Fundamentals
M2
PHYSICS

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Training Manual

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M2 PHYSICS

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M2.1 MATTER

Nature of matter

Definition

Matter is defined as anything that occupies space, hence everything that we can see and feel constitutes matter. It is now universally accepted that matter is composed of molecules, which, in turn, are composed of atoms.

If a quantity of a common substance, such as water, is divided in half and the half is then divided, and the resulting quarter divided, and so on, a point will be reached where any further division will change the nature of the water and turn it into something else.

Molecule

Matter is composed of several molecules. The molecule is the smallest unit of a substance that exhibits the physical and chemical properties of the substance. All molecules of a particular substance are exactly alike and unique to that substance.

A molecule consists of a fixed amount of atoms.

- in an element, all atoms of a molecule are the same.
- in a chemical compound, each molecule has atoms from at least two different elements.

Hydrogen is normally found as a gas. This gas consists of molecules which have two hydrogen atoms each.

Not all elements form molecules.

Atom

If a molecule of a substance is divided, it will be found to consist of particles called atoms. An atom is the smallest possible particle of an element.

Element

An element is a single substance that cannot be separated into different substances except by nuclear disintegration.

There are more than 100 recognized elements, several of which have been artificially created from various radioactive elements. Common elements are iron, oxygen, aluminum, hydrogen, copper, lead, gold, silver, and so on. The smallest division of any of these elements will still have the properties of that element. A compound is a chemical combination of two or more different elements, and the smallest possible particle of a compound is a molecule. For example, a molecule of water (H_2O) consists of two atoms of hydrogen and one atom of oxygen. A picture of a water molecule is illustrated in figure 6.

Compounds

Compounds are pure substances made up of different elements (at least two) which have been joined together by a chemical reaction. Therefore the atoms are difficult to separate.

Each composition has a fixed number of atoms with a constant relation of the number of elements.

For example, water always has two hydrogen atoms and one oxygen atom which form a water molecule.

The properties of a compound are different from the atoms that make it up.

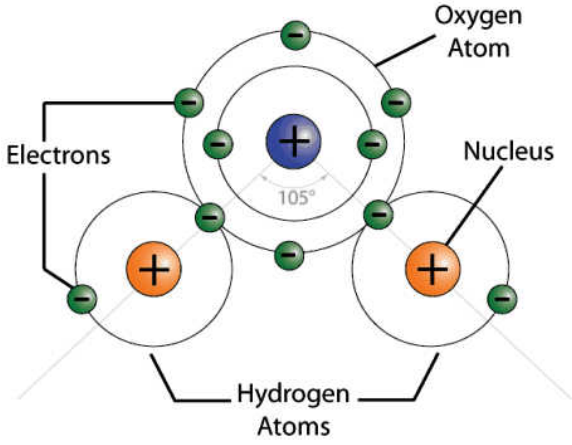
Splitting of a compound is called analysis.

Building of Chemical Compounds

When mixed, some elements form molecules immediately.

Other mixtures of elements need energy, i.e. heat, to form molecules.

However, many mixtures of elements do not form molecules at all.



WATER MOLECULE

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Protons, Electrons and Neutrons

Structure of Atoms

Many discoveries have been made that greatly facilitate the study of electricity and provide new concepts concerning the nature of matter. One of the most important of these discoveries has dealt with the structure of the atom. It has been found that an atom consists of infinitesimal particles of energy known as electrons, protons and neutrons. All matter consists of two or more of these basic components.

The simplest atom is that of hydrogen, which has one electron and one proton, as shown in figure A.

The structure of an oxygen atom is indicated in figure B.

This atom has eight protons, eight neutrons and eight electrons. The protons and neutrons form the **nucleus** of the atom, electrons revolve around the nucleus in orbits varying in shape from elliptical to circular and may be compared to planets as they move around the sun.

Charges

A **positive** charge is carried by each proton, no charge is carried by the neutrons, and a **negative** charge is carried by each electron. The charges carried by the electron and the proton are equal in magnitude but opposite in nature. An atom that has an equal number of protons and electrons is electrically neutral; that is, the charge carried by the electrons is balanced by charge carried by the protons.

Ions

It has been explained that an atom carries two opposite charges, protons in the nucleus have a positive charge, and electrons have a negative charge. When the charge of the nucleus is equal to the combined charges of the electrons, the atom is neutral, but if the atom has a shortage of electrons it will be **positively charged**. Conversely, if the atom has an excess of electrons, it will be **negatively charged**. A positively charged atom is called a **positive ion**, and a negatively charged atom is called a **negative ion**. Charged molecules are called ions, too. It should be noted that protons remain within the nucleus, only electrons are added or removed from a atom, thus creating a negative or positive ion.

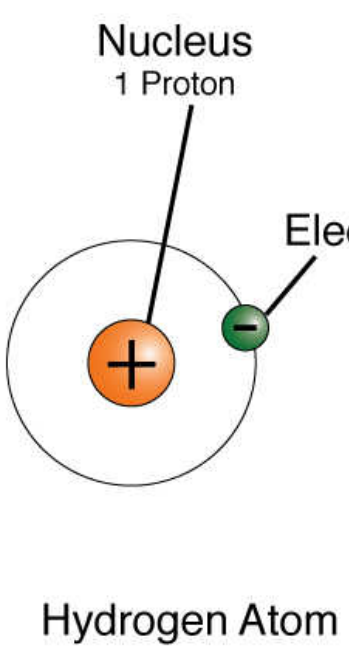


Figure A

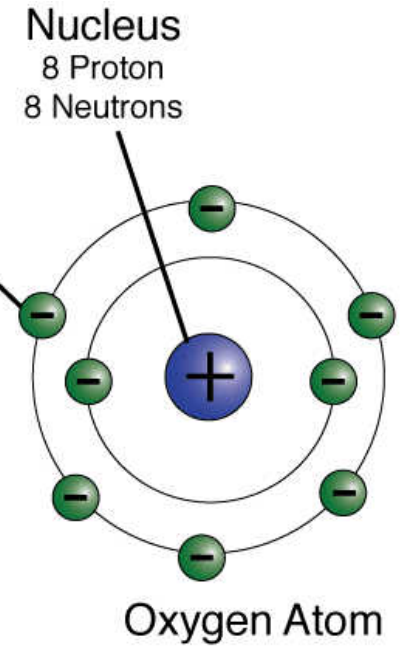


Figure B

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Structure of atoms and Free Electrons

Shells

The path of an electron around the nucleus of an atom describes an imaginary sphere or shell. Hydrogen and helium atoms have only one shell, but the more complex atoms have numerous shells. Figure B illustrates this concept. When an atom has more than two electrons, it must have more than one shell, since the first shell will accommodate only two electrons. The number of shells in an atom depends on the total number of electrons surrounding the nucleus.

The atomic structure of a substance is of interest to the electrician because it determines how well the substance can conduct an electrical current.

Free Electrons

Certain elements, chiefly metals, are known as **conductors** because an electric current will flow through them easily. The atoms of these elements give up electrons or receive electrons in the outer orbit with little difficulty. The electrons that move from one atom to another are called **free electrons**. The movement of free electrons from one atom to another is indicated in figure C, and it will be noted that they pass from the outer shell of one atom to the outer shell of the next atom. The only electrons shown are those in the outer orbits.

As shown in figure C, the movement of free electrons does not always constitute electric current flow. There are often several free electrons randomly drifting through the atoms of any conductor. It is only when these free electrons move in the same direction that electric current exists. A power supply, such as a battery, typically creates a potential difference from one end of a conductor to another. A strong negative charge on one end of a conductor and a positive charge on the other is the means to create a useful electron flow.

Electrical Conductivity

An element can be either a conductor, nonconductor (insulator) or semiconductor depending on the number of electrons in the valance orbit of the materials atoms.

The **valance orbit** of any atom is the outer most orbit (shell) of that atom. The electrons in this valance orbit are known as **valance electrons**. All atoms desire to have their valance orbit completely full of electrons, and the fewer valance electrons in an atom, the easier it will accept extra electrons. Therefore, atoms with fewer than half of their valance electrons tend to easily accept (carry) the moving electrons of an electric current flow. Such materials are called **conductors**. Materials that have more than half of their valance electrons are called **insulators**. Insulators will not easily accept extra electrons.

Materials with exactly half of their valance electrons are **semiconductors**. Semiconductors have very high resistance to current flow in their pure state, however, when exact numbers of electrons are added or removed, the material offers very low resistance to electric current flow.

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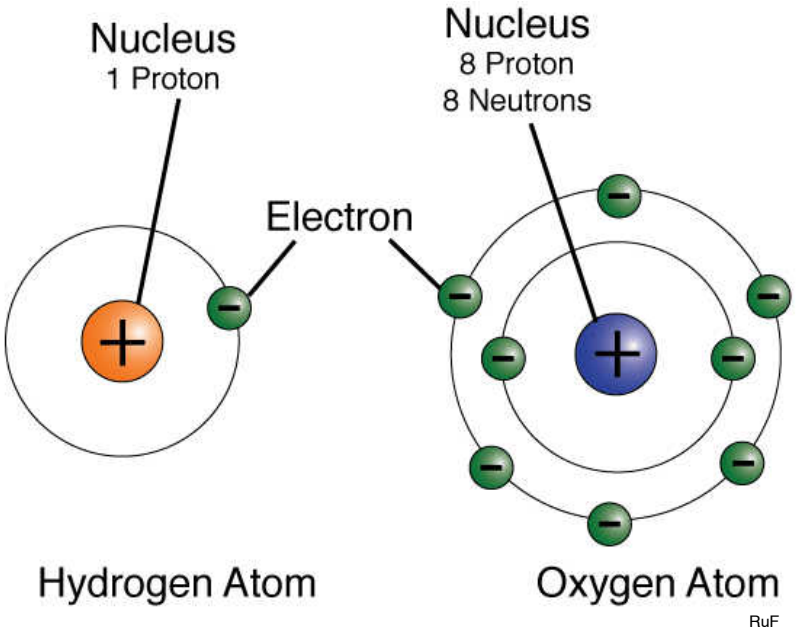


Figure B

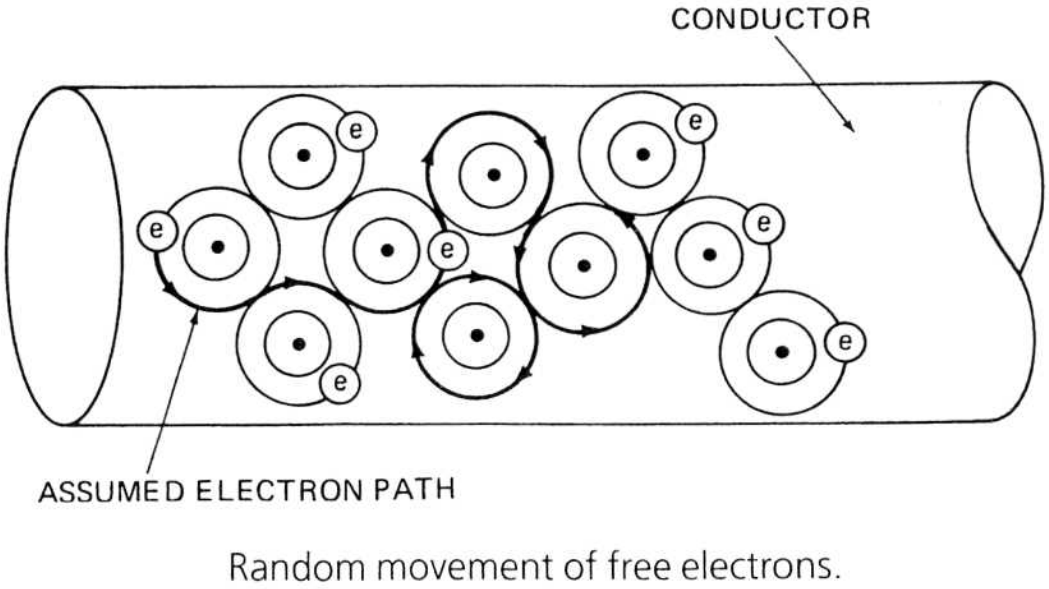


Figure C

Figure 1 Atomic Shell and Free Electrons

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The Electronic Structure of Atoms

General

The electrons are arranged in energy levels or shells around the nucleus and with increasing distance from the nucleus.

Our knowledge about the structure of atoms depends on the mathematical formulations predicted by Niels Bohr. He suggested that electrons are distributed in orbits and the number of electrons held in the orbit depends on the number of the orbit. The orbits are counted outwards from the nucleus. The higher the orbit number, the further the electrons are from the nucleus.

The electrons in one orbit form a shell.

If the orbit number is “n”, then the maximum electrons held in the orbit is given as $2n^2$. The first orbit has n = 1, and will hold 2 electrons, the second orbit has n = 2 and is capable of holding a total of 8 electrons, similarly the third orbit will be able to contain 18 electrons and so on.

Atomic/Proton Number

This is the number of protons in the nucleus.

Mass/Nucleon Number

This is the total number of protons and neutrons in the nucleus.

Shells

The shells are lettered from the innermost shell outwards from K to Q.

There are rules about the maximum number of electrons allowed in each shell:

- The 1st shell (K) has a maximum of 2 electrons
- The 2nd shell (L) has a maximum of 8 electrons
- The 3rd shell (M) has a maximum of 18 electrons
- The 4th shell (N) has a maximum of 32 electrons.

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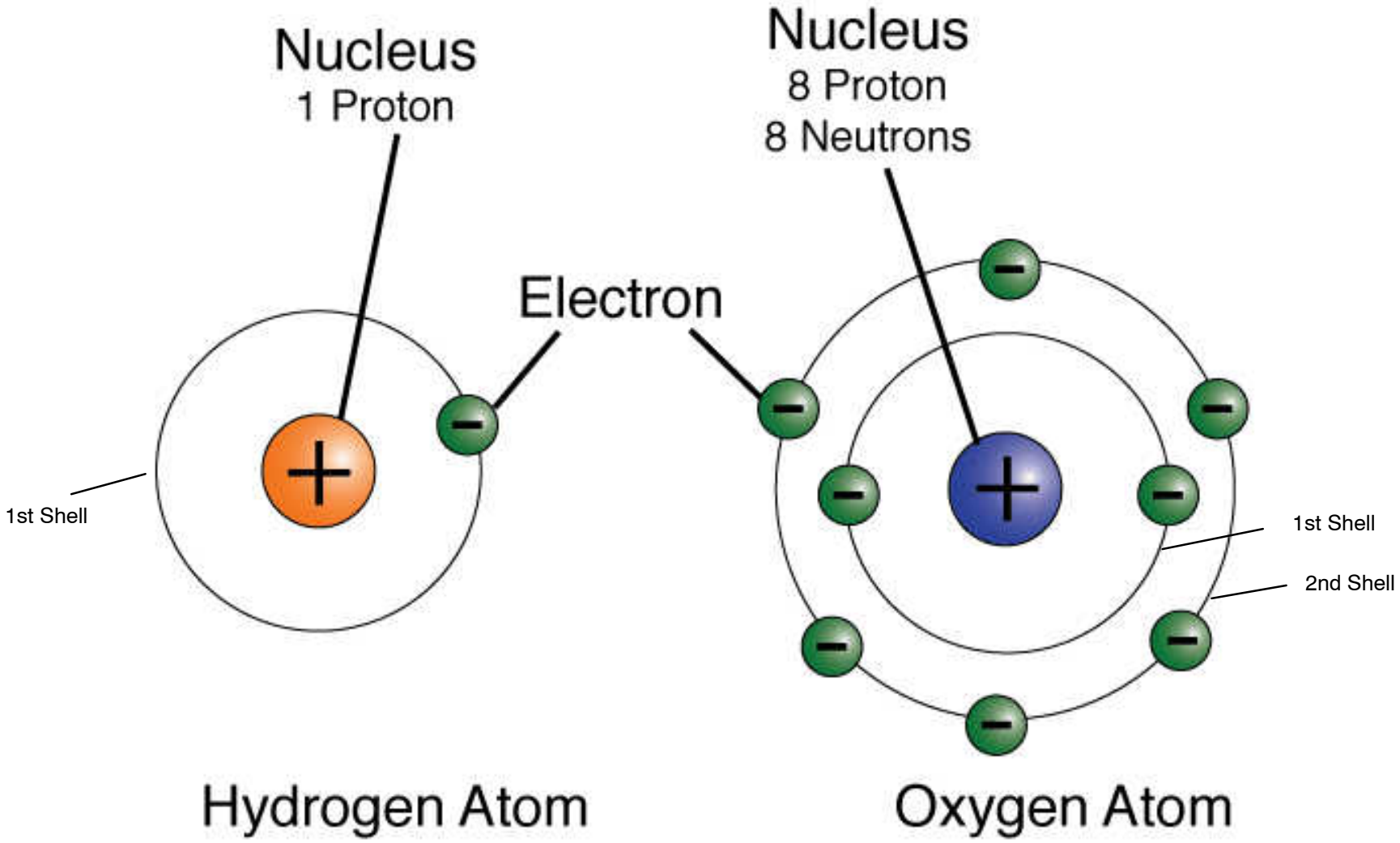


Figure A **Figure B**

RuF

Figure 2 Shells

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The chemical elements

General

An element is a pure substance, made up of atoms with the same number of protons.

Isotope

Isotopes of an element is are atom of the same number of protons but different number of neutrons.

The majority of atoms which have a specific number of neutrons is regarded as normal, and the minority with a different number of neutrons is regarded as an isotope of this atom.

Some elements have only “normal“ atoms and therefore there are no isotopes of that element.

Other elements may have two isotopes with different atomic mass.

Isotopes of an element have the same chemical properties but with a different atomic mass.

Mixtures

Mixtures are compositions of two or more different elements. In nature mixtures appear in uniform (homogeneous) or nonuniform (heterogeneous) form.

Mixtures have the properties of the different elements that make it up.

In mixtures, the elements are easy to seperate. For example, heat in a special range of temperatures is used for destillation to separate oil which change the state of one element from liquid to gaserous, but the other element stays liquid.

Table of Elements

The “Table of elements“ contains each of the known elements and their corresponding atomic numbers and atomic masses.

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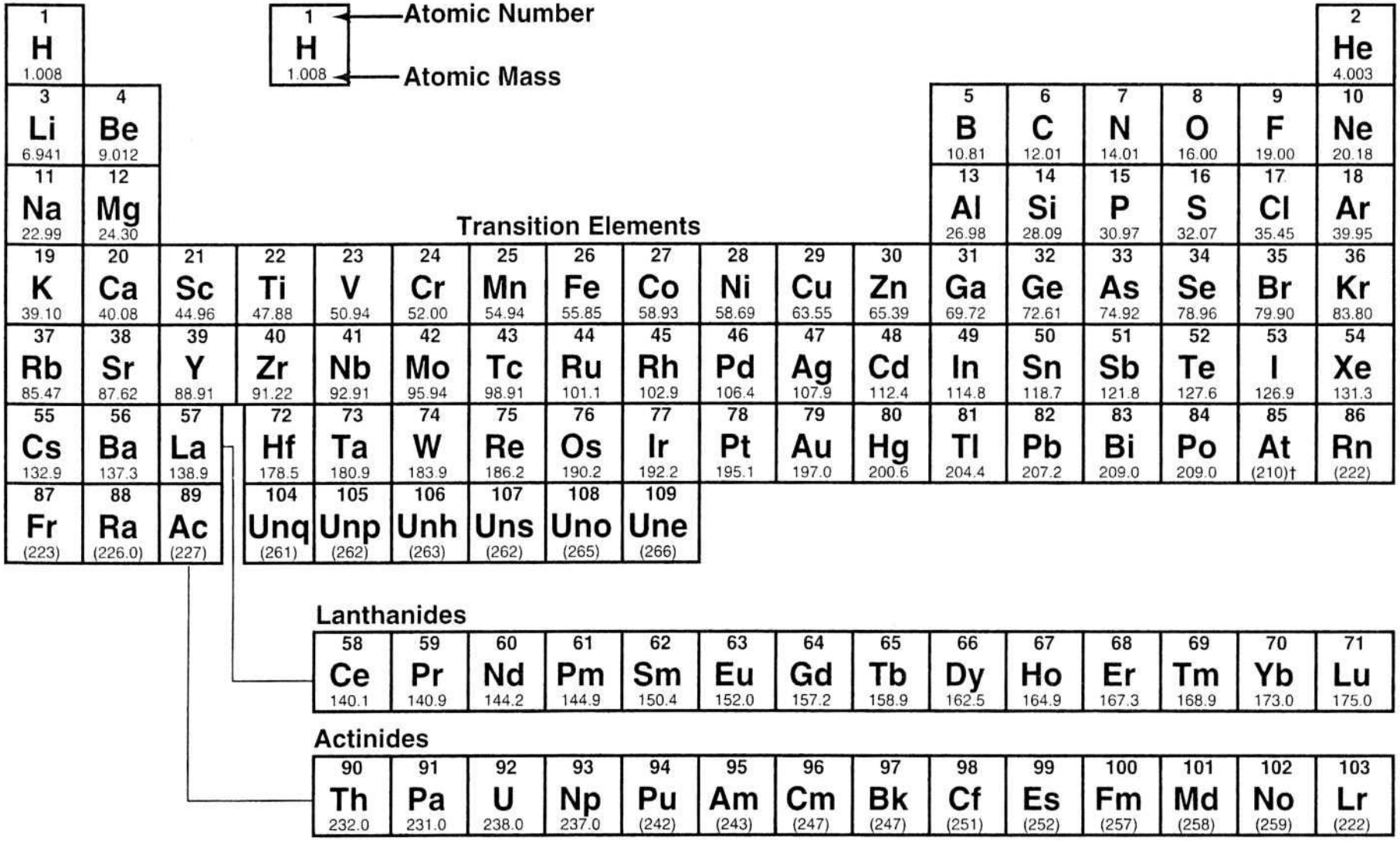


Figure 3 Table of Elements

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States of Matter

General

Matter may exist in one of three physical states:

- Solid
- Liquid or
- Gas.

