CHAPTER 2: FORCES AND MOTION

2.1 Linear Motion

Linear Motion is motion in a straight line with constant acceleration.

Classification	Scalar	Vector
Physical quantity with…	Magnitude only	Magnitude and direction
Example	Distance Speed	Displacement Velocity Acceleration

Definitions:
Speed: Rate of change of distance
Velocity: Rate of change of displacement
Acceleration: Rate of change of velocity

2.1.1 Equations of Linear Motion

$$s = ½ (u + v) t$$

$$a = \frac{v - u}{t}$$

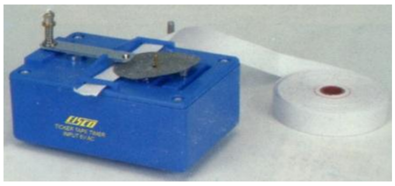
$$s = ut + ½ at^2$$

$$v^2 = u^2 + 2as$$

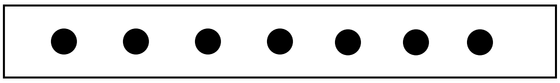
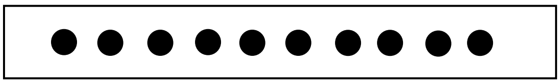
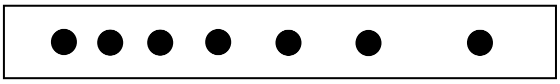
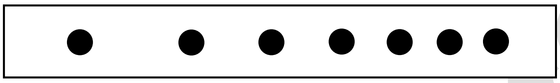
where s = displacement [m]
u = initial velocity [m s^{-1}]
v = final velocity [m s^{-1}]
t = time [s]

2.2 Linear Motion Graphs

2.2.1 Ticker timer



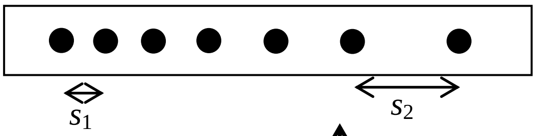
- Ticker timers work with alternating current (AC) only.
- Ticker timers typically have a frequency of 50 Hz.
- The period of one tick is $\frac{1}{50}$= 0.02 s.

Movement	Explanation
	Consistent distance = uniform velocity
	Short distance = low velocity
	Long distance = high velocity
	Increasing distance = increasing velocity / acceleration
	Decreasing distance = decreasing velocity / deceleration

To calculate the average velocity from a ticker tape strip or graph:

$$\text{Average velocity} = \frac{\text{Total distance}}{\text{Total time}}$$

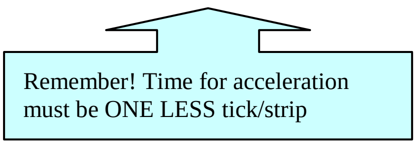
To calculate the acceleration from a ticker tape strip or graph:

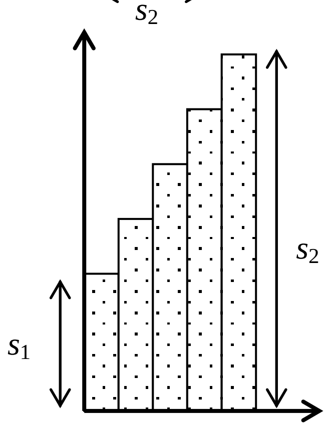


Step 1: Calculate the initial velocity, $u = \frac{s_1}{t}$.

