02 | |
| rubber on concrete, wet | 0.97 | |
| rubber on ice | 0.005 | |
| leather on oak, dry | 0.50 | |

### Types of Friction: Static and Kinetic

- Static: Force that prevents a stationary object from moving
- Kinetic: Force that acts against an object's motion in a direction opposite the motion.
- Types of kinetic: Rolling friction, sliding friction, fluid friction, etc.
- $F_{kinetic} < F_{static}$
- Coefficients of friction, for a given pair of surfaces, will change depending on whether they are moving or stationary relative to each other, so we have:

### What Causes Friction?

Since friction is actually an electromagnetic force, it is caused by chemical bonding between the moving surfaces; it is caused by stickiness. When the surfaces are moving, it is best described by "stick & slip" processes. When thinking about friction, don't think about grains of sand on sandpaper. Instead think about sticky adhesive tape being dragged along a surface.

Friction is *not* to be confused with traction, as friction (chemical bonding processes between surfaces) is independent of surface area, whereas traction does (along with several other factors).