All matter exists in one of these states.

A physical state refers to the physical condition of a substance and has no affect on a substances chemical structure. In other words, ice, water and steam are all H_2O and the same type of matter appears in all of these states.

All atoms and molecules in matter are constantly in motion. This motion is caused by heat energy in the material. The degree of motion determines the physical state of matter.

Solid

A solid has a definite volume and shape, and is independent of its container. For example, a rock that is put into a jar does not reshape itself to form to the jar. In a solid there is very little heat energy and, therefore, the molecules or atoms cannot move very far from their relative position.

For this reason a solid is incompressible.

Liquid

Liquids are also considered incompressible. Although the molecules of a liquid are farther apart than those of a solid, they are still not far enough apart to make compressing possible. In a liquid the molecules still partially bond together. This bonding force is known as surface tension and prevents liquids from expanding and spreading out in all directions. Surface tension is evident when a container is slightly over filled.

Gas

As heat energy is continually added to a material, the molecular movement increases further until the liquid reaches a point where surface tension can no longer hold the molecules down. At this point the molecules escape as gas or vapour. The amount of heat required to change a liquid to a gas varies with different liquids and the amount of pressure a liquid is under. For example, at a pressure that is lower than atmospheric, water boils at a temperature less than 100 °C. Therefore, the boiling point of a liquid is said to vary directly to pressure.

Gases differ from solids and liquids in the fact that they have neither a definite shape nor volume. Chemically, the molecules in a gas are exactly the same as they were in their solid or liquid state.

However, because the molecules in a gas are spread out, gases are compressible.

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Solid



Liquid



Gas

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Figure 4 Physical States

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Changes between States

General

We can use the diagrams shown below, to explain changes of state and the energy changes involved.

Evaporation & Boiling (liquid to gas)

In evaporation and boiling the highest kinetic energy molecules can escape from the attractive forces of the other liquid particles. The particles lose any order and become completely free. Energy is needed to overcome the attractive forces in the liquid and is taken in from the surroundings. This means heat is taken in (endothermic). Boiling is rapid evaporation at a fixed temperature called the boiling point and requires continuous addition of heat. Evaporation takes place more slowly at any temperature between the melting point and boiling point and results in the liquid becoming cooler.

Condensing (gas to liquid)

On cooling, gas particles lose kinetic energy and eventually become attracted together to form a liquid. There is an increase in order as the particles are much closer together and can form clumps of molecules.

The process requires heat to be lost to the surroundings i.e. heat given out, so condensation is exothermic.

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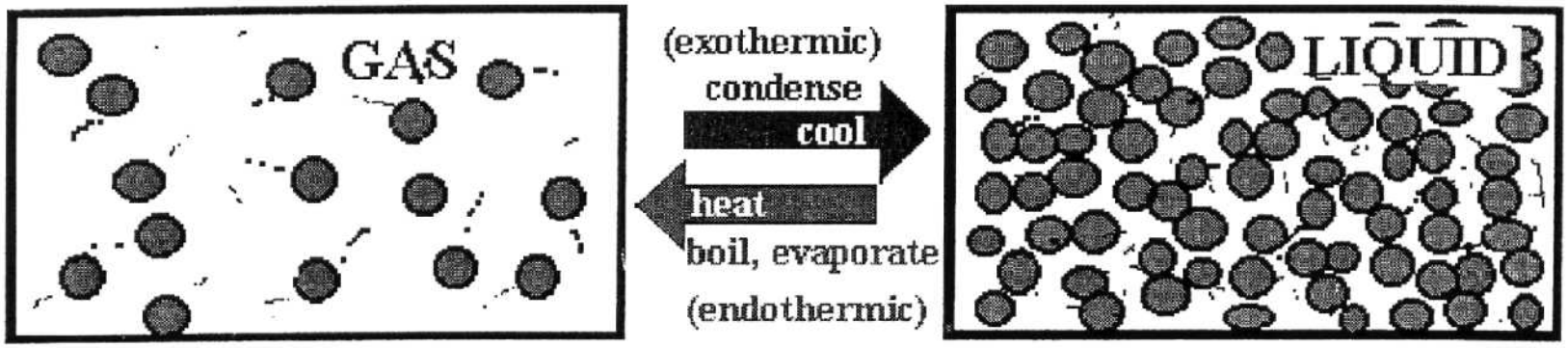


Figure 5 Boiling and Condensing

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Melting (solid to liquid)

When a solid is heated the particles vibrate more strongly and the particle attractive forces are weakened. Eventually, at the melting point, the attractive forces are too weak to hold the structure together and the solid melts. The particles become free to move around and lose their order arrangement.

Energy is needed to overcome the attractive forces, so heat is taken in from the surroundings and melting is an endothermic process.

Freezing (liquid to solid)

On cooling, liquid particles lose kinetic energy and become more strongly attracted to each other. Eventually at the freezing point the forces of attraction are sufficient to remove any remaining freedom and the particles come together to form the ordered solid arrangement.

Since heat must be removed to the surroundings freezing is an exothermic process.

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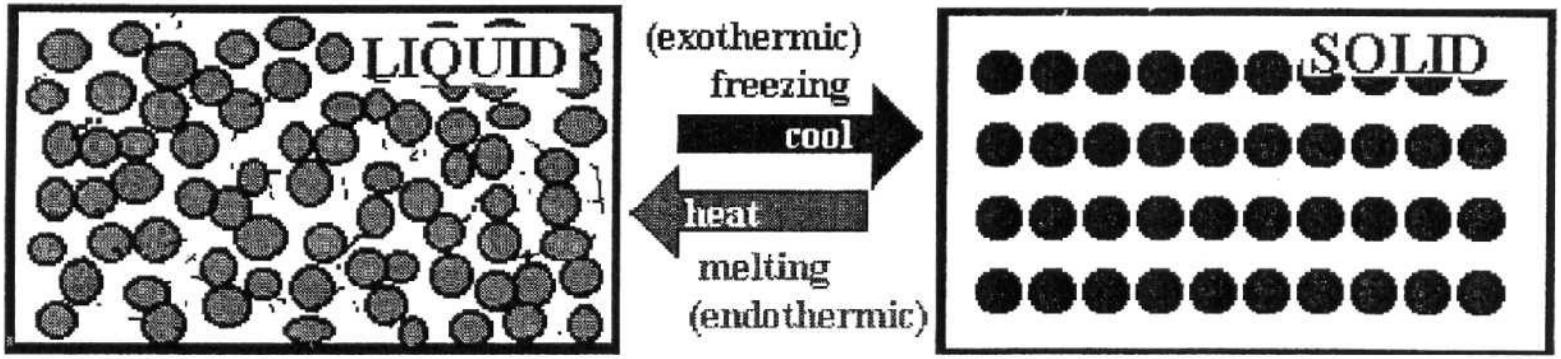


Figure 6 Melting and Freezing

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M2.2 MECHANICS

M2.2.2 KINETICS

Linear Movement

UNIFORM MOTION IN A STRAIGHT LINE

When a body is moving in a straight line with constant speed it is not accelerating. We say, that it is moving with constant velocity. If a body's velocity is not constant, it is accelerating. A body accelerates if it is changing its speed and/or its direction.

When we discuss a body's straight line motion, then we do not have any change in direction. In this instance, any acceleration is due to a change in speed.

Special formulas which deal with straight line motion use certain symbols to represent specific quantities. These symbols are summarized below:

v_{av} = average velocity
t = time
u = initial velocity
v = final velocity
a = acceleration
s = distance covered*

*Note that "s" is the traditional notation for distance in almost all physics textbooks. This choice reduces confusion with the symbol "d" for derivative, a concept from calculus.

There is a formula dealing with the motion of a body that you have used for many years.

distance = average speed · time

Using our above symbols, we could write:

Formula 1:

$$s = v_{av} \cdot t$$

Note: For the velocity we have used the average velocity.

We all know that is is almost impossible to go or drive a distance with always the same speed. Sometimes we move faster and sometimes we move slowlier. To simplify our formula we use the average speed.

Assume we go 10 meters within 10 seconds. That mean our speed is 1 m per second (m/s). For the following 10 meters we need 5 seconds, which mean our speed is 2 m/s. If we add both values and divide it by two we will get an average speed of 1.5 m/s. In other words with an average speed of $10\frac{m}{s}$ for 10 seconds, we cover 100 meters, $\frac{10m \times 10s}{s} = 100m$.

MOTION UNDER CONSTANT ACCELERATION

Extending our treatment of motion to include the concept of acceleration. Acceleration (for straight line motion) is the rate of change of speed in time.

We define acceleration (for straight line motion) in the following:

Formula 2:

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

In using this formula, acceleration (a) may be either positive or negative. If final velocity (v) is less than initial velocity (u), then our value of acceleration (a) turns out to be a negative number.

When a problem is given to you to solve, be sure to determine which of these three quantities are given to you, and which quantity is to be found. Choose the formula which involves these four quantities. If the formula is not solved for the unknown quantity, solve for this quantity algebraically. Finally substitute the known quantities and solve for the unknown quantity.

Calculation of Acceleration

An object has an initial speed u and a final speed v. While it is undergoing this change of speed, it travels a distance s.

In attacking this problem it is wise to write down exactly what is known and what is unknown.

Formula 3 involves these four quantities.

Formula 3:

$$v^2 = u^2 + 2a \cdot s$$

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MOTION UNDER GRAVITY

General

On earth, gravity is a force which pulls on every mass. This force causes the weight of a mass.

Vector

The vector of this force has a clear direction: the middle of the earth.

Acceleration by Gravity

The bigger the mass, the bigger is the force needed to accelerate it with a constant acceleration.

However, the bigger the mass, the bigger the weight which causes this force.

By this, the acceleration by gravity is the same on small masses and big masses.

It is said that Galileo Galilei proved this by an experiment in Pisa (Italy): at the same time he dropped two bullets with different weight. The hit the ground the same time. While there are no historical proves for this experiment, the statement has been proved true.

Earth's Gravity

Accelerations often have the symbol *a*.

For the acceleration caused by the earth's gravity, *g* is used.

The standard gravity is defined as follows: $g = 9,81 \frac{m}{s^2}$

Converted into the imperial system, the gravity is: $g = 32,2 \frac{ft}{s^2}$

However, this value is only correct on the earth's surface.

The bigger the height, the smaller the force of the gravity.

Free Fall

When things fall to earth, the mass could accelerate faster and faster.

But in reality, bodies are slowed down because of their drag.

Drag depends on surface and form of the object.

By this, bombs fall fast and parachuters fall slowly.



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Figure 7 Galileo Dropping the Bullets

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Falling Bodies

Here thre are some more examples.

If a compact body, such as a stone, is dropped (not thrown) from a height of 100 meters above the surface of the earth, it will take about 4.5 seconds for the body to reach the ground. It will have obtained a speed of 44 m/s (160 km/h, 100 mph). At this speed, the effects of air resistance are still quite negligible.

Above this speed of 160 km/h (100 mph), the effects of air resistance must be observed.

Therefore, we can conclude that the fall of a body from a height of 100 m or less can be handled quite accurately with the ordinary acceleration formulas. The value of the acceleration will be 9.81 m/s^2 or 32 ft/s^2.

Terminal Velocity

If a body falls from a height greater than 100 m above the surface of the earth, the air resistance becomes very important. As we said, a height of 100 meters corresponds to a fall of 4.5 seconds.

When the time of fall increases to about 8 seconds, the speed of fall has increased in a non−linear manner from 160 km/h (100 mph) to 185 km/h (115 mph). As the time of fall increases beyond 8 seconds the speed of fall remains constant at about 185 km/h.

This speed of fall is called the “terminal velocity”.

Example:

A body started from rest and has been falling freely for 3 seconds.

At what speed is it falling?

$u = 0$

$t = 3\ s$

$a = 9{,}81\ m/s^2$ $\qquad v = ?$

Use formula 2:

$v = u + a \cdot t$

$v = 0 + 9{,}81\ m/s^2 \cdot 3\ s$

$v = 29\ m/s$

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Figure 8 Free Fall

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Rotational Movement

UNIFORM CIRCULAR MOTION (CENTRIFUGAL AND CENTRIPETAL FORCES)

General

A ball whirled in a circle experiences an acceleration toward the center of the circle. This can be proven by considering that the ball is continually changing direction as it moves in a circle.

The ball would “like“ to follow a straight path. For a deviation from the straight path, force must be applied on it.

Hammer Throwing

A hammer thrower must continually pull towards the center of rotation, applying his full weight to make the hammer accelerate continually towards the center of rotation to absorb the centrifugal force. The **centrifugal force** is caused by the inertia of a rotating body and tries to draw this body away from the center of rotation.

As soon as the athlete stops applying the force towards the center (she releases the hammer) the hammer travels in a straight line, at a tangent to the circle.

The acceleration is in the same direction as the force which makes it move in a circle. This force opposite to the centrifugal force is called **centripetal force** (from the Latin meaning “center seeking“). Since we have a constant change in the direction of the motion of the hammer, we have a constant acceleration. This is called **centripetal acceleration** and can be calculated by the square of the velocity divided by the radius of the circular path.

$$\text{Centripetal Acceleration} = \frac{\text{Velocity}^2}{\text{Radius}} = \frac{v^2}{R}$$

For circular motion,

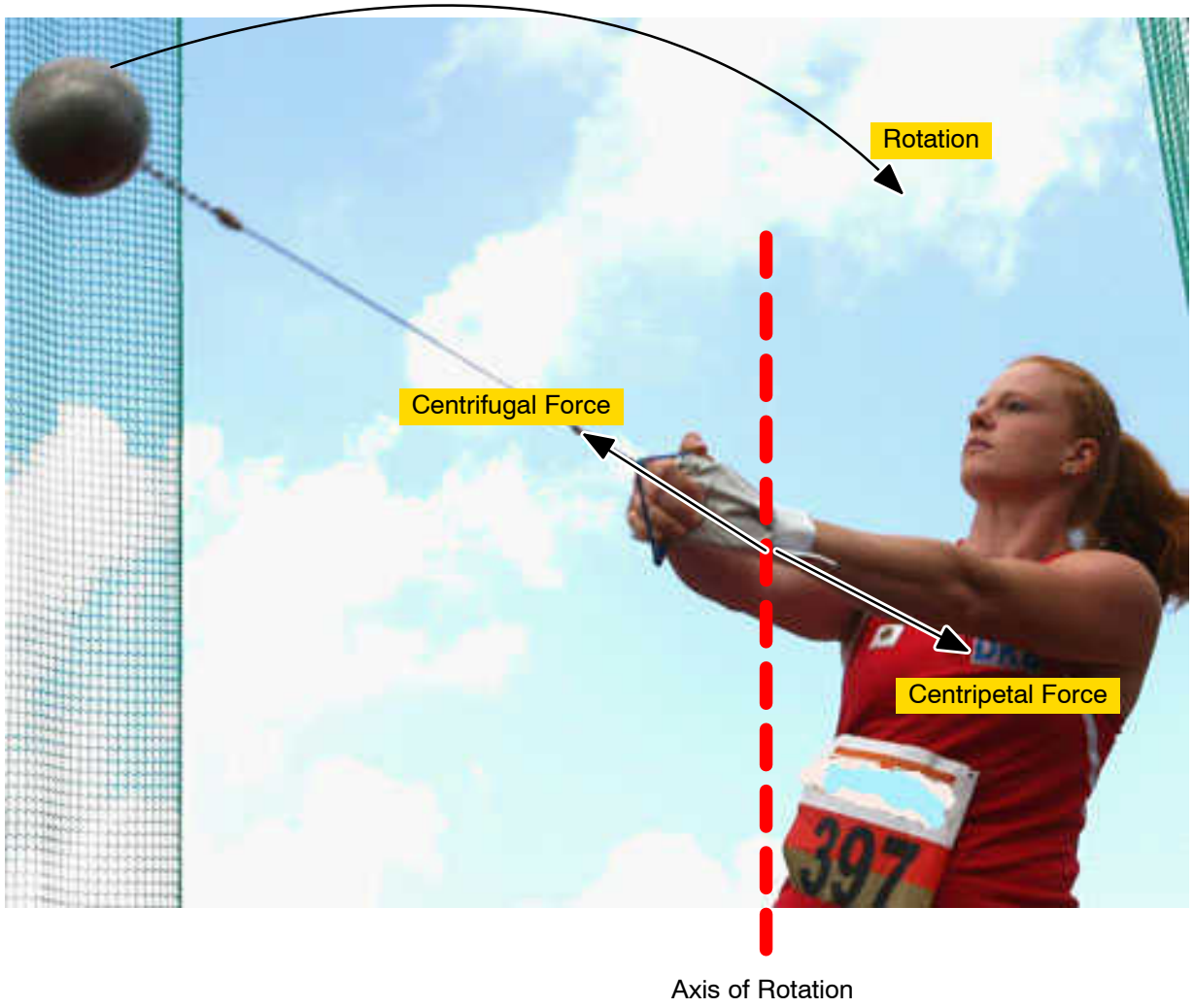
$$\text{Centripetal Force} = \frac{\text{Mass} \times \text{Velocity}^2}{\text{Radius}} = \frac{m \times v^2}{R}$$

Concerning bodies moving in a circular path the force directed toward the center of the path must equal the mass of the body times the square of the speed of the body divided by the radius of the path.

This force is called the centripetal force.

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Figure 9 Hammer Throwing

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Pendular Motion

General

A pendulum is a weight, suspended in the earth's gravitational field which is free to pivot at it's top end. Pendular motion describes the movement which the pendulum will undergo if it is given a small displacement from it's vertical position and is then allowed to swing freely under gravity.

For experimental purposes, a pendulum can be constructed by attaching a small weight to a piece of non extendible string and suspending the string by it's top end.

Terminology

When describing pendular motion the angular displacement of the pendulum from it's rest position to it's maximum swing position is known as the angular amplitude and one complete swing to and fro is known as one oscillation or vibration.

The length of the pendulum is defined as the distance from the pivot point to the center of gravity of the bob and the time taken to complete one oscillation is referred to as the periodic time.

PENDULAR MOVEMENT

General

Observations taken during experiments show that, provided the pendulum has a displacement of only a few degrees, then the periodic time remains constant even as the movement slows down.