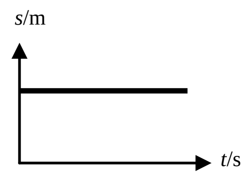
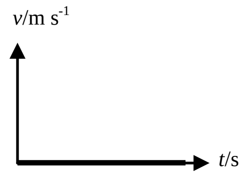
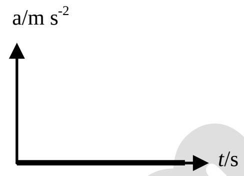
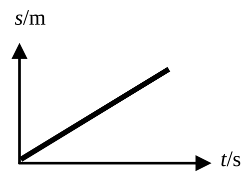
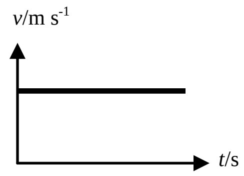
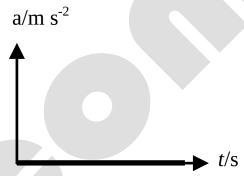
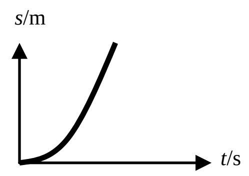
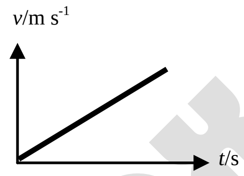
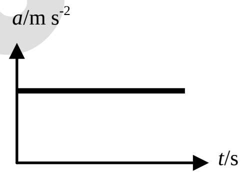
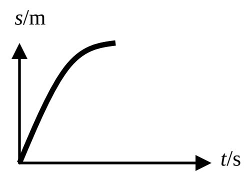
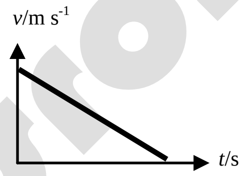
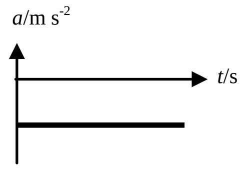
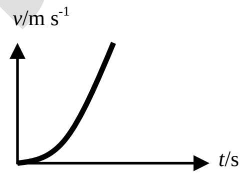
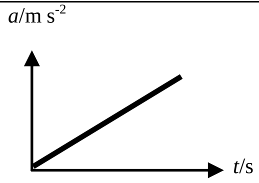
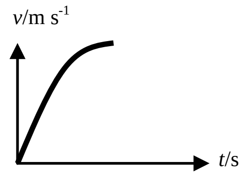
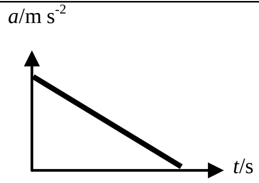
Step 2: Calculate the final velocity, $v = \frac{s_2}{t}$.

Step 3: Calculate the acceleration, $a = \frac{v-u}{t}$.

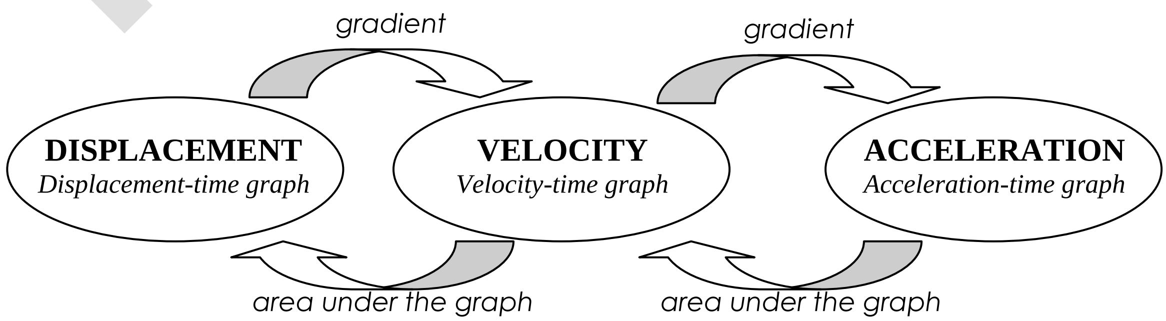




2.2.2 Linear Motion Graphs

	Displacement-time graphs	**Velocity-time graphs**	**Acceleration-time graphs**
	Velocity = *slope of the graph*	Acceleration = *slope of the graph* Displacement = *area under the graph*	Velocity = *area under the graph*
v = 0 (*a* = 0)			
v = constant (*a* = 0)			
v ↑ *a* = constant			
v ↓ *a* = constant			
v ↑ *a* ↑			
v ↑ *a* ↓			

REMEMBER!



2.3 Inertia

Inertia is the natural characteristics of an object to oppose any attempted change on its original state, whether at rest or in motion. It is the tendency of an object to remain at rest, or to keep moving at constant speed in a straight line

Newton's First Law of Motion*(Law of Inertia)*
Every object in a state of uniform motion tends to remain in that state of motion unless an external force is applied to it.

2.4 Momentum

Momentum = mass × velocity

$$p = mv$$

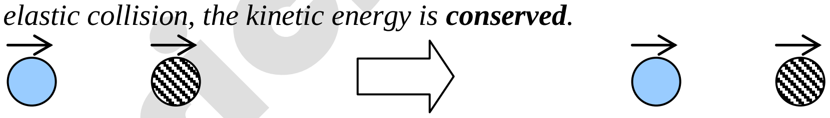
where p = momentum [kg m s^{-1}]
m = mass [kg]
v = velocity [m s^{-1}]

Principle of conservation of momentum
In any collision or interaction between two or more objects in an isolated system, the total momentum before collision is **equal** to the total momentum after collision.

$$m_1u_1 + m_2u_2 = m_1v_1 + m_2v_2$$

Three types of collisions:

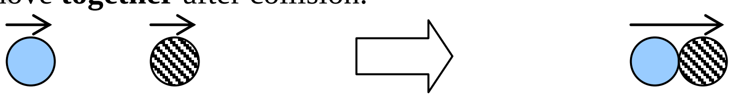
1) **Elastic collision**
Both objects move **separately** after collision.
*Note: In an elastic collision, the kinetic energy is **conserved**.*



$$m_1u_1 + m_2u_2 = m_1v_1 + m_2v_2$$

E.g.: a cue ball hitting a snooker ball, bowling ball striking a pin, bumper cars colliding into each other

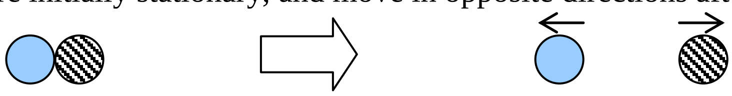
2) **Inelastic collision**
Both objects move **together** after collision.



$$m_1u_1 + m_2u_2 = (m_1 + m_2)v$$

E.g.: a boy running and jumping onto a skateboard and both move together after collision

3) **Explosion**
Both objects are initially stationary, and move in opposite directions after the explosion.



$$m_1v_1 = - m_2v_2$$

E.g. : a bullet fired from a stationary gun, a man jumping out of a stationary boat, a boy jumping off a stationary skateboard

2.5 Force

Force is a push or pull.

- **Force** changes the size, shape, state of rest, velocity and/or direction of an object.
- Force is a vector quantity.

Newton's Second Law of Motion
The acceleration of a body, *a*, is directly proportional to the net force acting upon it, *F*, and inversely proportional to its mass, *m*.

$$F = ma$$

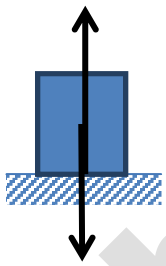
where F = force [N]
m = mass [kg]
a = acceleration caused by F [m s^{-2}]

2.5.1 Balanced Forces (Forces in Equilibrium)

Balanced forces is a state where net force is zero.

When an object is in a state of **balanced forces** or **forces in equilibrium**, the object will either be:
- **stationary,** or
- **moving with uniform velocity.**

Examples of balanced forces:

<table>
<tr>
<td>
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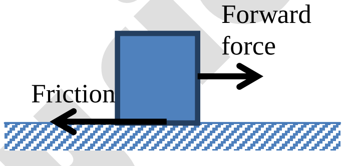
<td>
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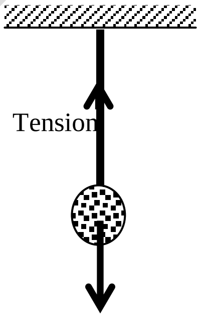
<td>
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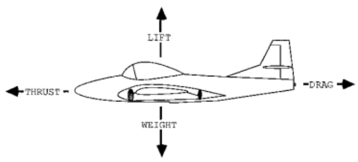
<td>
</td>
</tr>
<tr>
<td>Normal reaction is the reaction force generated perpendicular from the surface</td>
<td>Friction is the resistance force generated between the object and surface when a force is applied to move the object</td>
<td>Tension is the force generated in a taut string when a force is applied on the string</td>
<td>An airplane moving with uniform velocity at constant height is in a state of balanced forces.