This observation was first made by the physicist Galileo Gallilei in Italy in the 17th century and he was quick to realize that the pendulum could be very useful in the manufacture of clocks which up to that time were not particularly accurate. It can also be observed that the mass of the bob makes no difference to the periodic time. This can be readily seen when two people of different sizes sit on swings in a park and, as long as the swings are the same length, they will swing with the same periodic time. If, however we change the length of one of the swings then the shorter one will have a reduced periodic time compared to the longer one. We can describe this relationship by saying that **the square of the periodic time is proportional to the length of the pendulum**.

Or in mathematical terms $\frac{T^2}{l} = constant$

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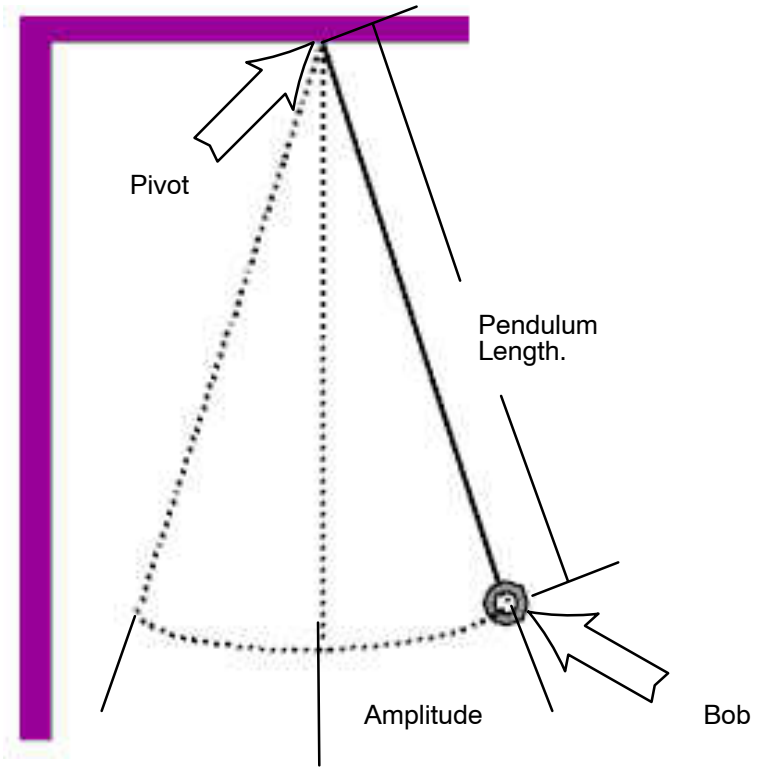


Figure 10 Simple Pendulum

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Simple theory of Vibration, Harmonics and Resonance

Vibration

Now we look at reflected waves.

The most common example is the case of waves originating in a disturbance impressed on a string of definite length i.e. a string that is fixed at both ends. Many musical instruments depend on such vibrations. If a sinusoidal wave disturbance is impressed on a very long cord a sinusoidal wave travels continuously along the cord. However, if the sinusoidal wave meets a fixed end, a reflected wave moves back along the cord.

The wave patterns which are observed are called the normal modes of vibration of the cord. In the figure below the length of the cord is L. The wavelength in the various modes of vibration are λ_n. The n is the index of the mode. In the equations which follow, n has an integral value, that is n = 1, 2, 3, 4.

We can write a general relation as follows:

$$\lambda_n = \frac{2}{n} \cdot L$$

Resonance

The vibration where n = 1 is called the fundamental mode of vibration of the body. The other vibrations are called overtone vibrations. Every body which can vibrate has a certain fundamental mode of vibration that has a definite frequency associated with it. If this frequency is impressed on the body, it will vibrate with a relatively large amplitude. We say that the body is vibrating in resonance with the impressed frequency.

Aircraft designers must take resonant frequencies into account when designing aircraft structure. For example, if a component on an aeroplane or helicopter is allowed to vibrate at its resonant frequency the amplitude of the vibration can become very large and the component will destroy itself by vibration.

Let us examine the case of a helicopter which has a tail boom with a natural or resonant frequency of 1Hz. That is, if you were to strike the boom with your fist it would oscillate once each second. The normal rotational speed of the rotor is 400 rpm and the helicopter has three blades on its main rotor.

Each time a rotor blade moves over the tail boom the blade is going to cause a downward pulse of air to strike the tail boom. The designer must determine the speed at which the pulses will be equal to the resonant frequency of the boom. One cycle per second is equivalent to 60 cycles/minute. Since each of the three blades causes a pulse each revolution, there will be 3 x 60 or 180 pulses/minute. Therefore a rotor speed of 180 rpm would be critical and the pilot would be warned against operating at that speed.

Overtone

The boom also has a secondary, or overtone, resonant frequency of twice the fundamental resonant frequency, 360 rpm would also have to be avoided but would not be as critical as 180 rpm. The third frequency of concern would be 3 x 180 or 540, but that is above the rotor operating speed, so is not a problem.

The natural frequency of vibration is also an extremely important consideration in designing the wings, horizontal and vertical stabilizers of an aircraft. The designer must be certain that the resonant frequency when the surface is bent is different from that resonant frequency when it is twisted.

If that is not the case, an aerodynamic interaction with the elasticity of the surface can result in “flutter” which can cause the surface to fracture in a fraction of a second after it begins.

Harmonics

A harmonic of a wave is a component frequency of the signal that is an integer multiple of the fundamental frequency.

In the figure below, one harmonic wave is shown. The first harmonic wave is shown for the given wave length 2L.

For example, the fundamental frequency is 25 Hz. The first harmonic is 50 Hz, the second harmonic is 75 Hz and so on.

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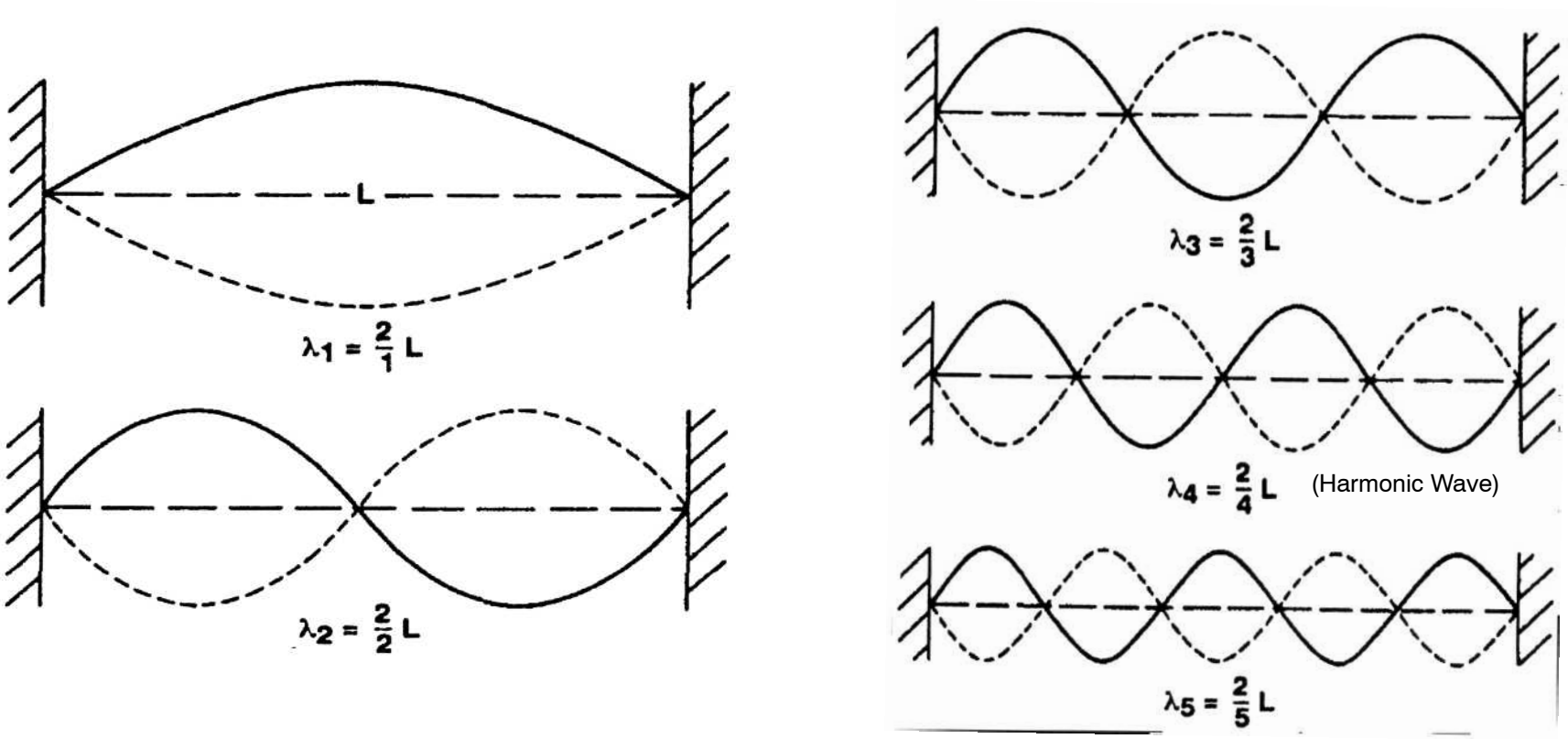


Figure 11 Resonance

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Mechanical Advantage, Velocity ratio and Efficiency

General

There is no application of the basic machine that is used more than the gear. The gear is used in clocks and watches, in automobiles and aircraft, and in just about every type of mechanical device.

Gears are used to gain mechanical advantage, or to change the direction of movement.

Mechanical Advantage

To gain a mechanical advantage when using gears, the number of teeth on either the drive gear or driven gear is varied.

For example, if both the drive gear and the driven gear have the identical number of teeth, no mechanical advantage is gained.

However, if a drive gear has 50 teeth and a driven gear has 100 teeth a mechanical advantage of 2 is gained. In other words, the amount of power required to turn the driven gear is reduced by half.

Many machines use a mechanical advantage to change the amount of force required to move an object. Some of the simplest mechanical advantage devices used are levers, inclined planes, pulleys and gears.

Mechanical advantage is calculated by dividing the weight, or resistance (R) of an object by the force used to move the object.

Usually, this force is called “effort“ with the symbol “E“.

This is seen in the formula:

$$\text{Mechanical Advantage (MA)} = \frac{\text{Resistance}}{\text{Effort}} = \frac{R}{E}$$

A mechanical advantage of 4 indicates that for every 1 newton of force applied, 4 newtons of resistance can be moved.

This advantage is also known as **AMA** which mean **Actual Mechanical Advantage**.

The actual mechanical advantage (AMA) is the ratio of the output force to the input force. The actual mechanical advantage tells us how much easier it is for the worker.

AMA = $F_0 : F_i$

Example 1:

A worker is able to raise a body weighing 300 N. By applying a force of 75 N.

What is the AMA of the machine that he is using?

AMA = $F_0 : F_i$

= 300 N : 75 N

= 4

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Velocity Ratio

Another thing to keep in mind is that the revolution or velocity ratio between two gears is the reverse ratio of their teeth.

Using the earlier example of a drive gear with 50 teeth and a driven gear with 100 teeth, the gear ratio is 1:2. However, for every revolution of the drive gear the driven gear makes half a turn. This results in a revolution ratio of 2:1.

To calculate the velocity ratio (v_r) the following formula is used:

$$VR = \frac{distance\ moved\ by\ E}{distance\ moved\ by\ R} = \frac{d_E}{d_R}$$

If we assume that an ideal machine existed, we would be able to calculate its advantage by using the same formula as menioned above. This calculated advantage is then called **IMA** which stands for **Ideal Mechanical Advantage**.

The ideal mechanical advantage (IMA) is the mechanical advantage that would exist if there were no friction in the machine. It is the ratio of the input distance d_i to the output distance d_o.

IMA = $d_i : d_0$

Example 2:

A worker applied his force through a distance of 15 m. The load is raised a distance of 2.5 m.

What is the IMA of the machine that he used?

IMA = $d_i : d_0$
= 15 m : 2.5 m
= 6

Efficiency

For comparison of machines it is essentiel to know the efficiency. That means the amount of force that is brought IN compared to the amount of force that comes OUT of the machine.

To make a statement about the mechanical efficiency we can combine both formulas mentioned above as follows.
Multiplying the resistance (R) of the object that we want to move with the distance we want to move (d_R) it and dividing both by the effort that is used to move the object multiplied by the distance to move it (d_E):

$$mechanical\ effort = \frac{work\ done\ by\ R}{work\ done\ by\ E} = \frac{R \cdot d_r}{E \cdot d_E} = \frac{MA}{VR}$$

As we usually express efficiency in percent, we multiply the result of the mechanical effort by 100%:

$$Efficiency\ \% = \frac{MA}{VR} \times 100\%$$

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PULLEYS

General

Pulleys are another type of simple machine that allow you to gain mechanical advantage. A single fixed pulley is identical to a first class lever. The fulcrum is the center of the pulley and the arms that extend outward from the fulcrum are identical in length. Therefore, the mechanical advantage of a single fixed pulley is 1. When using a pulley in this fashion, the effort required to raise an object is equal to the object's weight.

If a single pulley is not fixed, it takes on the characteristics of a second class lever. In other words, both the effort and weight act in the same direction. When a pulley is used this way, a mechanical advantage of 2 is gained.

A common method used to determine the mechanical advantage of a pulley system is to count the number of ropes that move or support a moveable pulley.

Distance Ratio

Another thing to keep in mind when using pulleys is that as mechanical advantage is gained, the distance the effort is applied increases. In other words, with a mechanical advantage of 2, for every 1 meter the resistance moves, effort must be applied to 2 meter of rope.

This relationship holds true wherever using a pulley system to gain mechanical advantage.

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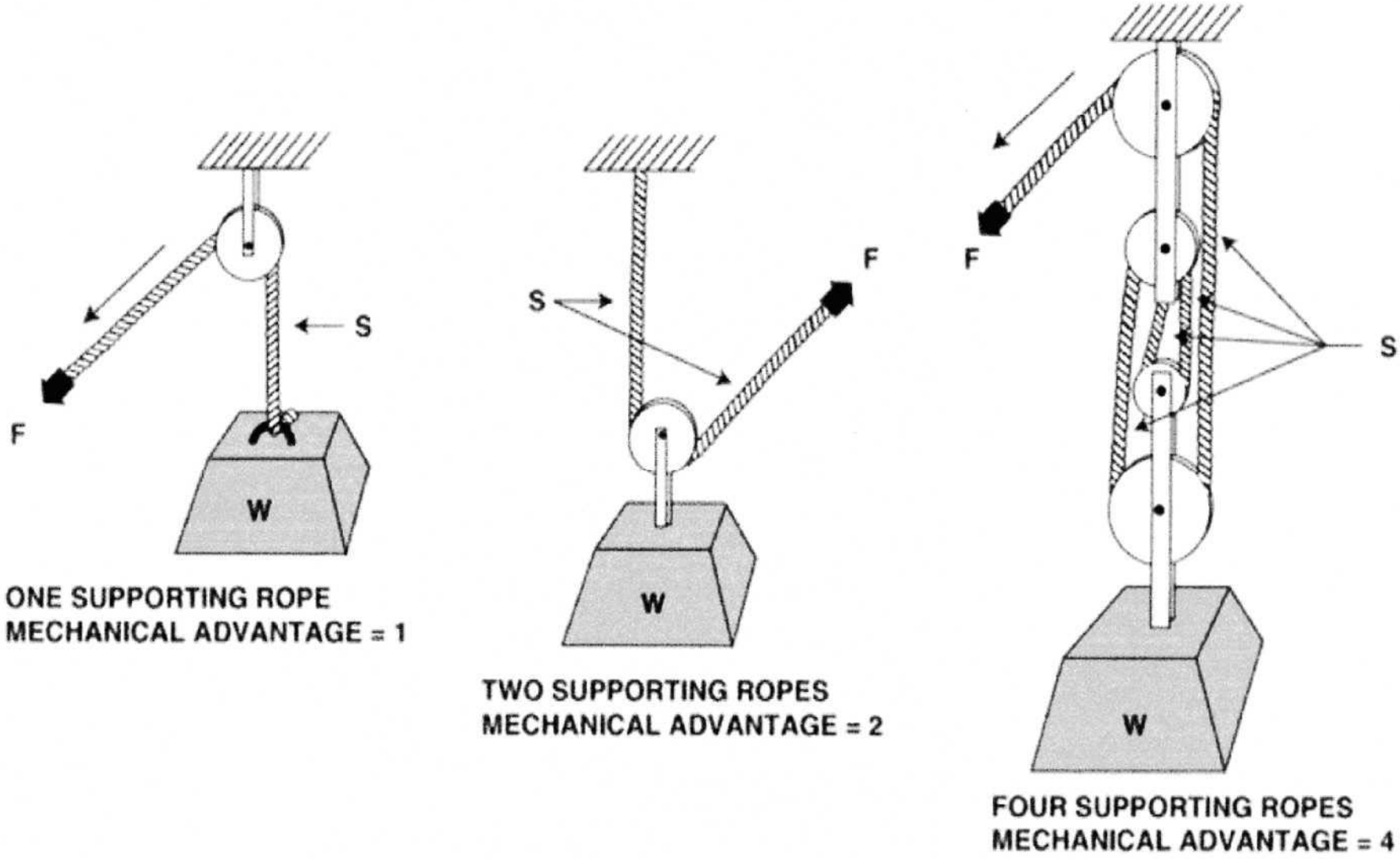


Figure 12 Pulleys and Mechanical Advantage

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M2.2.1 STATICS

Scalars and Vectors

Scalars

In physics, scalars are all quanities which have no direction.

Examples are mass, time and temperature.

Vectors

When geomety is applied for practical tasks, very often vectors are used.

A vector helps to explain effects in a two or three dimensional area.

Each vector consist of two different parts:

- direction
- intensity

In physics, vectors are all quanities which have a direction.

Examples are velocity and force.

The direction of an effect is simply shown by the direction of an arrow. It shows the direction of an effect related to a basic direction, e.g. north.

The intensity is shown by the length of that arrow. By this, you have the possibility to illustrate the intensity of velocity, force or other quantities.

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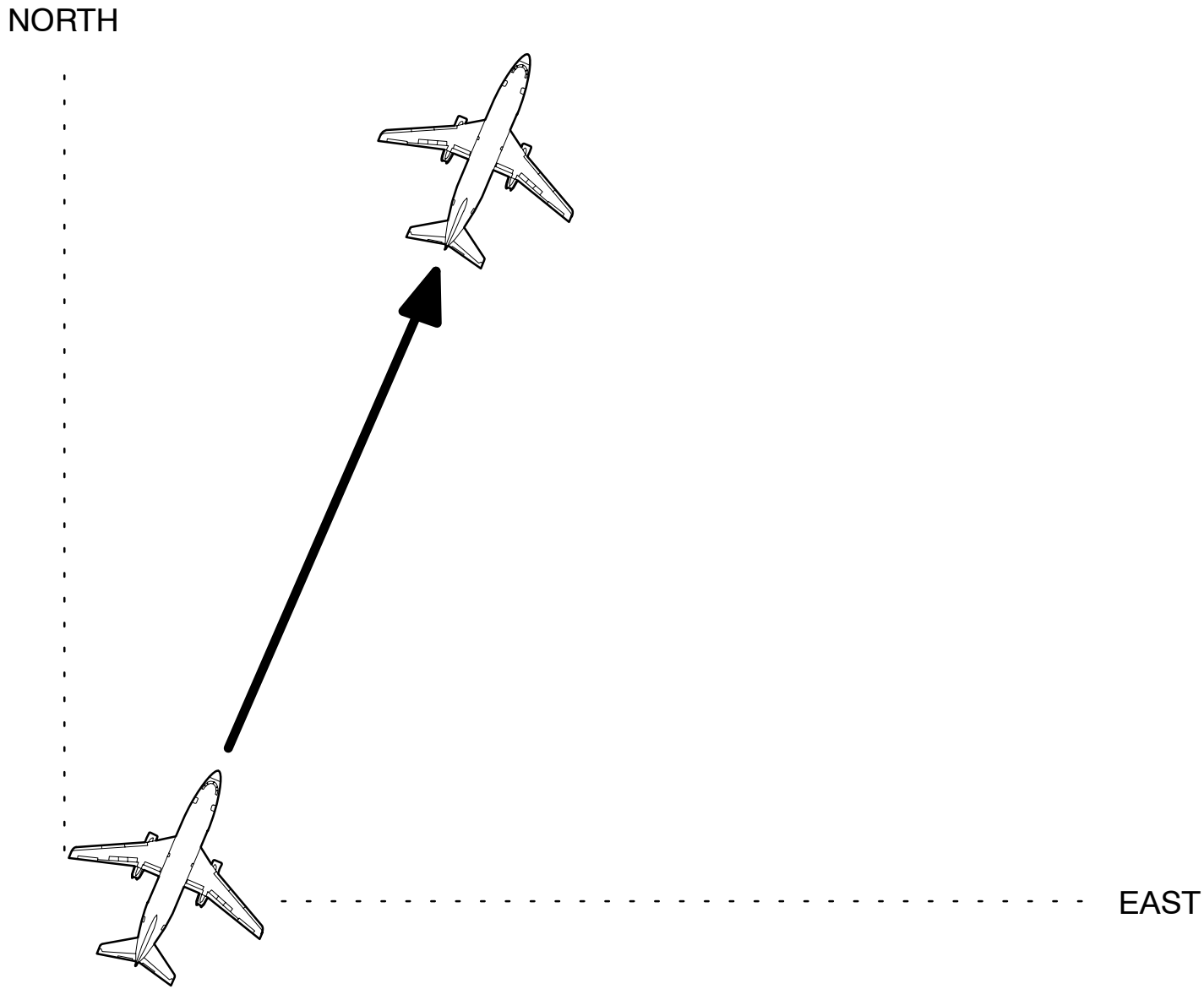


Figure 13 Vector

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Addition of Vectors

Vectors which work on the same object can be added.