Weight = Lift
Thrust = Drag</td>
</tr>
</table>

2.5.2 Unbalanced Forces

Unbalanced forces may cause an object to start moving, to speed it up, to slow it down, or to bring it to a stop. The greater the unbalanced force, the greater the acceleration or deceleration produced.

2.6 Impulse and Impulsive Force

Impulse = change of momentum

$$Ft = mv - mu$$

Impulsive force = rate of change of momentum

$$F = \frac{mv - mu}{t}$$

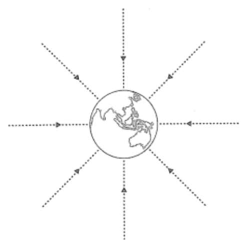
where Ft = impulsive [kg m s^{-1}]
F = impulsive force [N]
m = mass [kg]
u = initial velocity [m s^{-1}]
v = final velocity [m s^{-1}]

2.7 Safety Features in Vehicles

1. Padded dashboards
2. Shatterproof windscreen glass
3. Inflatable airbags
4. Collapsible steering wheels
5. Headrest
6. Padded seats
7. Seatbelt
8. Antilock brake systems (ABS)
9. Steel struts
10. Steel cage
11. Reverse collision warning systems
12. Bumper bars

2.8 Gravity

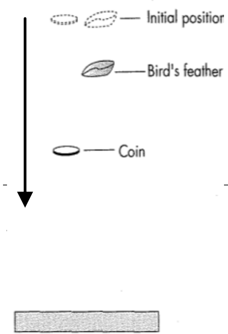
All objects are pulled towards the centre of the earth by a force known as **the earth's gravitational force**. Any object dropped towards earth which falls under the influence of the earth's gravitational force (without any influence of other external forces, such as air friction) is said to be going through a **free fall**. In reality, free falls only happen within a vacuum space.



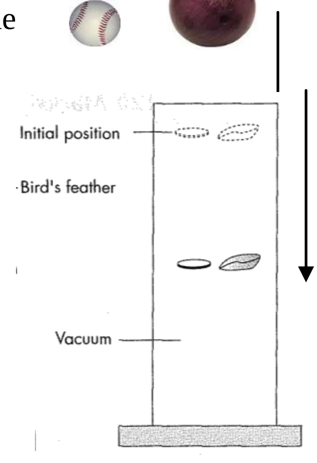
The diagram on the right shows the non-uniform gravitational field of the Earth, $\boldsymbol{g}$ which is represented by radial lines directed towards the centre of the Earth. The field is strongest where the lines are closest.

2.6.1 Free fall

An object undergoing **free fall** will fall at the rate of **gravitational acceleration** which is at a constant of **9.81 m s^{-2}** at sea level. The gravitational acceleration is *not* influenced by the size or mass of the object.



Objects dropped from the same height will fall at the same rate and will hit the ground at the same time, regardless of the mass.



However, for objects with very small mass and very large surface area like feathers, pieces of paper and cloth, they will fall at a lower rate. This is because the larger the surface area, the greater the air resistance.

If the same objects are placed in a vacuum tube, they will fall at the same rate.