In most cases, time is an important factor. Sometimes, the vectors act on an object one vector after the other.

Addition of Velocities

For example, vector 1 shows speed and direction of an airplane. When the airplane changes direction and speed, vector 2 shows the new speed and the new direction.

When the result should be calculated, you need the angle and the length of each vector.

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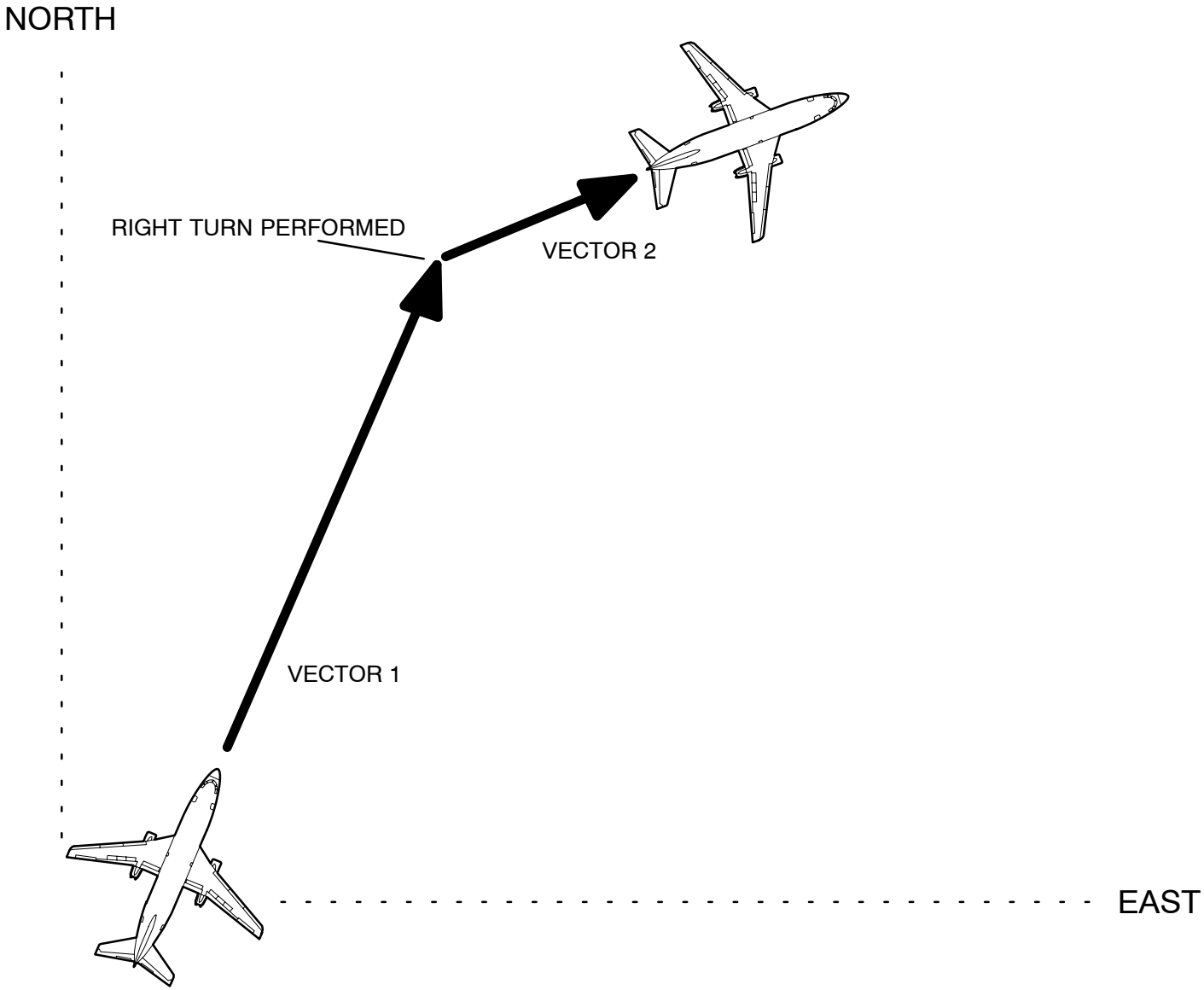


Figure 14 Addition of Vectors (Velocity)

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Addition of Forces

When two forces work on an object on the same time, then the vectors start at the same time and not one after the other.

When the result should be calculated, you need the angle and the length of each vector.

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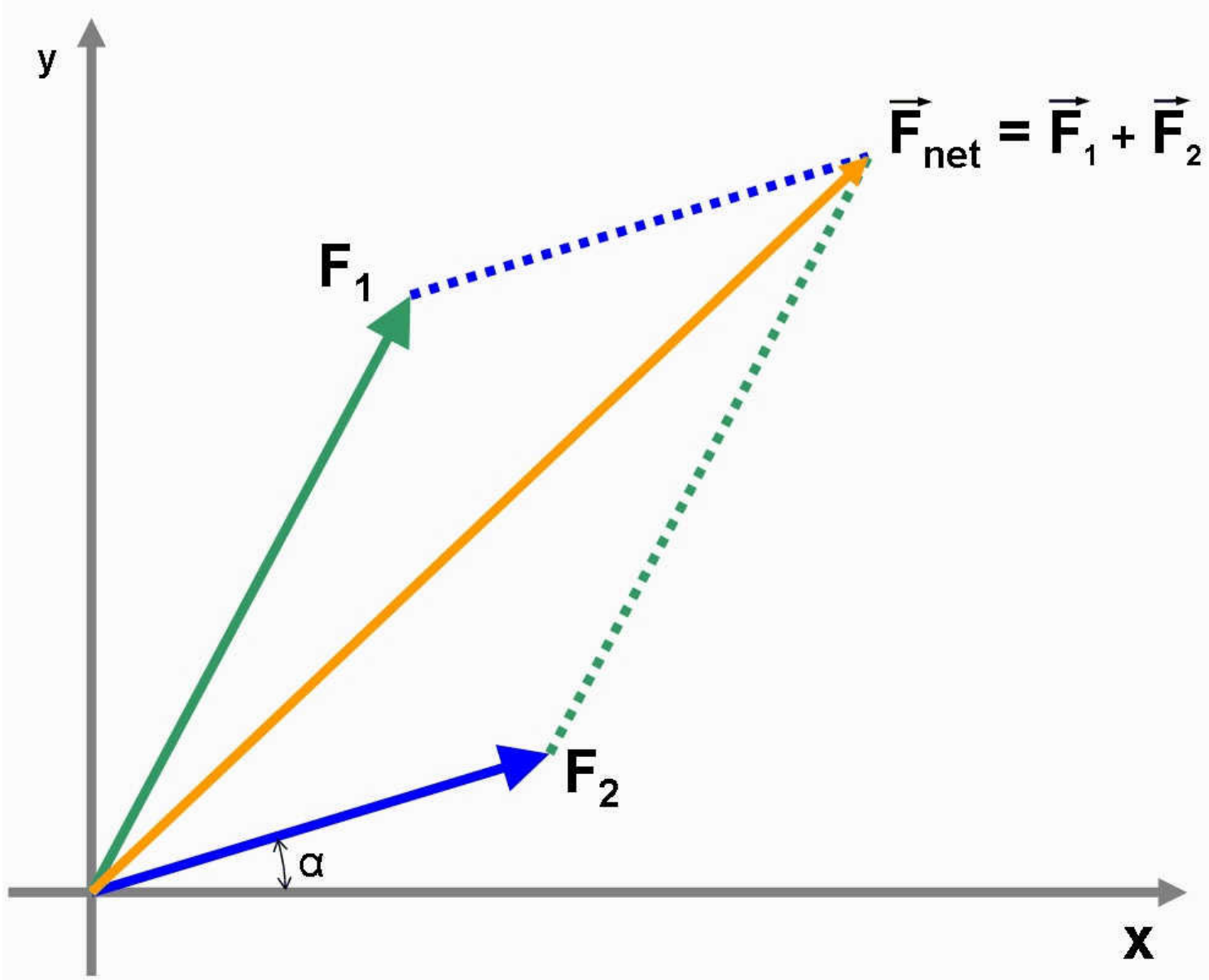


Figure 15 Addition of Vectors (Force)

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Vector Calculation

General

When you want to calculate the sum of two or more vectors, you must have a definition for the direction. For this, you need an x-axis and an y-axis which form a right angle.

When you have a plane (two dimensions only), you can seperate the direction of each vector into two components:

- along the x-axis
- along the y-axis.

These two axes form a right angle.

When no axes are given, it is possible to use the directions which are used since hundreds of years: east/west for the x-axis and noth/south for the y-axis.

Analysis of a Vector

Trigonometry can only be used in triangles with one right angle.

For this reason, a vector must be regarded related to an x axis and an y axis.

For orientation on a plane, we can use the east/west axis and the north/south axis.

In the figure below, you can see the angles for the force F2.

The component of this force which works to the east direction can be named $F2_{east}$.

It is calculated like this: $F2_{east} = F2 \times \cos\alpha$

The component of this force which works to the north direction can be named $F2_{north}$.

It is calculated like this: $F2_{north} = F2 \times \sin\alpha$

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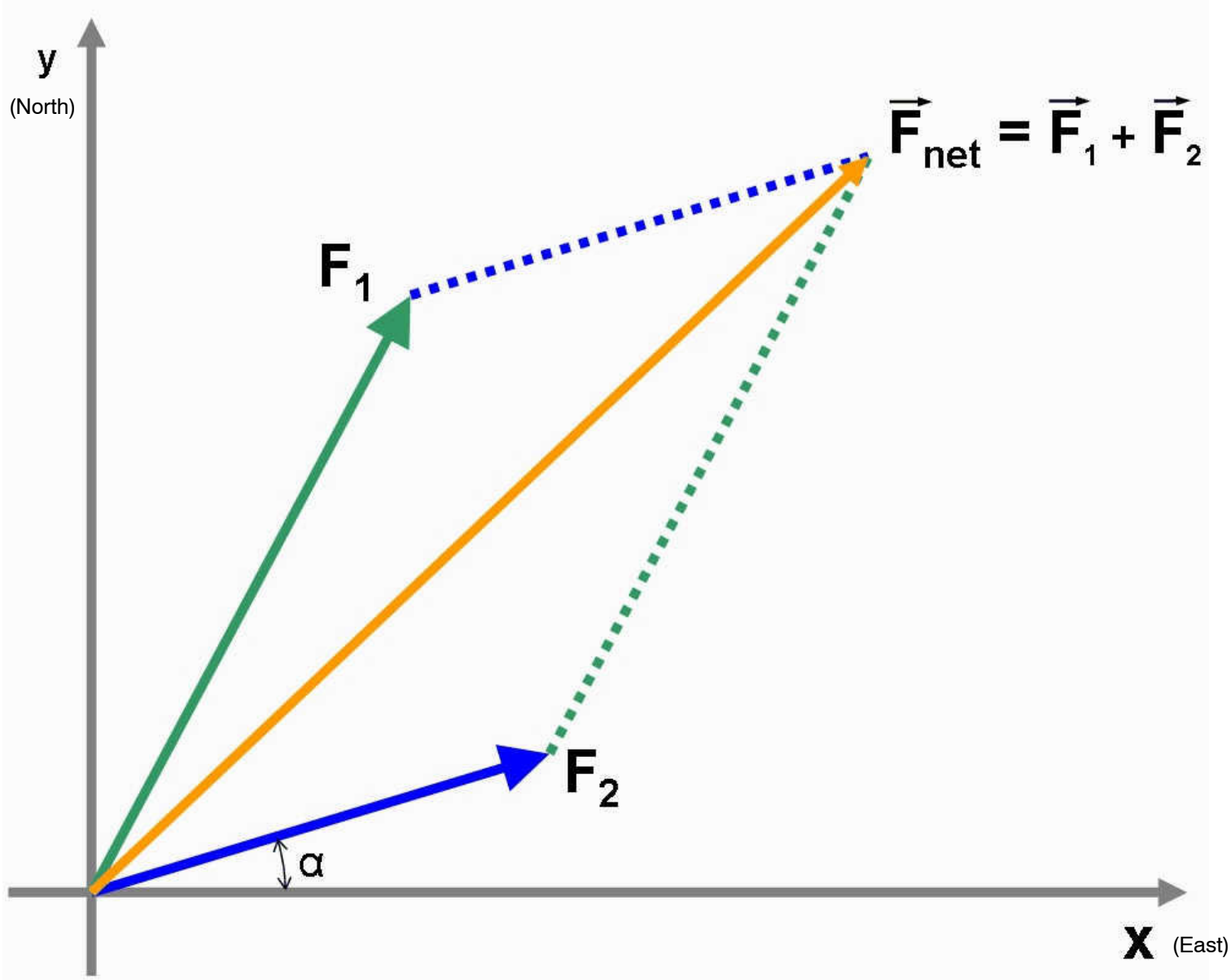


Figure 16 Addition of Vectors (Force)

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Addition of Vectors

When all vectors which act on a single point are analyzed, you can add all components working east.

You can also add all components working north.

The result are two forces, working rectangular.

The forces can be added according to the Pythagoral Theorem: $C^2 = A^2 + B^2$.

Direction of the Resulting Vector

With the sum off all components working east (A) and the sum of all components working north (B) you can calculate the cosinus of the angle which defines the direction of the resulting force (C or F_{net}) related to the x-axis (east).

With the help of tables or a calculator, you can change this cosinus to an angle.

Third Dimension

In space, we need a third axis which is rectangular to the two other axes.

This axis is often named Z-Axis.

When the two other axes define east/west and north/south, this axis defines the height.

Such, a vector can be seperated into three components:

- east/west
- north/south
- height.

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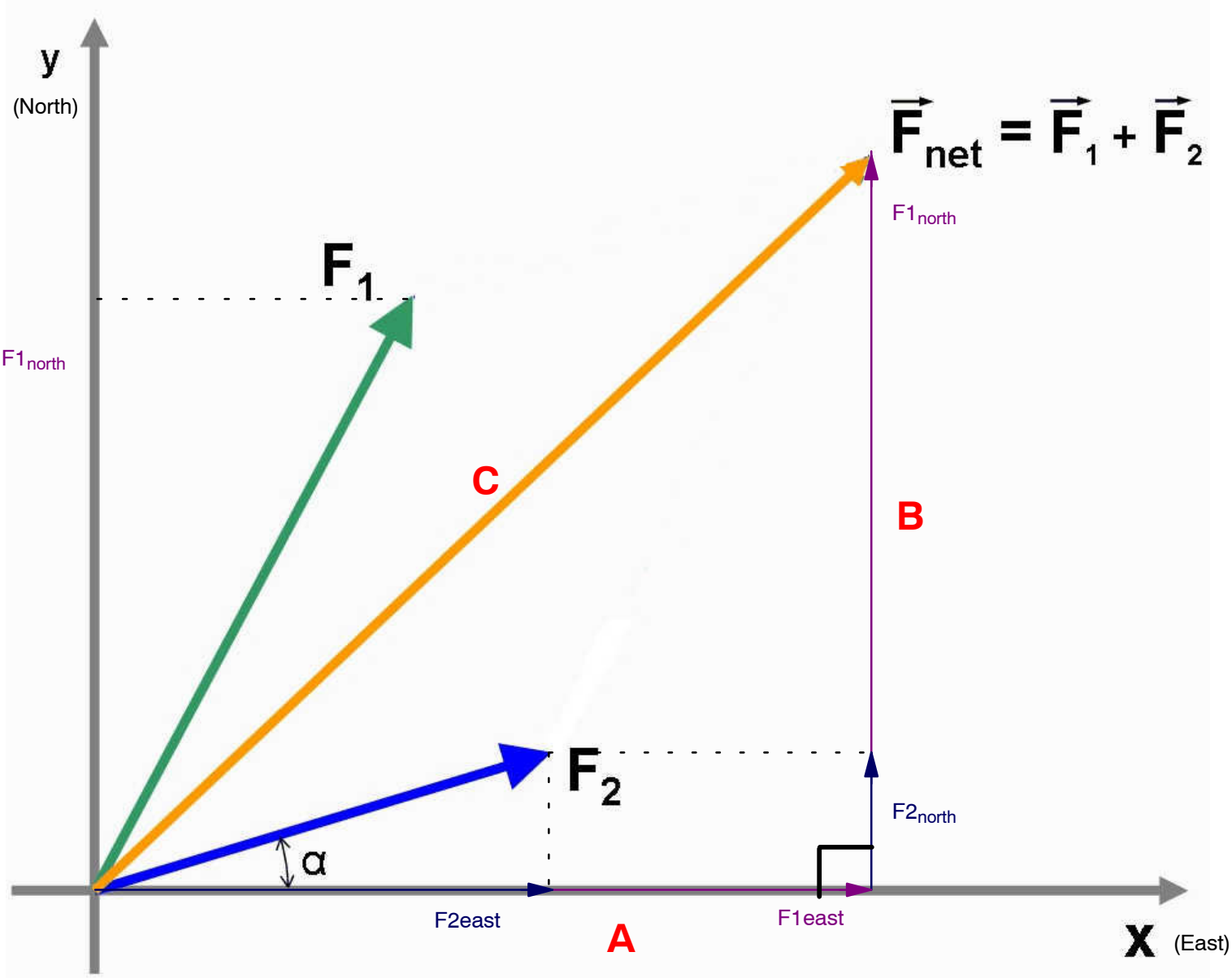


Figure 17 Addition of Vectors (Force)

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Center of Gravity

General

The form of a body causes its center of gravity, when the body has the same density.

By this you can see if forces will cause a rotation of the body or not. When the sum of forces acts left of the center of gravity, this will cause a counterclockwise rotation of this body if the body is not stabilized anyway.

In the figure below you see two forces shown as vectors, which act on a body.

Examples

Engineers try to design a sports car's center of mass as low as possible to make the car handle better.

The same is with a human body: the higher the center of gravity, the higher the risk to tumble.

For a flying aircraft, you can calculate the effects of forces on the vertical and horizontal axes.