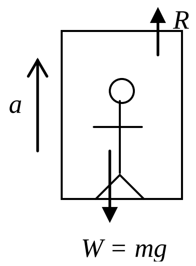
2.6.2 Weight

Weight is the product of mass and gravitational acceleration.

$$W = mg$$

where W = weight [N]
m = mass [m]
g = gravitational acceleration [m s^{-2}]

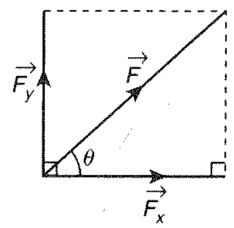
2.6.3 Lifts

<table>
<tr><td rowspan="6">
</td><td>Common formula:
$R = mg + ma$

Where R = reading of the scale [N]
m = mass of person [kg]
g = gravitational acceleration [m s^{-2}]
a = upward acceleration of the lift [m s^{-2}]</td></tr>
<tr><td>If the lift is stationary or moving with uniform velocity (a = 0):
$R = mg$</td></tr>
<tr><td>If the lift is moving upwards with acceleration:
$R = mg + ma$</td></tr>
<tr><td>If the lift is movingupwards with deceleration:
$R = mg + m(-a)$
$R = mg – ma$</td></tr>
<tr><td>If the lift is moving downwards with acceleration:
$R = mg - ma$</td></tr>
<tr><td>If the lift is moving downwards with deceleration:
$R = mg – m(-a)$
$R = mg + ma$</td></tr>
</table>

2.9 Forces in Equilibrium

Equilibrium:
- resultant force = 0
- acceleration = 0 (stationary *or* uniform velocity)

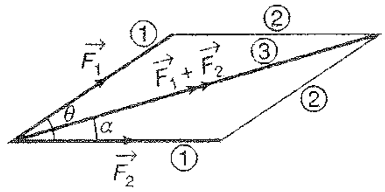


$F_x = F \cos\theta$
$F_y = F \sin\theta$

Newton's Third Law
For every action there is an equal and opposite reaction.

2.9.1 Nett / Resultant Forces

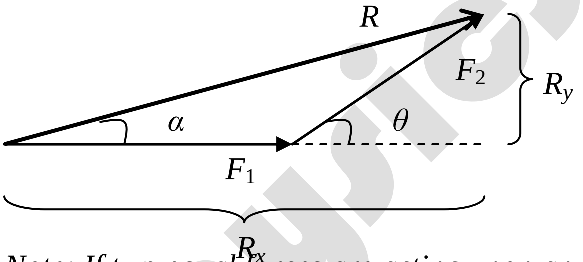
Using the parallelogram method



You can solve resultant force by using **scaled diagram** or **calculation**.

1. Scaled diagram
   Draw the forces to scale using a ruler and a protractor.
   Magnitude of resultant force is obtained by measuring and converting back to value using the scale, and the angle is measured with a protractor.

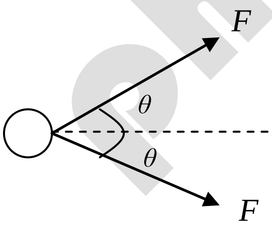
2. Calculator



$R_x = F_1 + F_2\cos\theta$
$R_y = F_2$
$R = \sqrt{R_x^{\ 2} + R_y^{\ 2}}$

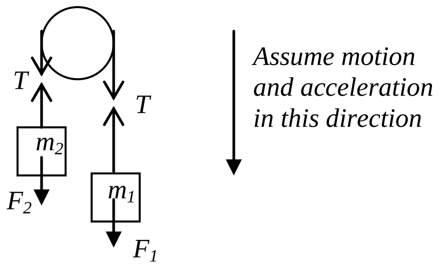
Angle of R, $\alpha = \tan^{-1}\dfrac{R_y}{R_x}$

Note: If two equal forces are acting upon an object at an angle, the simplified solution is:



$R = F\cos\theta + F\cos\theta$
$R = 2F\cos\theta$

2.9.2 Pulleys



Based on the force formula:

$$F = ma$$

F = Net force acting on the system
m = Total mass of the system
a = Acceleration of the system

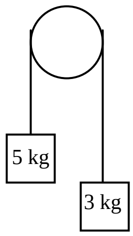
$$F_1 - F_2 = (m_1 + m_2)\,a$$

To find out the rope tension:

$$F = ma$$
$$F_1 - T = m_1 a$$
$$T = F_2 - m_2 a$$

Example:
Calculate the acceleration and rope tension in the following system.

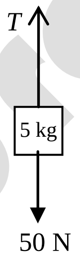
To calculate acceleration:



$F = ma$
$50 - 30 = (5+3)a$
$a = 2.5 \text{ m s}^{-2}$

To calculate tension:

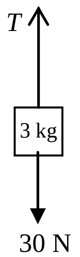
Isolate the *left* side of the pulley (5 kg object is moving *down*):



$F = ma$
$50 - T = 5(2.5)$
$T = 37.5 \text{ N}$

OR

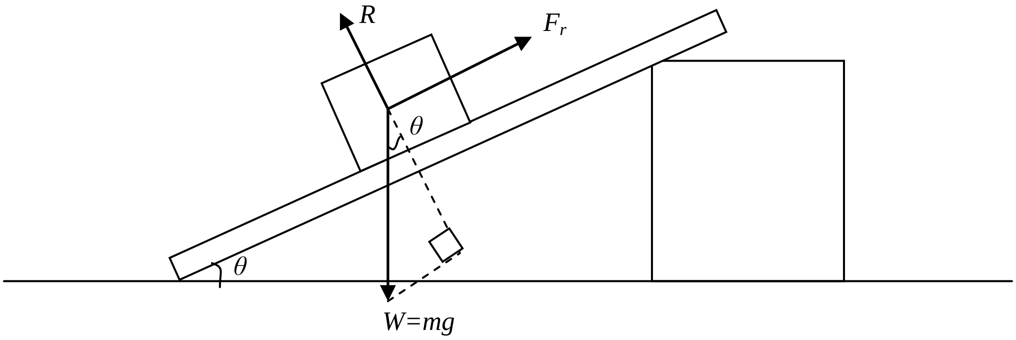
Isolate the *right* side of the pulley (3 kg object is moving *up*):



$F = ma$
$T - 30 = 3(2.5)$
$T = 37.5 \text{ N}$

You will get the same value of tension whether you isolate the left or right side.

2.9.3 Inclined Planes

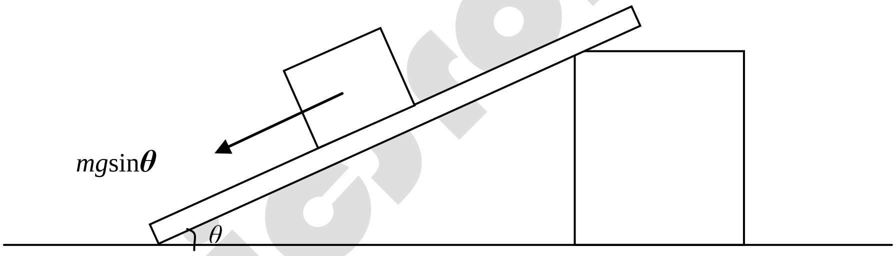


R = mg cos θ
Fr = mg sin θ

where *W* = weight of object [N]
m = mass of object [kg]
g = gravitational acceleration [m s^{-2}]
R = reaction caused by weight of object perpendicular to plane [N]
F_r = friction caused by weight of object parallel to plane [N]

When solving questions with inclined planes, use the following shortcut:

Weight of object parallel to the plane = *mg* sin *θ*



2.10 Work, Energy, Power and Efficiency

2.10.1 Work

- **Work** is the product of the applied force and its displacement in the direction of the net force.
- Work is a scalar quantity.
- When work is done, energy is transferred to the object or changed into a different form.
- Work is only done when the object has been displaced. If there is no displacement, there is no work done.
- Displacement *must be* parallel to the force exerted.

$$W = Fs$$

where *W* = work [J]
F = force creating the work [N]
s = displacement [m]

2.10.2 Energy

- **Energy** is the potential or ability of a system to do work.
- Energy is a scalar quantity.

First law of thermodynamics *a.k.a.* **the principle of conservation of energy** states that energy may neither be created nor destroyed; it can only change form.