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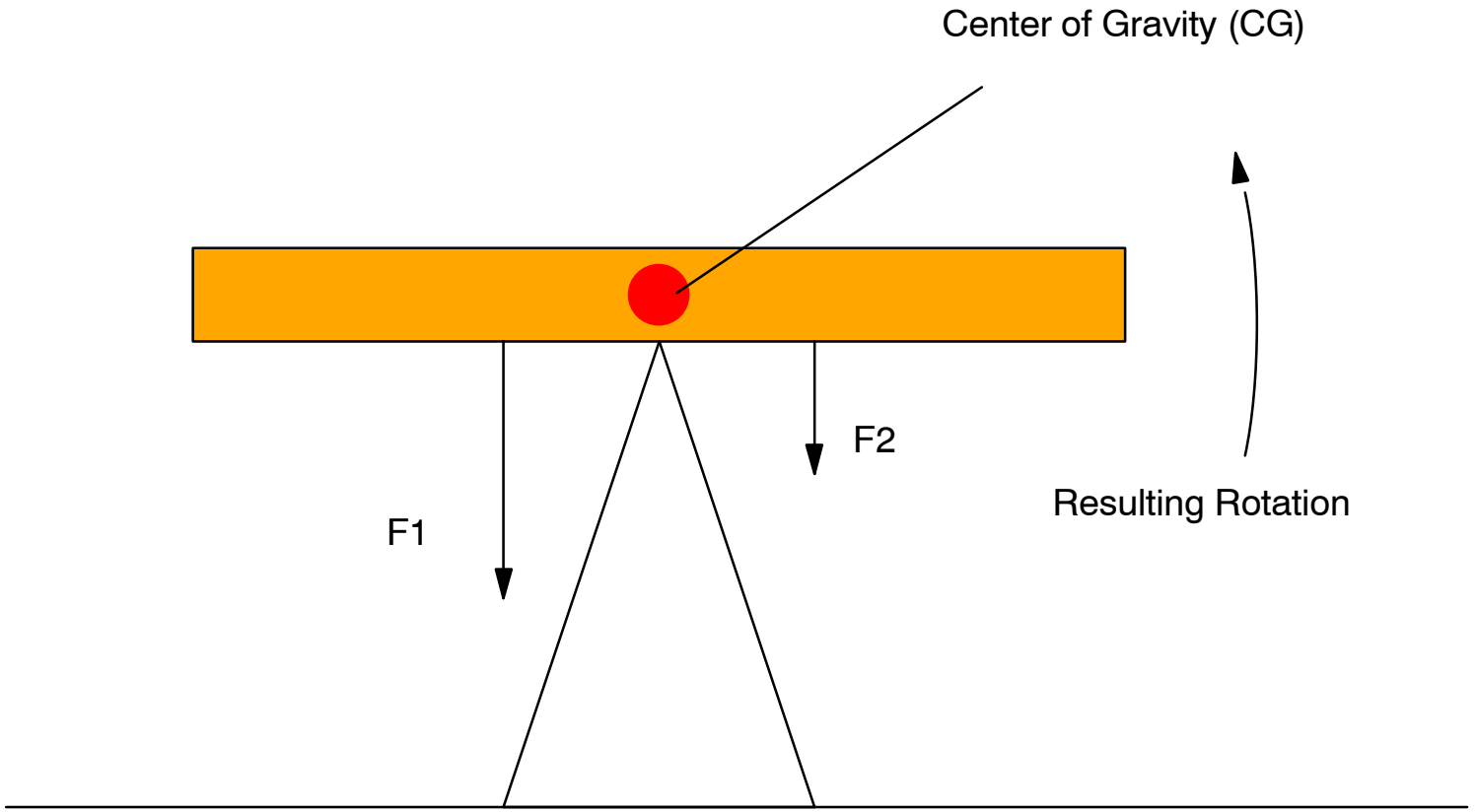


Figure 18 Center of Gravity

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Stress, Elasticity and Strain

General

When an external force acts on a body, it is opposed by an internal force called stress.

Symbol and Unit

The symbol for stress is typically σ (greek sigma).

The unit for stress is Pa (Pascal).

Formula

Stress is shown as the ratio:

$$\text{Stress} = \frac{\text{External Force}}{\text{Area of applied Force}}$$

Structural Integrity

Structural integrity is a major factor in aircraft design and construction. No production aircraft leaves the ground before undergoing extensive analysis of how it will fly, the stresses it will tolerate and its maximum safe capability.

Every aircraft is subject to structural stress. Stress acts on an aircraft whether on the ground or in flight and is defined as a load applied to a unit area of material. Stress produces a deflection or deformation in the material called strain. Stress is always accompanied by strain.

Current production of general aviation aircraft are constructed of various materials, the primary being aluminium alloys. Rivets, bolts, screws and special bonding adhesives are used to hold the sheet metal in place.

Regardless of the method of attachment of the material, every part of the fuselage must carry a load, or resist a stress placed on it. Design of interior supporting and forming pieces, and the outside metal skin all have a role to play in assuring an overall safe structure capable of withstanding expected loads and stresses.

The stress a particular part must withstand is carefully calculated by engineers. The material a part is made of is also extremely important and is selected by designers based on its known properties. Aluminium alloy is the primary material for the exterior skin on modern aircraft. This material possesses a good strength to weight ratio, is easy to form, resists corrosion, and is relatively inexpensive.

Five Kinds of Stress

There are five basic structural stresses to which aircraft are subjected to:

- Tension
- Compression
- Torsion
- Shear
- Bending

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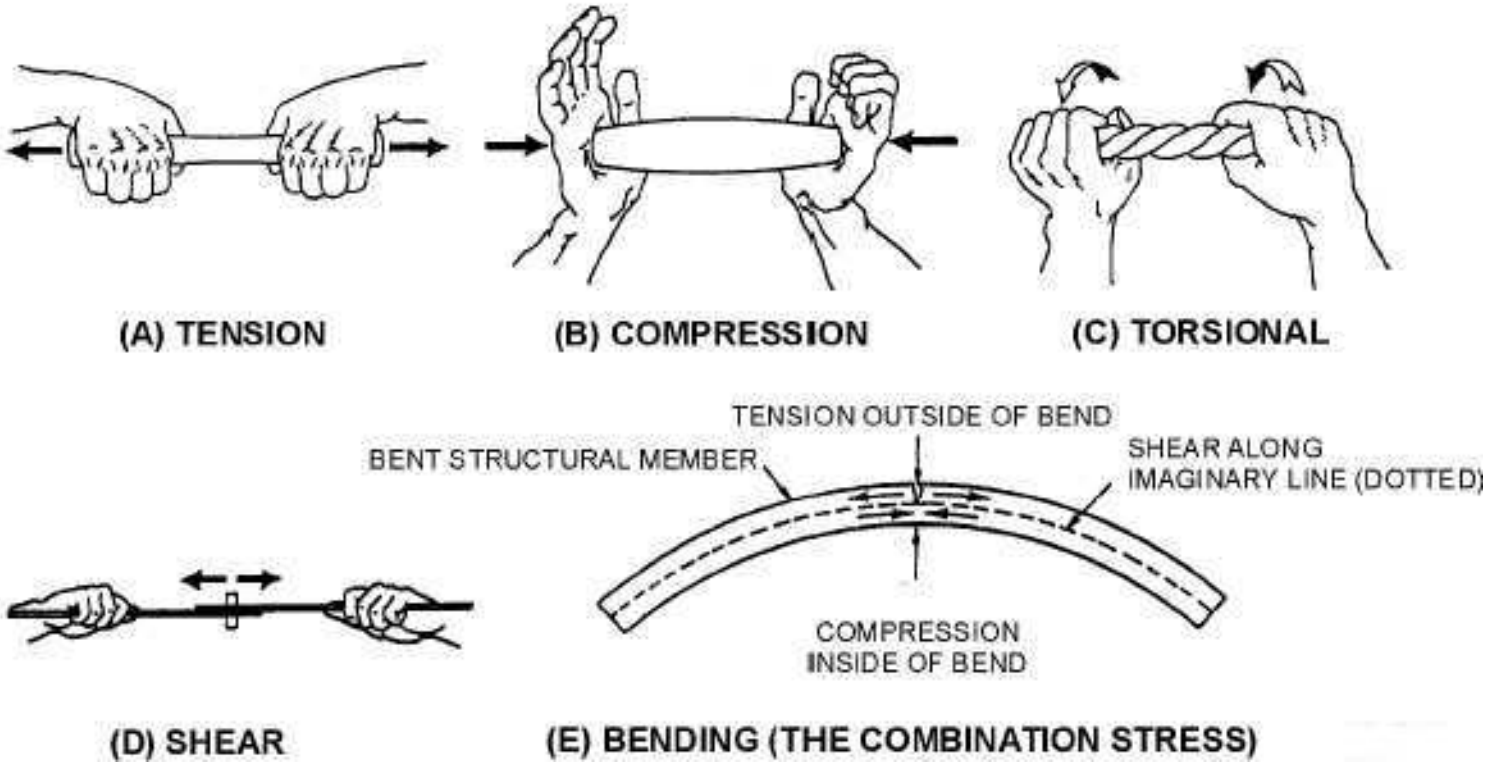


Figure 19 Stress

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Terms for Behavior of Materials

- **Elastic**

  Material deforms under stress but returns to its original size and shape when the stress is released. There is no permanent deformation. Some elastic strain, like in a rubber band, can be large, but in metals it is usually small.

- **Brittle**

  Material deforms by fracturing. Glass is typically brittle.

- **Ductile**

  Materials deforms without breaking. Metals and most plastics are ductile.

- **Viscous**

  Materials that deform steadily under stress. Purely viscous materials like liquids deform under even the smallest stress. Even metals may behave like viscous materials under high temperatures and pressure. This known as creep and affects plastics far more than metals.

Elasticity

In physics, elasticity is the physical property of a material that returns to its original shape after the external force that made it deform is removed.

Note that there are limits of the material: when the force is too big, the material may be torn apart.

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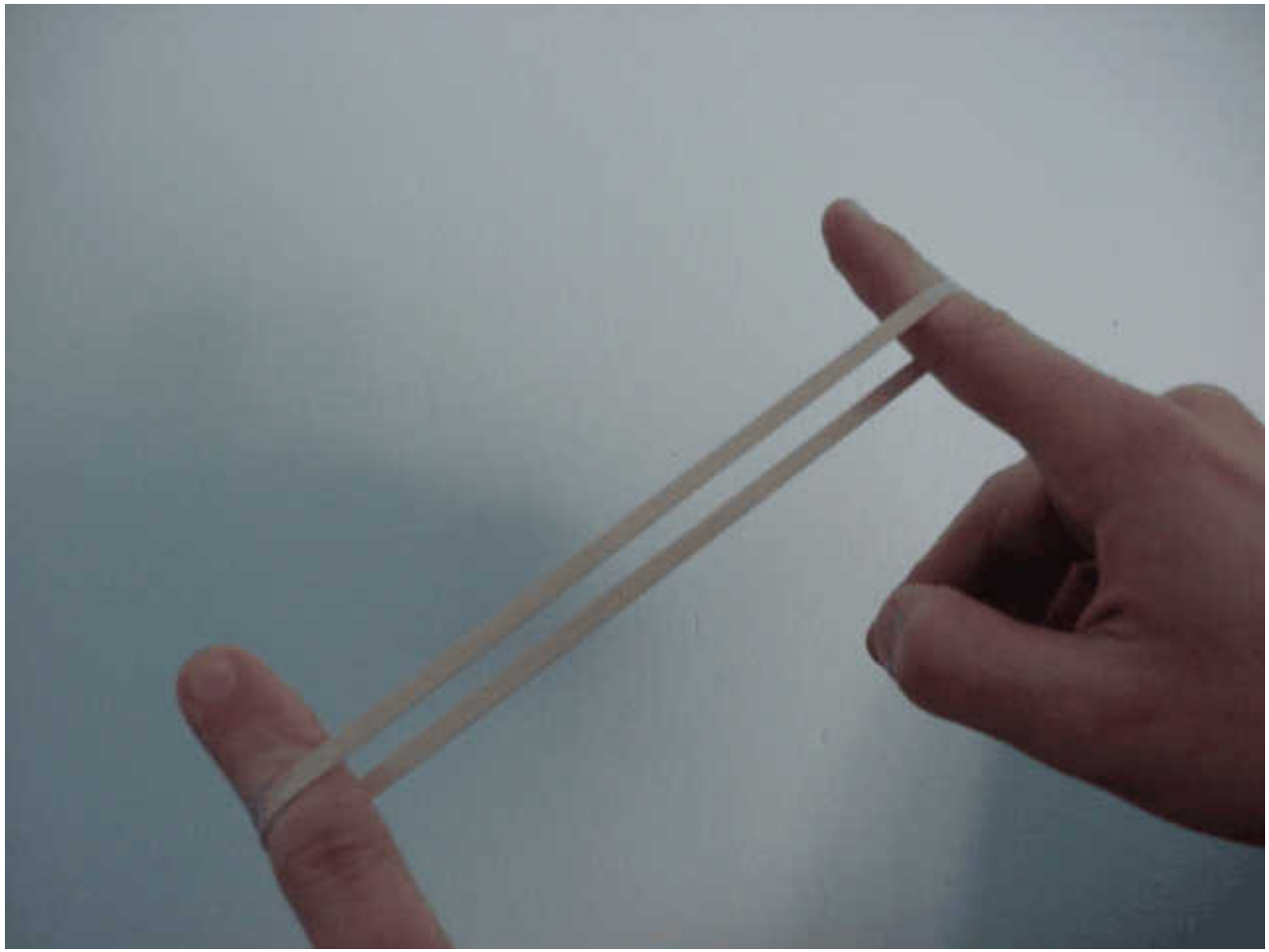


Figure 20 Rubber Band

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Strain

Stress is a force within an object that opposes an applied external force. Strain is the measurable amount of deformation that is caused by stress.

Hooke's law states that if strain does not exceed the elastic limit of a body, it is directly proportional to the applied stress. This fact allows beams and springs to be used as measuring devices.

For example, as force is applied to a hand torque wrench, its deformation or bending, is directly proportional to the strain it is subjected to. Therefore, the amount of torque deflection can be measured and used as an indication of the amount of stress applied to a bolt.

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Figure 21 Torque Wrench

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Tension

General

Tension describes forces that tend to pull an object apart. Flexible steel cable used in aircraft control systems is an example of a component that is designed to withstand tension loads. Steel cable is easily bent and has little opposition to other types of stress. However, when subjected to purely tensional load it performs exceptionally well.

Tensile Stress

What is known as tensile stress (also called axial or normal stress), is defined as the force perpendicular to the cross sectional area of the member divided by the cross sectional area:

$$\text{Stress} = \frac{\text{Force}}{\text{Area}}$$

units $\frac{lb}{in^2}$ *or* $\frac{N}{m^2}$

In the figure below, a solid rod of a length L, is under simple tension due to a force F, as shown.

If we divide that axial force, F by the cross sectional area of the rod A, this would be the axial stress in the member. Axial stress is the equivalent of pressure in a gas or liquid.

Pressure is the $\frac{force}{unit\ of\ area}$. So axial stress is really the pressure in a solid member. Now the question is, how much pressure can a material bear before it fails.

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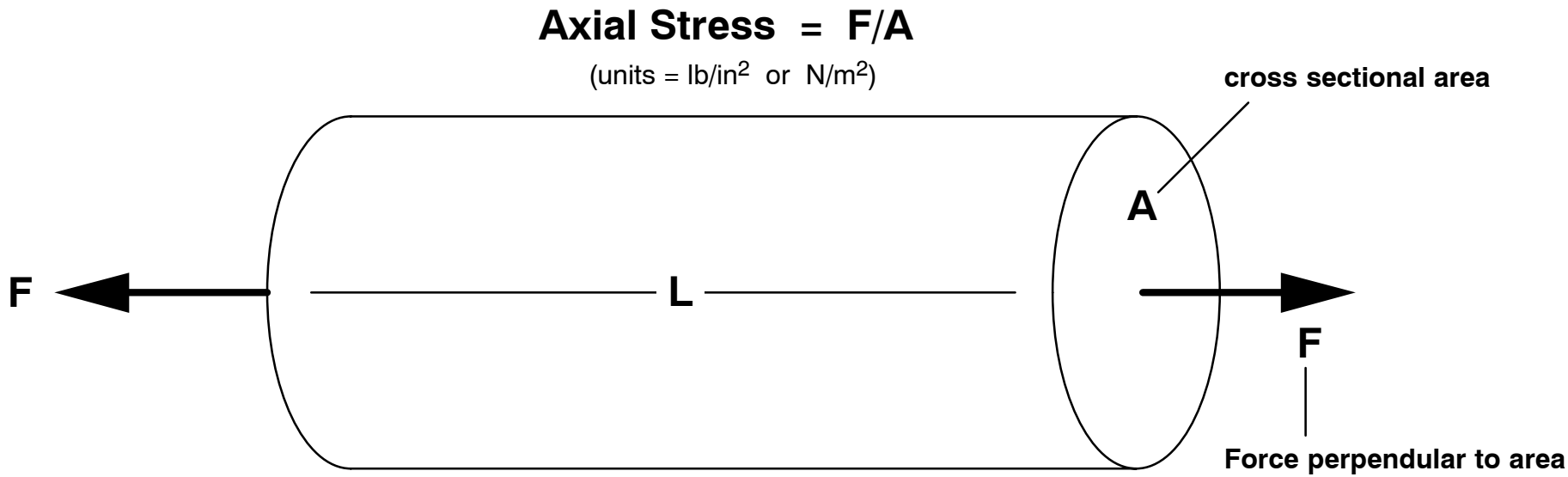


Figure 22 Tension Stress

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Compression

General

Compression is the resistance to an external force that tries to push an object together.

Aircraft rivets are driven with a compressive force. When compression stresses are applied to a rivet, the rivet shank expands until it fills the hole and forms a butt to hold materials together.

Symbol and Unit

The symbol for pressure is typically *p*, from the English word “Pressure“.

The pascal (Pa) is the SI unit of pressure.

$$1Pa = 1\frac{N}{m^2}$$

Formula

Pressure = p

Force = F

Area = A

$$p = \frac{F}{A}$$

History

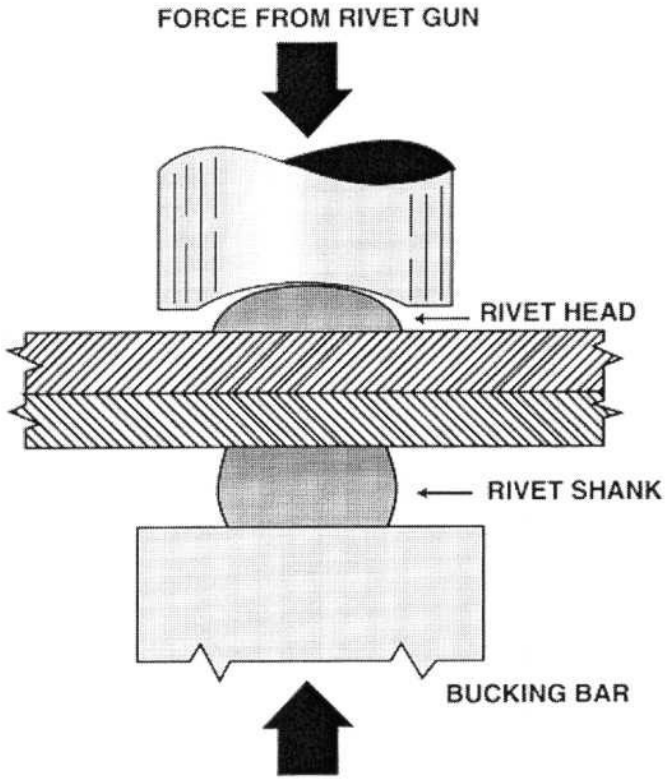
The metric unit of pressure is the N/m^2 (Newton per square metre) which is less than the pressure a sheet exerts on you while you lie in bed. This pressure (1 N/m^2) has been named the pascal (Pa) in honour of the french scientist and mathematician, Blaise Pascal, who did much to advance our knowledge of fluids. The pascal is a very small unit expressed in thousands of pascals or KiloPascal (KPa).

For example, normal atmospheric pressure is nearly 101 KPa. Another unit just about equal to normal atmospheric pressure is the bar. Our bar is defined to be 100 KPa.

The English unit of pressure is the lb/ft^2 or the lb/in^2 (psi - pounds per square inch).

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An aircraft rivet is upset by the application of compression stresses

Figure 23 Compression Stress

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Torsion

General

A torsional stress is applied to a material when it is twisted.