2.10.2.1 Kinetic Energy

- Kinetic energy is energy acquired by an object during movement.

$$E = ½ mv^2$$

where E = kinetic energy [J]
m = mass [kg]
v = velocity of the object [m s^{-1}]

2.10.2.2 Potential Energy

- Potential energy is the energy within an object because of its position or state.
- Potential energy is *stored* energy giving the body potential to do work.

Gravitational potential energy:

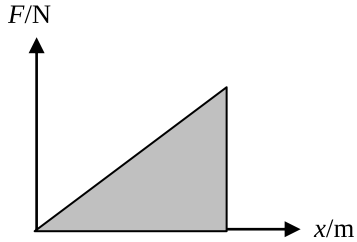
$$E = mgh$$

where E = potential energy [J]
m = mass [kg]
g = gravitational acceleration [m s^{-2}]
h = height of the location of the object [m]

Elastic potential energy:

$$E = ½Fx$$

where E = potential energy [J]
F = force exerted [N]
x = extension or compression of the spring [m]



2.10.3 Power

- Power is the rate at which energy is used OR the rate at which work is done.

$$P = \frac{E}{t} = \frac{W}{t}$$

where P = power [W]
E = energy [J]
W = work [J]
t = time [s]

2.10.4 Efficiency

Efficiency is the ratio at which the output power is compared to the input power.

$$\text{Efficiency} = \frac{\text{Output power}}{\text{Input power}} \times 100\%$$

2.11 Maximising Efficiency

The second law of thermodynamics *a.k.a.* **the law of entropy** states that in any energy transformation, some energy will be lost in the form of heat.

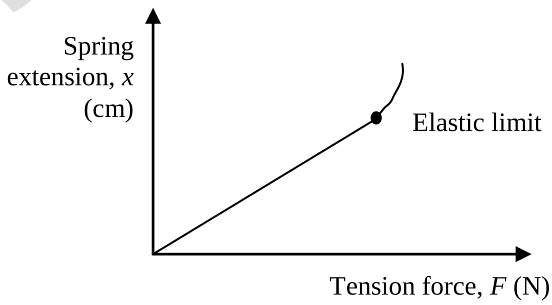
- ❖ Efficiency should be maximized in order to conserve energy resources.
- ❖ For example, to maximize efficiency of refrigerators:
  - ✓ Use refrigerators that have freezers at the top instead of the side
  - ✓ Keep the cooling coils clean
  - ✓ Do not put the fridge too near the wall or in a room that is too hot
  - ✓ Door seals should be in good condition
  - ✓ Do not open the fridge door unnecessarily
  - ✓ Defrost the fridge regularly
  - ✓ Don't set the thermostat low all the time
  - ✓ Send it for repair if the motor is not working properly

2.12 Elasticity

- ❖ Elasticity is the ability of an object to return to its original shape and size after the applied external force applied onto it has been removed.

2.10.1 Hooke's Law

Hooke's Law states that the extension or compression of a spring is **directly proportional** to the force acting on it provided the **elastic limit** of the spring has not been exceeded.



$$F = kx$$

where F = force exerted on the spring [N]
k = spring constant [N m^{-1}]
x = spring extension / compression [m]

Note: Because $F=kx$ and $E=½Fx$, you can derive it to:

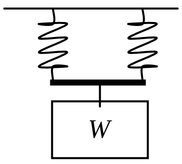
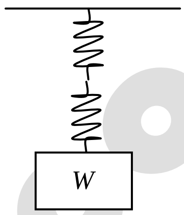
$$E = ½ kx^2$$

2.10.2 Spring stiffness

Factors which affect the stiffness of a spring:

1) Length of spring — *The greater the length the spring, the lower the stiffness*
2) Diameter of wire — *The greater the diameter of wire, the higher the stiffness*
3) Diameter of coil — *The greater the diameter of coil, the lower the stiffness*
4) Material of wire — *Different materials have different stiffness values*

2.10.3 Spring systems

Parallel arrangement	**Series arrangement**
	
The load is equally distributed among the springs. If n springs are used: Total extension = $\frac{x}{n}$	The same load is applied to each spring. If n springs are used: Total extension = nx

END OF CHAPTER

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