Torsion is actually a combination of both tension and compression. For example, when an object is subjected to torsional stress, torsional stresses operate diagonally across the object while compression stresses act at right angles to the tension stresses.

Example

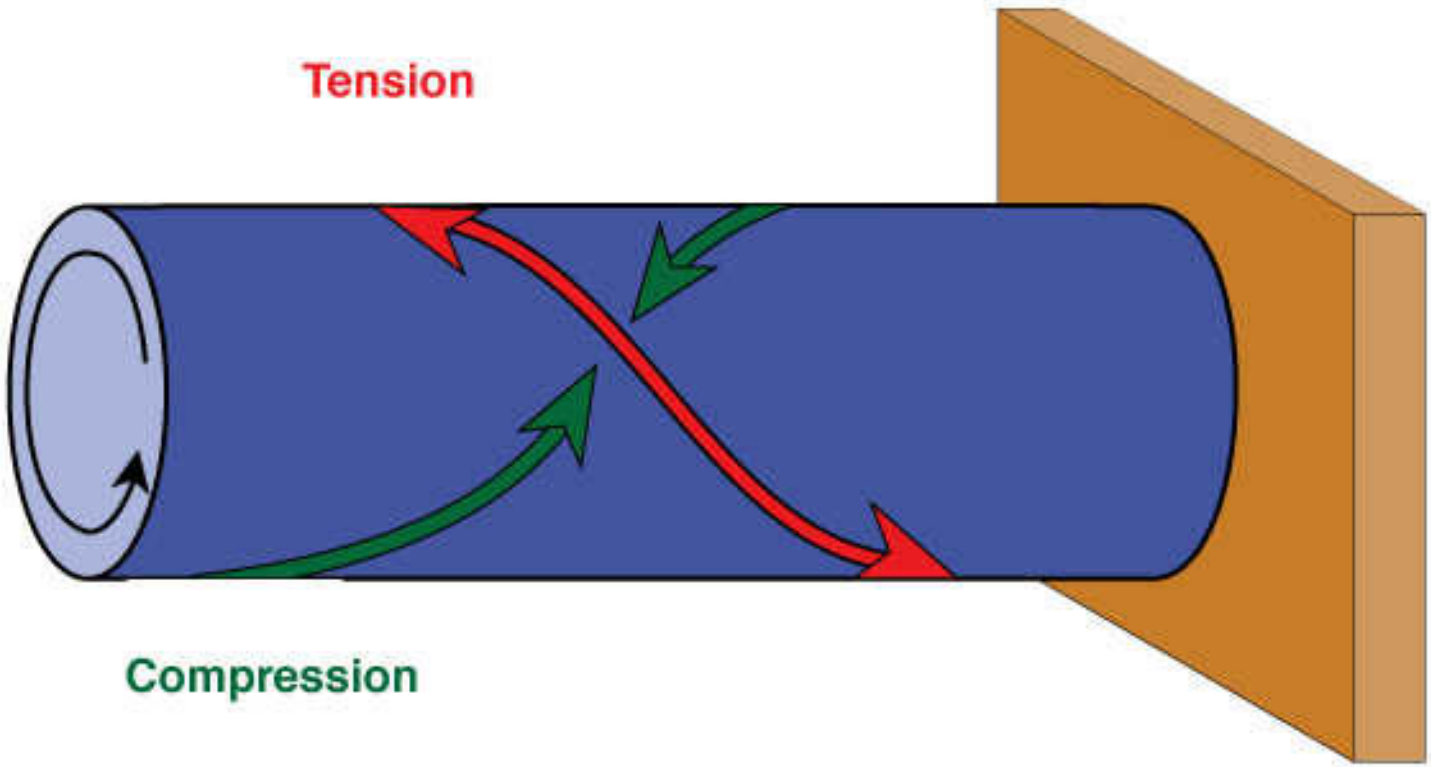
An engine crankshaft is a component whose primary stress is torsion.

The pistons pushing down on the connecting rods rotate the crankshaft against the opposition caused by the propeller.

The resulting stresses attempt to twist the crankshaft.

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Torsional stresses are a combination of tension and compression stresses.

Figure 24 Torsion Stress

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Shear

General

A shear stress tries to slice a body apart.

Clevis Bolt

A clevis bolt in an aircraft control system is designed to withstand shear loads. Clevis bolts are made of a high strength steel and are fitted with a thin nut that is held in place by a cotter pin. Whenever a control cable moves, shear forces are applied to the bolt.

However, when no force is present, the clevis bolt is free to turn in its hole.

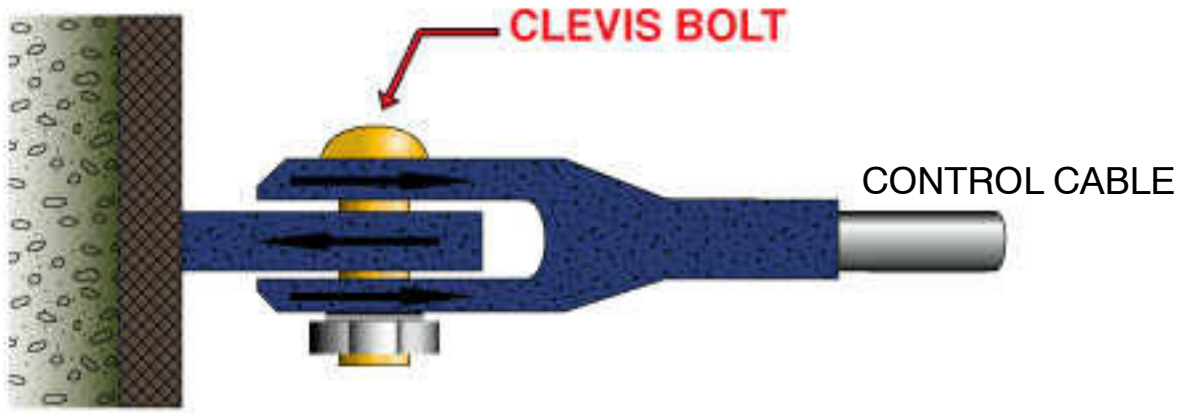
Shear Pins

Some bolts are designed as shear pins. They are created by a way that bears shear stress up to a certain limit. Beyond this limit, they are sliced apart.

This is done to prevent other, more expensive or sensitive parts of the systems from being torn apart by an excessive force.

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When the control cable moves, the forces created attempt to slice the bolt apart, or shear it.

RuF

Figure 25 Shear Stress

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Bending

General

In flight, the force of lift tries to bend an aircraft's wings upward.

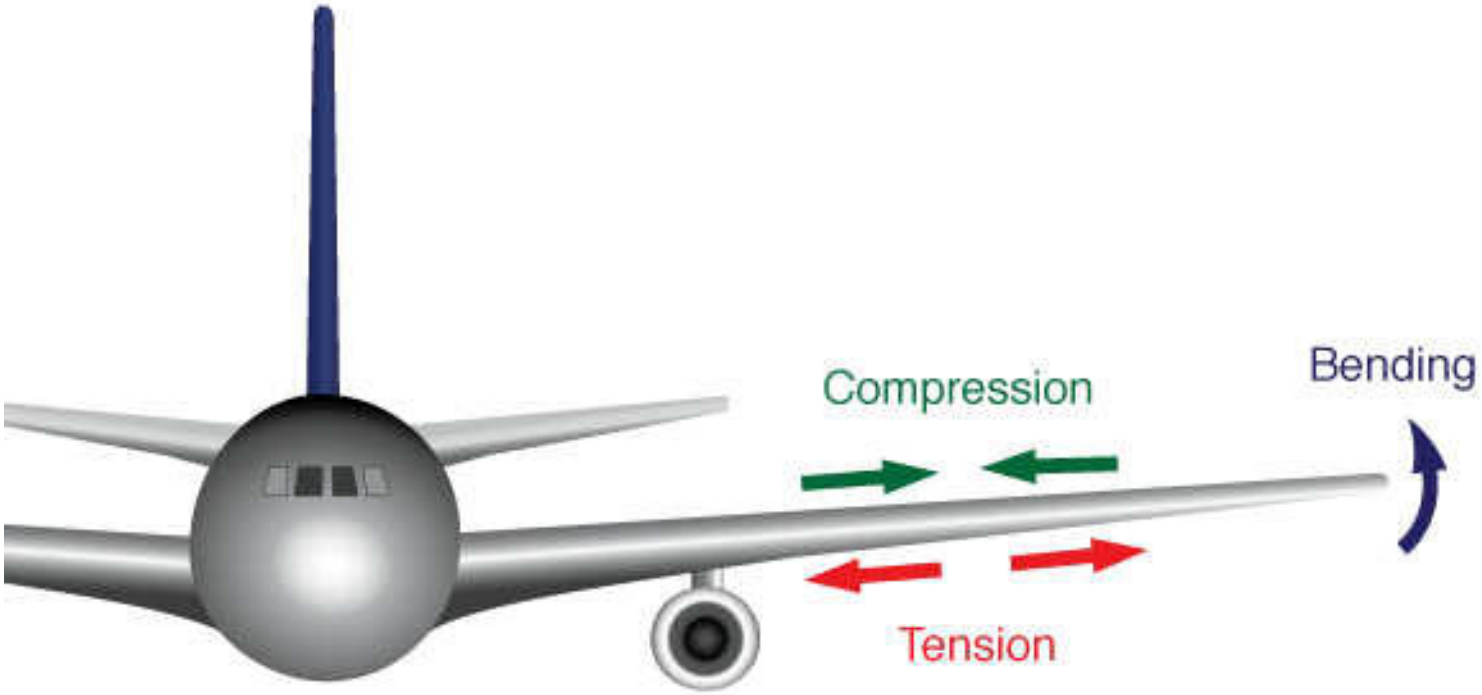
When this happens the skin on top of the wing is subjected to a compression force, while the skin below the wing is pulled by a tension force.

When the aircraft is on the ground the force of gravity reverses the stresses. In this case, the top of the wing is submitted to tension stress while the lower skin experiences compression stress.

In general words bending is always a combination of compression and tension.

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Like torsional stress, bending stresses are a combination of tension and compression.

Figure 26 Effect of Stress: Bending

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Elasticity Details

Introduction

If we look at a metal rod in simple tension, we see that there will be an elongation (or deformation) due to the tension.

If we then graph the tension (force) versus the deformation we obtain a result as shown below. We see that if our metal rod is tested by increasing the tension in the rod, the deformation increases. In the first region the deformation increases in proportion to the force.

That is, if the amount of force is doubled, the amount of deformation is doubled.

Hooke's Law

This is the form of Hooke's Law and could be written this way: $F \propto K$ (deformation), where K is a constant depending on the material (and is sometimes called the spring constant).

Elastic Region

The Region where Hooke's Law is effective is called the elastic or linear region.

The point at which the elastic region ends is called the elastic limit, or the proportional limit. In reality, these two points are not quite the same, but they are only slightly different.

Elastic Limit

The Elastic Limit is the point at which permanent deformation occurs, that is, after the elastic limit, if the force is taken off the sample, it will not return to its original size and shape, permanent deformation has occurred.

Proportional Limit

The Proportional Limit is the point at which the deformation is no longer directly proportional to the applied force (Hooke's Law no longer applies).

Plastic Region

After enough force has been applied the material enters the plastic region, where the force and the deformation are not proportional, but rather a small amount of increase in force produces a large amount of deformation.

In this region, the rod often begins to "neck down", which means, the diameter becomes smaller as the rod is about to fail. Finally the rod actually breaks.

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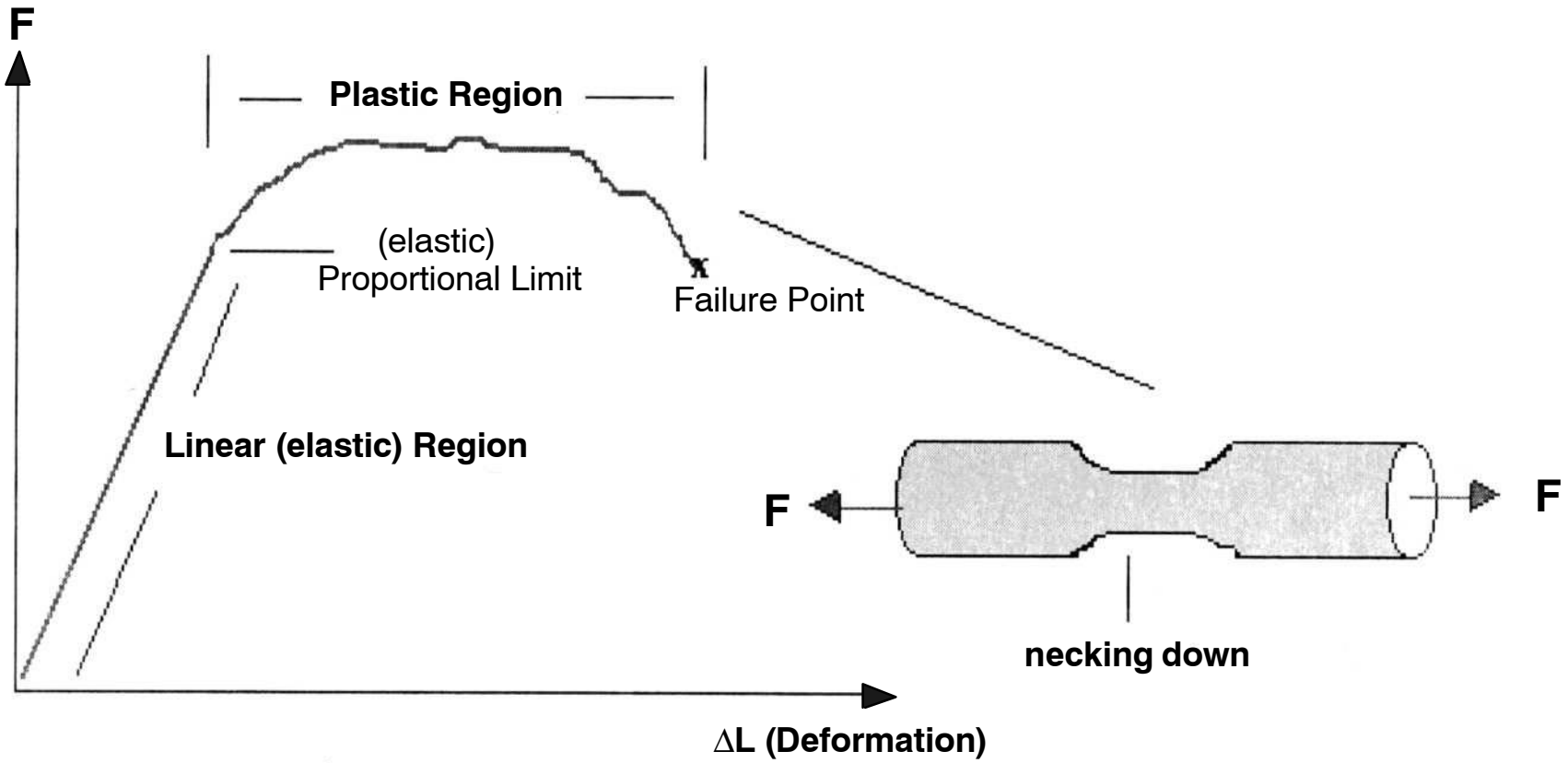


Figure 27 Force and Deformation

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Strain Details

Axial Strain

Axial strain is caused by tensile stress (also called axial or normal stress).

The axial strain is defined as the fractional change in length.

Rather than examining the applied force and resulting deformation, we will instead graph the axial stress versus the axial strain.

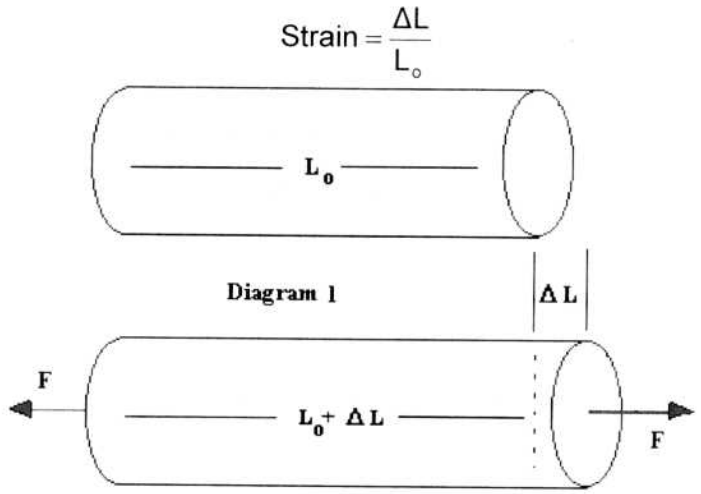


Figure 28 Strain

We may write:

$$\text{Strain} = \frac{\text{Deformation}}{\text{Original Length}}$$

where L_o is the original length of the member.

Strain has no units, since its length divided by length, however it is sometimes expressed as in/in (or inches per inch) in some texts.

Young's Modulus

The stress versus strain graph has the same shape and regions as the force versus deformation graph. In the elastic (linear) region, since stress is directly proportional to strain, the ratio of stress/strain will be a constant (and actually equal to the slope of the linear portion of the graph).

The constant is known as Youngs Modulus, and is usually symbolized by an E (sometimes Y). We will use E only for the Young's Modulus.

$$E = \frac{\text{Stress}}{\text{Strain}}$$

The value of Youngs Modulus, which is a measure of the amount of force needed to produce a unit deformation depends on the material.

Formula

$$\text{Stress} = \frac{\text{Force}}{\text{Area}}$$

$$\text{Strain} = \frac{\text{Deformation}}{\text{Original Length}}$$

Unit

Young's modulus is the ratio of stress, which has units of pressure, to strain, which is dimensionless; therefore Young's modulus itself has units of pressure.

The SI unit of modulus of elasticity E is the pascal (Pa).

In the imperial system, it is expressed as pounds (force) per square inch (psi).

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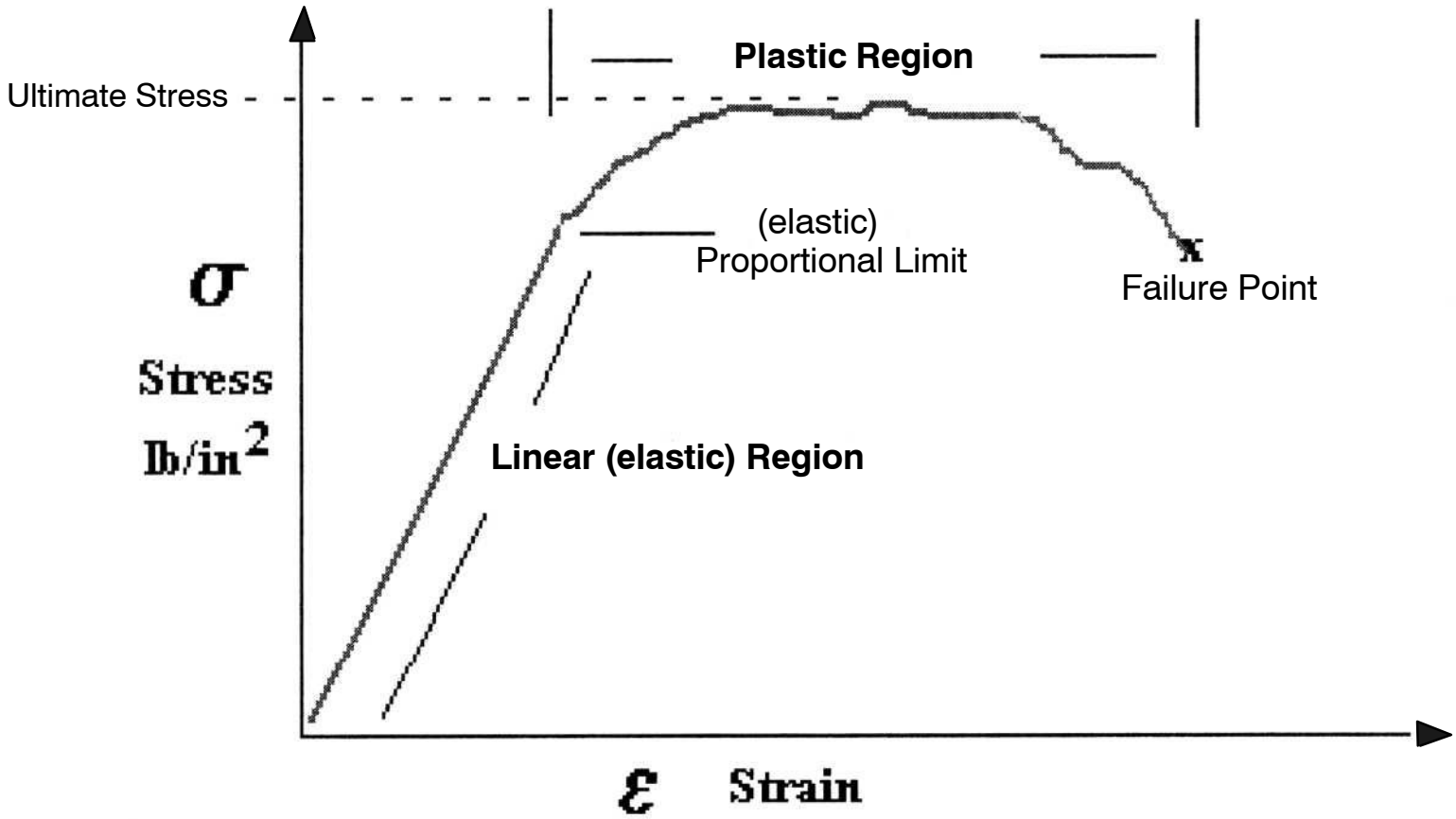


Figure 29 Stress and Strain

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Bulk Modulus

The bulk modulus gives the change in volume of a solid substance as the pressure on it is changed. The formula for bulk modulus is very similar to that of for Youngs modulus:

$$\text{Bulk Modulus (B)} = \frac{\text{pressure}}{\text{volumetric strain}} = \frac{F / A}{\Delta V / V_0} = \text{pressure x } \frac{V_0}{\Delta V}$$

Some examples of Bulk modulus for different materials are given in the tables below.

Symbol and Unit

The symbol for the bulk modulus is *K.*

The pascal (Pa) is the SI unit of the bulk modulus.

Formula

The formula looks like the one for the young's modulus.

$$K = \frac{\text{pressure}}{\text{volumetric strain}} = \frac{F / A}{\Delta V / V_0} = \text{pressure x } \frac{V_0}{\Delta V}$$

Poisson's Ratio

As a member is stressed in tension, its length increases (axial strain) and its width decreases (transverse strain).

Poisson's Ratio is the ration of transverse strain to the axial strain in a stressed member.

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	Youngs Modulus E	Bulk Modulus B
Material	**lb/in^2**	**lb/in^2**
Aluminum	10 x 10^6	10 x 10^6
Brass	13 x 10^6	8.5 x 10^6
Copper	16 x 10^6	17 x 10^6
Glass	7.8 x 10^6	5.2 x 10^6
Iron	13 x 10^6	1.45 x 10^6
Steel	29 x 10^6	23 x 10^6
Ethyl Alcohol		0.16 x 10^6
Oil		0.25 x 10^6
Water		0.31 x 10^6
Mercury		4.0 x 10^6

	Elastic Limit	Ultimate Stress
Material	**lb/in^2**	**lb/in^2**
Aluminum	1.9 x 10^4	2.1 x 10^4
Brass	5.5 x 10^4	6.6 x 10^4
Copper	2.3 x 10^4	4.9 x 10^4
Iron	2.4 x 10^4	4.7 x 10^4
Annealed Steel	3.6 x 10^4	7.1 x 10^4
Spring Steel	6.0 x 10^4	10 x 10^4

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Cantilever

General

A cantilever is a beam supported on only one end.

In a cantilever structure, the beam is under bending stress (which is greatest at the root end) and the shear stress (which is constant along the beam).

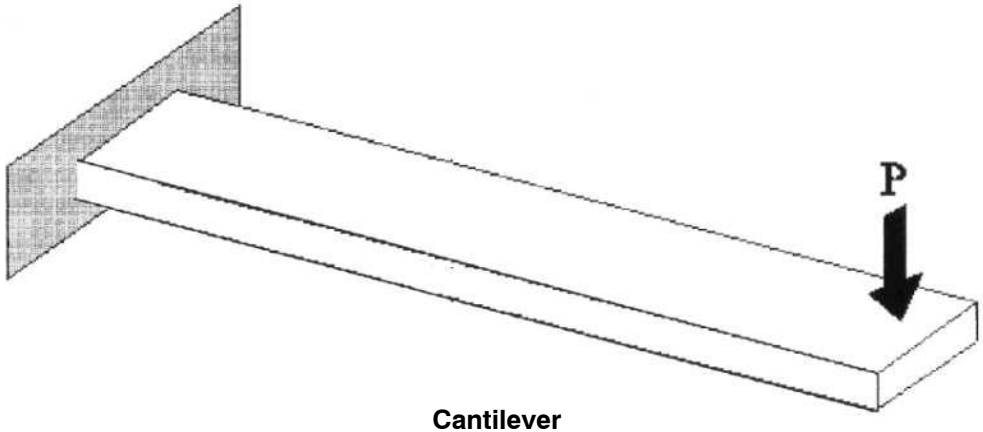
Cantilever Wing

On biplanes, two parallel wings stabilized each other. The wings were braced with crossed wires so they would stay parallel, as well as front–to–back to resist twisting. The wires and struts generated considerable drag.

The first cantilever wing was constructed by Hugo Junkers in 1915.

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Cantilever



Static load test on the first cantilever wing (1915)

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WeR

Figure 30 Cantilever

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Moments of Force

General

Consider the diagrams below.

The distance between the point and the position where the force attacks is named r. This is, because when the force is applied and the tool moves it will move in a circle with the radius r.

We define torque as the force (F) applied to a body that is provided at a point (0) multiplied by the distance r from the pivot point to the place where the force is applied and multiplied by the sine of the angle Θ between r and F.

For torque, we will use the Greek letter τ for Tau. The distance or lever arm is symbolized by the letter r.

Defining the equation:

$$\tau = r \cdot F \cdot \mathrm{Sin}\Theta$$

From the diagram below we note that the angle $\Theta = 90^\circ$. This is by far the most common case.

Since $\sin 90^\circ = 1$, this common case reduces to the more simple equation:

$$\tau = r \cdot F$$

Remember that in those cases where Θ is not 90°, the full equation must be used.

Symbols and Unit

The symbol for torque is typically τ , the Greek letter *tau* (small letter). When it is called moment, it is commonly denoted M.

Also note that the SI unit for torque is Nm (Newtonmeter).

Other units are the lb.ft or lb.in.

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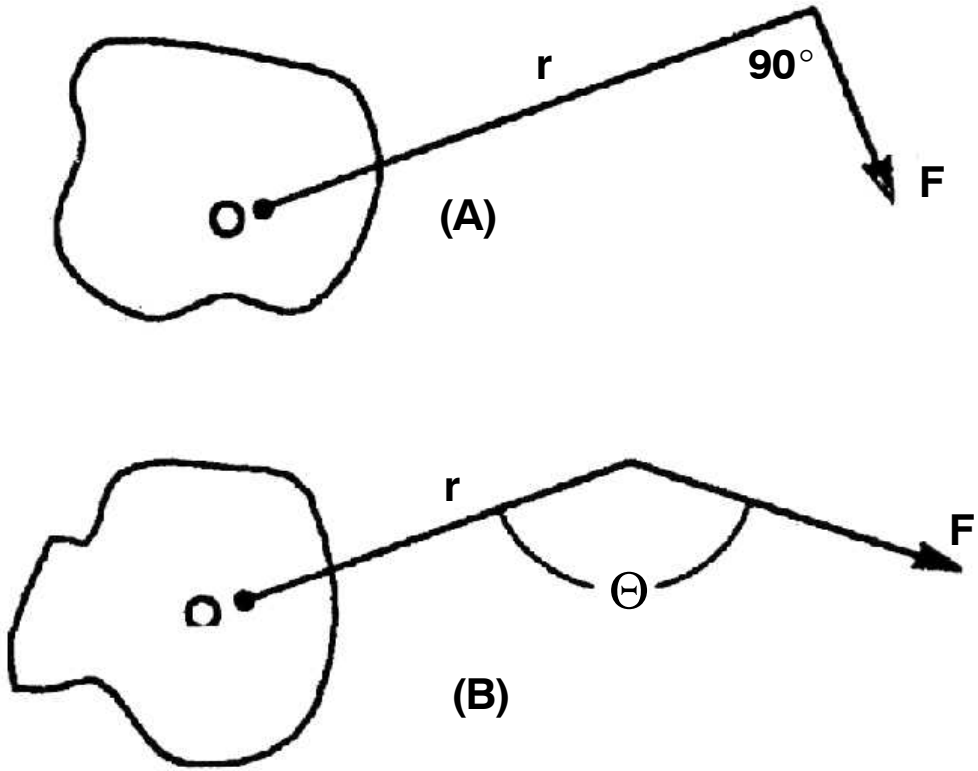


Figure 31 Torque

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Torque wrench calculations

General

A simple way of calculating the scale reading required without using the formula is set out in the following example, for which the specified torque loading is 300 in lbf and the length of the wrench and spanner are 10 and 5 inches respectively.

- Force required on wrench handle to produce a torque of 300 in lbf is 300 in lbf divided by the distance between nut and wrench handle, which is:

$$\frac{300\ \text{lbin}}{10\text{in} + 5\text{in}} = 20\text{lb}$$

- Scale reading when force on handle is:

  20 lb is 20 lb x 10 in = 200 in lbf

Force must therefore be applied to the wrench handle until a reading of 200 in lbf is shown on the wrench scale, and this will represent a 300 in lbf torque load applied to the nut. With the “break” type wrench, the adjustment must be preset at 200 in lbf.

Conversion to SI Units

lbf means pound-force. The pound–force is approximately equal to the gravitational force exerted on a mass of one avoirdupois pound on the surface of Earth.

For the purpose of conversion, 1 in lbf = 115 kg cm or 0.113 N m.

Extension Spanner

When using an extension spanner with a torque wrench, the spanner and wrench should be as nearly as possible in line. If it is necessary to diverge by more than 15 ° from a straight line (intervening structure), then the direct distance (D) between the nut and wrench handle must be substituted for L + X in the formula for calculating wrench scale reading. The scale reading in this instance will be equal to the specified torque.

Torque Wrench

Whenever a torque wrench is used, it must be confirmed that the specified torque and the wrench scale are in the same units, if not, then the specified torque should be converted, by calculation, to the units shown on the wrench scale, and any measurement taken in appropriate units.

When applying torque the wrench handle should be lightly gripped and force applied smoothly at 90 ° to the axis of the wrench.

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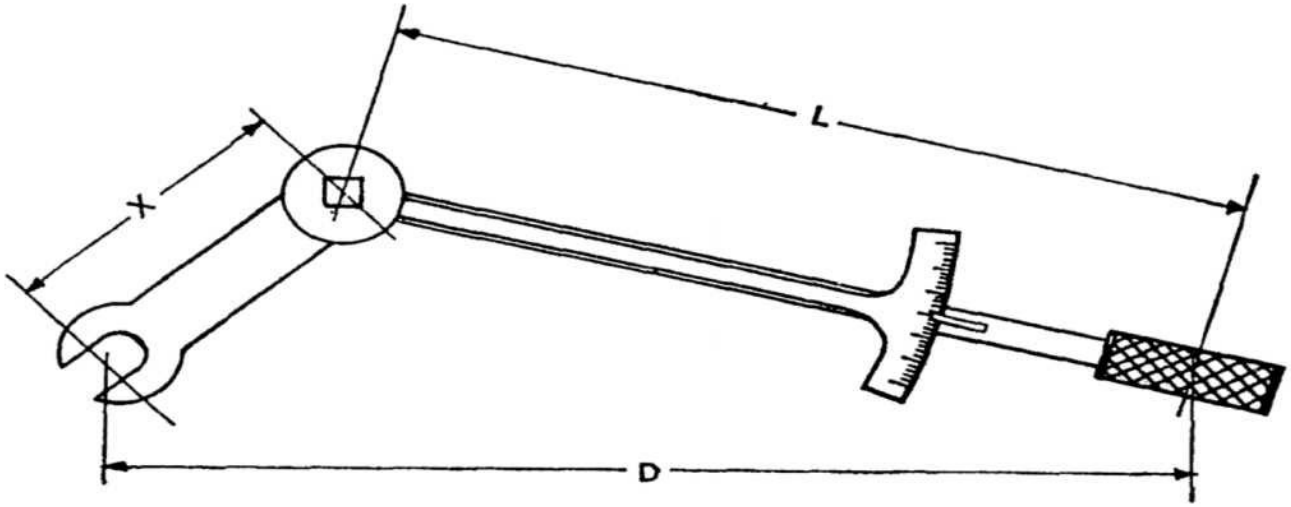


Figure 32 Example: Torque Calculation

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Couples

General

A “couple” is a pair of forces of magnitude F that are equal and opposite but applied at points separated by distance d perpendicular to the forces. The combined moment of the forces produces a torque F_d on the object on which they act.

Examples

Example 1

An example is the cutting of an internal thread with a tap and tap wrench. The force applied at one end of the wrench handle, multiplied by the distance to the centre of rotation is just half of the torque felt at the tap itself, since there is an equal torque applied at the other wrench handle.

Torque applied by a couple:

- One of the forces (F) x distance to centre of rotation (r) x 2
- One of the forces (F) x distance between the forces (d) = Fd

Example 2

Another example is the forces applied to a car steering wheel.

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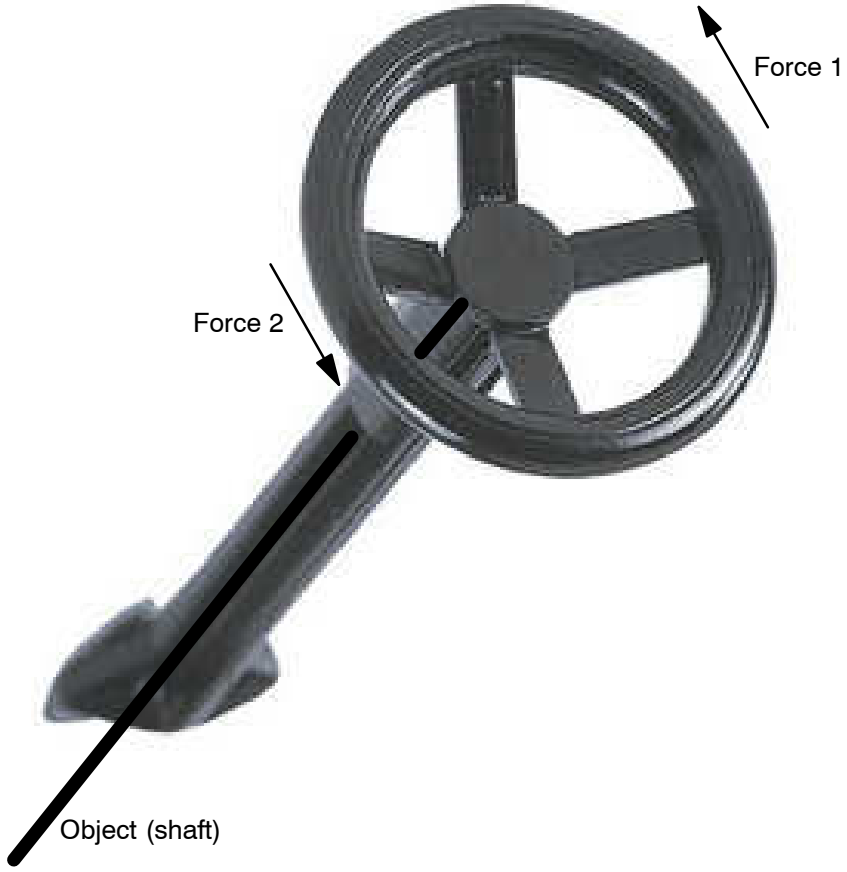


Figure 33 Control Wheel

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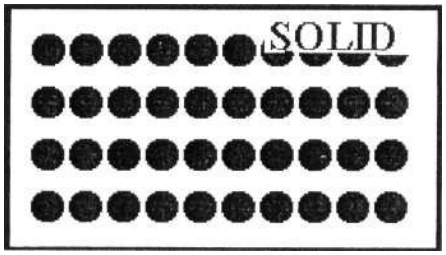
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Nature and Properties of Matter

General

All matters exists in one of three states – Solid, Liquid or Gas. The following characterizes the three states: solid, liquid and gas.

SOLID

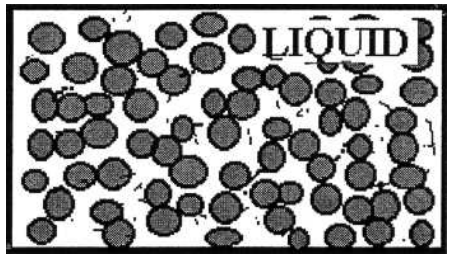


1. The greatest forces of attraction are between the particles in a solid and they pack together in a neat and ordered arrangement.
2. The particles are too strongly held together to allow movement from place to place but the particles vibrate about there position in the structure.
3. With increase in temperature, the particles vibrate faster and more strongly as they gain kinetic energy.

The Properties of a Solid

- Solids have the greatest density (heaviest) because the particles are closest together.
- Solids cannot flow freely like gases or liquids because the particles are strongly held in fixed positions.
- Solids have fixed surface and volume (at a particular temperature) because of the strong particle attraction.
- Solids are extremely difficult to compress because there is no real “empty” space between the particles.
- Solids will expand a little on heating but nothing like as much as liquids because of the greater particle attraction restricting the expansion (contract on cooling). The expansion is caused by the increased strength of particle vibration.

FLUID



1. Much greater forces of attraction between the particles in a liquid compared to gases, but not quite as much as in solids.
2. Particles quite close together but still arranged at random throughout the container, there is a little close range order as you can get clumps of particles clinging together temporarily.
3. Particles moving rapidly in all directions but more frequently colliding with each other than in gases.
4. With increase in temperature, the particles move faster as they gain kinetic energy.

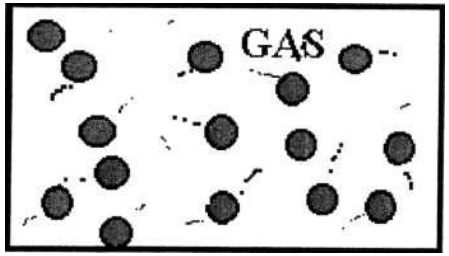
The Properties of a Fluid

- Fluids have a much greater density than gases (heavier) because the particles are much closer together.
- Fluids flow freely despite the forces of attraction between the particles but fluids are not as free as gases.
- Fluids have a surface, and a fixed volume (at a particular temperature) because of the increased particle attraction, but the shape is not fixed and is merely that of the container itself.
- Fluids are not readily compressed because of the lack of empty space between the particles.
- Fluids will expand on heating (contract on cooling) but nothing like as much as gases because of the greater particle attraction restricting the expansion. When heated, the liquid particles gain kinetic energy and hit the sides of the container more frequently, and more significantly, they hit with a greater force, so in a sealed container the pressure produced can be considerable.

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GAS



1. Almost no forces of attraction between the particles which are completely free of each other.
2. Particles widely spaced and scattered at random throughout the container so there is no order in the system.
3. Particles moving rapidly in all directions, frequently colliding with each other and the side of the container.
4. With increase in temperature, the particles move faster as they gain kinetic energy.

The Properties of a Gas

- Gases have a low density (light) because the particles are so spaced out in the container (density = Mass ÷ Volume).
- Gases flow freely because there are no effective forces of attraction between the particles.
- Gases have no surface, and no fixed shape or volume, and because of lack of particle attraction, they spread out and fill any container.
- Gases are readily compressed because of the empty space between the particles.
- If the container volume can change, gases readily expand on heating because of the lack of particle attraction, and readily contract on cooling. On heating, gas particles gain kinetic energy and hit the sides of the container more frequently, and more significantly, they hit with a greater force. Depending on the container situation, either or both of the pressure or volume will increase (reverse on cooling).
- The natural rapid and random movement of the particles means that gases readily spread or diffuse. Diffusion is fastest in gases where there is more space for them to move and the rate of diffusion increases with increase temperature.

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Fluid Pressure & Hydraulics

Fluid Mechanics

A fluid is any substance that flows or conforms to the outline of a container. Both liquids and gases are fluids that follow many of the same rules. However, for all practical purposes, liquids are considered incompressible, while gases are compressible.

Much of the science of flight is based on the principle of fluid mechanics. For example, the air that supports an aircraft in flight and the liquid that flows in hydraulic systems both transmit force through fluid mechanics.

Fluid Pressure

The pressure exerted by a column of liquid is determined by the height of the column and is not affected by the volume of the liquid.

This pressure is named **static pressure**.

Symbol and Unit

The symbol for pressure is typically *p*, from the English word “Pressure“.

The pascal (Pa) is the SI unit of pressure.

$$1Pa = 1\frac{N}{m^2}$$

Formula

Pressure = p

Force = F

Area = A

$$p = \frac{F}{A}$$

Example 1

Water has the mass of 998,6 kg per m^3.

If you stack 100,000 cubic centimeters (0,1 m^3) of water vertically in a column with a base of one square centimeter, the column would extend 100,000 cm (1,000 m) high and would have a weight w = 980 N.

There would also be a pressure, or force per unit area of 980 N per cm^2 at the bottom of the column. This is 9800 kN per m^2 or 9800 kPa.

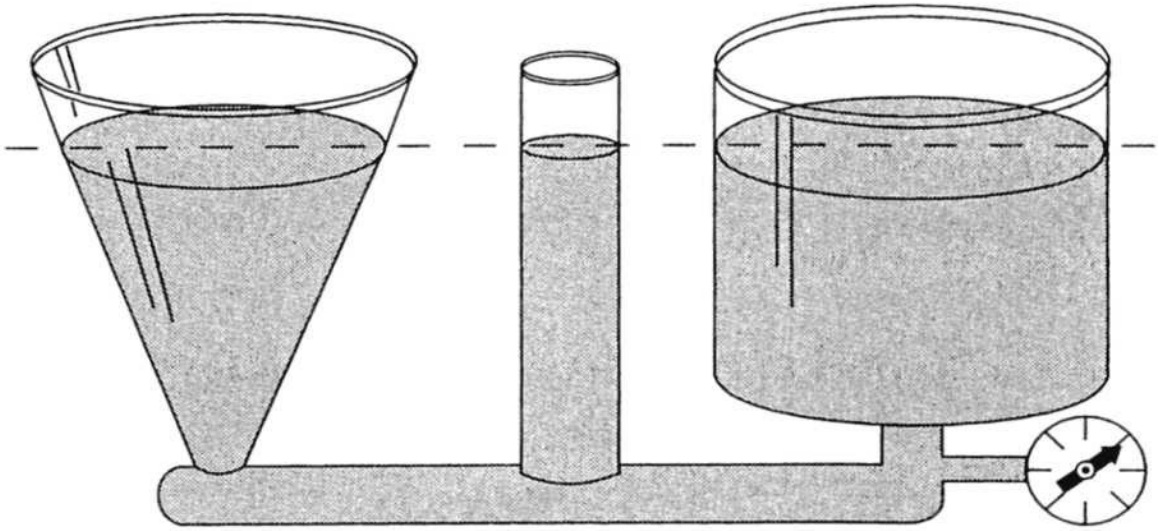
Example 2

Gasoline has a specific gravity of 0.72, which means its weight is 72% that of water, or 750 kg per cubic meter.

Therefore, a column with a base of 1 square centimeter and 1,000 meters high results in a pressure of 706 N per cm^2.

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The pressure exerted by a column of liquid is determined by the height of the column and is not affected by the volume of the liquid.

Figure 34 Fluid Pressure

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Relationship of Force, Pressure & Head

In dealing with fluids, forces are usually considered in relation to the areas over which they are applied. As previously discussed, a force acting over a unit area is a pressure, and pressure can alternately be stated in pounds per square inch or in terms of head, which is the vertical height of the column of fluid whose weight would produce that pressure.

In most of the applications of fluid power, applied forces greatly outweigh all other forces, and the fluid is entirely confined. Under these circumstances it is customary to think of the forces involved in terms of pressures. Since the term head is encountered frequently in the study of fluid power, it is necessary to understand what it means and how it is related to pressure and force.

Terms in General Use

At this point you need to review some terms in general use.

- Gravity head, when it is important enough to be considered, is sometimes referred to as head.
- The effect of atmospheric pressure is referred to as atmospheric pressure. (Atmospheric pressure is frequently and improperly referred to as suction.)
- Inertia effect, because it is always directly related to velocity, is usually called velocity head.
- Friction because it represents a loss of pressure or head, is usually referred to as friction.

Example 1

Gravity head causes a water column lasting on objects in the water. The weight of the water column causes static prassure.

The interior of the submarine has the same pressure like the surface. So, a differential pressure exists. Beyond the limit, it will crush the submarine.

Example 2

As internal pressure the kraken has the same pressure as the water around him. When the siling ship pulls him out quickly, the static pressure surrounding him is too low and the kraken will burst.

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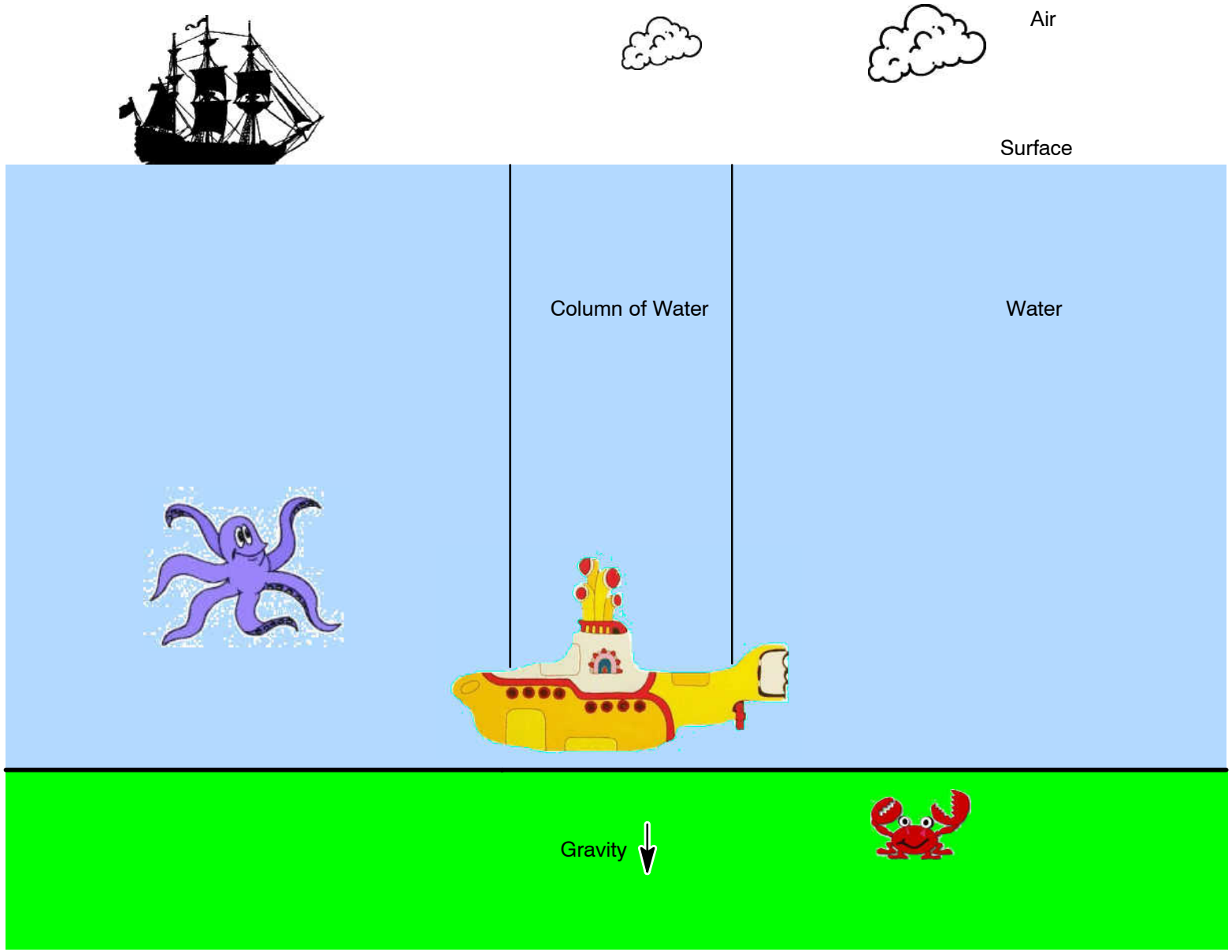


Figure 35 Static Pressure

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Pascal's Law

General

Pascal's Law explains that when pressure is applied to a confined liquid, the liquid exerts an equal pressure at right angles to the container that encloses it.

Formula

You can find the amount of force (F) produced by a hydraulic piston by multiplying the area (A) of the piston by the pressure (p) exerted by the fluid.

This is expressed in the formula $F = A \cdot p$

Formula

For example, assume a cylinder is filled with a liquid and fitted with a piston with A = one square centimetre. When a force of 1 N is applied to the piston, the resulting pressure of the confined liquid is 1 N/cm^2 everywhere in the container.

For example, when 5 MPa (725 psi) of fluid pressure is supplied to a cylinder with a piston area of 10 cm^2, 5,000 N of force is generated.

To determine the area needed to produce a given amount of pressure, divide the force produced by the pressure applied.

Force (N) = Pressure (P) · Area (m^2)

$F = P \cdot A$

To calculate the Area which is needed to generate a specific pressure, then you must divide the available force F by the designated pressure p.

$$A = \frac{F}{p}$$

Advantage

Since the shape of a container has no effect on pressure, connecting one cylinder to a large cylinder results in a gain in mechanical advantage.

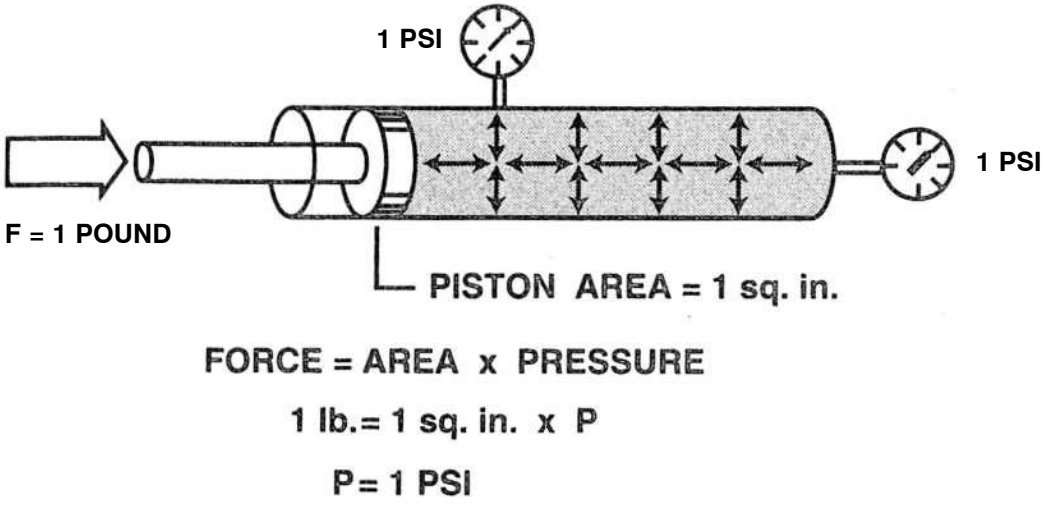
For example, a cylinder with a 1 square centimeter piston is connected to a cylinder with a 10 square centimeter piston. When 5 N of force is applied to the smaller piston, the resulting pressure inside both cylinders is 50 kPa (7,25 psi).

This means that the piston in the larger cylinder has an area of 10 cm^2, and 50 kPa of pressure acts on every square inch of the piston, the resulting force applied to the larger piston is 50 N.

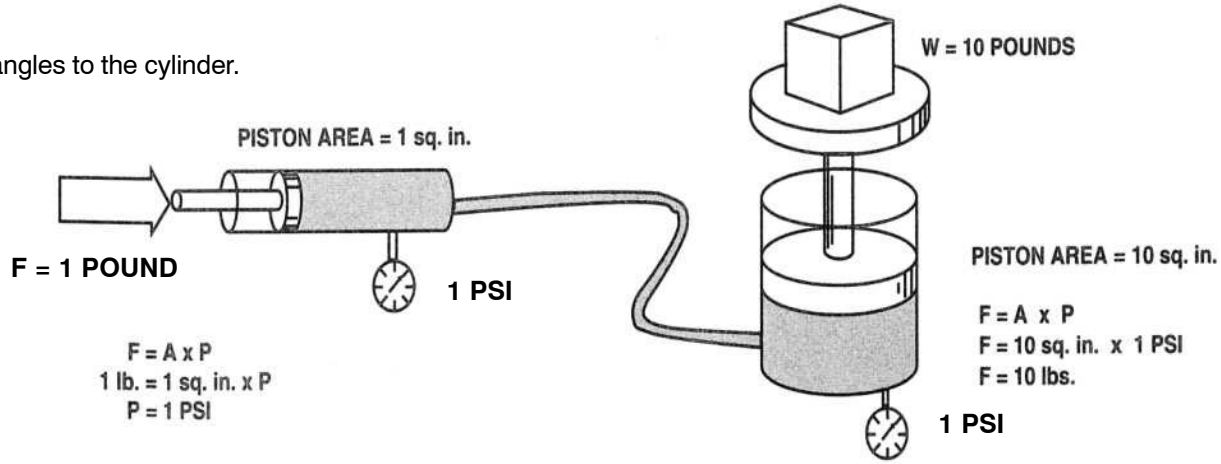
When gaining mechanical advantage this way it is important to note that the pistons do not move the same distance. In the previous example, when the small piston moves inward 5 cm, it displaces 5 cm^3 of fluid. When this is spread out over the 10 cm^2 of the larger piston, the larger piston only moves 0.5 cm.

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The pressure produced in a hydraulic cylinder acts at right angles to the cylinder.



A mechanical advantage may be obtained in a hydraulic system by using a piston with a small area to force fluid into a cylinder with a larger piston. For example, when applying a force of 1 pound to a 1 square inch piston, you push upward against the 10 square inch piston with a force of 10 pounds.

Figure 36 Pascals Law

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Pistons

General

The amount of force produced by a piston is calculated by multiplying the area of the piston by the pressure applied to the fluid.

However, consider a piston that is subjected to pressure on both ends.

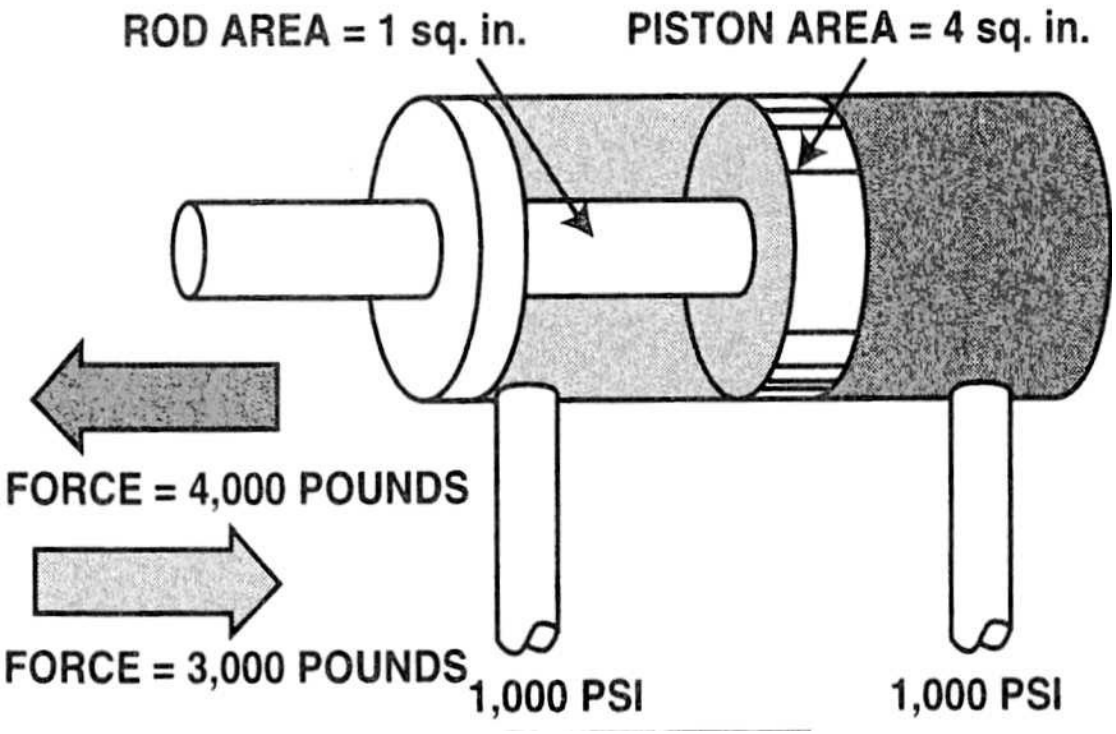
Example

For example, a cylinder has a piston with a surface area of four square inches on one side, while the other side is connected to a one square inch rod. When 1,000 psi of pressure is applied to the side of the piston without the rod. 4,000 pounds of force is produced (4sq.in x 1,000 psi = 4,000 lb).

However, when the same amount of pressure is applied to the opposite side, the fluid acts on only three square inches. Therefore, only 3,000 pounds of force is produced (3 sq.in x 1,000 psi = 3,000lb).

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A pressure of 1,000psi produces 4,000 pounds of force moving the piston outward, but because the area of the rod decreases the piston area, the same pressure produces only 3,000 pounds of force moving the piston inward.

Figure 37 Differential Areas

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Hydraulic Components

General

To transmit and control power through pressurized fluids, an arrangement of interconnected components is required. Such an arrangement is commonly referred to as a system.

The number and arrangement of the components vary from system to system, depending on the particular application. In many applications, one main system supplies power to several sub−systems, which are sometimes referred to as circuits. The complete system may be a small compact unit, more often, however, the components are located at widely separated points for convenient control operation of the system.

Basic Components

The basic components of a fluid power system are essentially the same, regardless of whether the system uses a hydraulic or a pneumatic medium.

The five basic components are as follows:

- Reservoir or Receiver
- Pump or Compressor
- Lines (pipe, tubing or flexible hose)
- Directional Control Valve (DCV)
- Actuating Device.

Several applications of fluid power require only a simple system, that is, a system which uses only a few components in addition to the five basic components.

A few of these applications are presented in the following paragraphs. We will explain the operation of these systems briefly at this time so you will know the purpose of each component and can better understand how hydraulics is used in the operation of these systems.

Hydraulic Jack

The hydraulic jack is perhaps one of the simplest forms of a fluid power system. By moving the handle of a small device, an individual can lift a load weighing several tons. A small initial force exerted on the handle is transmitted by a fluid to a much larger area. to understand this better, see diagram below. The small input piston has an area of 5 square inches and is directly connected to a large cylinder with an output piston having an area of 250 square inches. The top of this piston forms a lift platform. If a force of 25 pounds is applied to the input piston, it produces a pressure of 5 psi in the fluid, that is, of course, if a sufficient amount of resistance force is acting against the top of the output piston.

Disregarding friction loss, this pressure acting on the 250 square inch area of the output piston will support a resistance of 1.250 pounds. In other words, this pressure could overcome a force of slightly under 1.250 pounds. An input force of 25 pounds has been transformed into a working force of more than half a ton; however, for this to be true, the distance travelled by the input piston must be 50 times greater than the distance travelled by the output piston. thus, for every inch that the input piston moves, the output piston will move only one−fiftieth of an inch.

This would be ideal if the output piston needed to move only a short distance.

However, in most instances, the output piston would have to be capable of moving a greater distance to serve a practical application. The diagram shown is not capable of moving the output piston further than that shown, therefore, some other means must be used to raise the output piston to a greater height.

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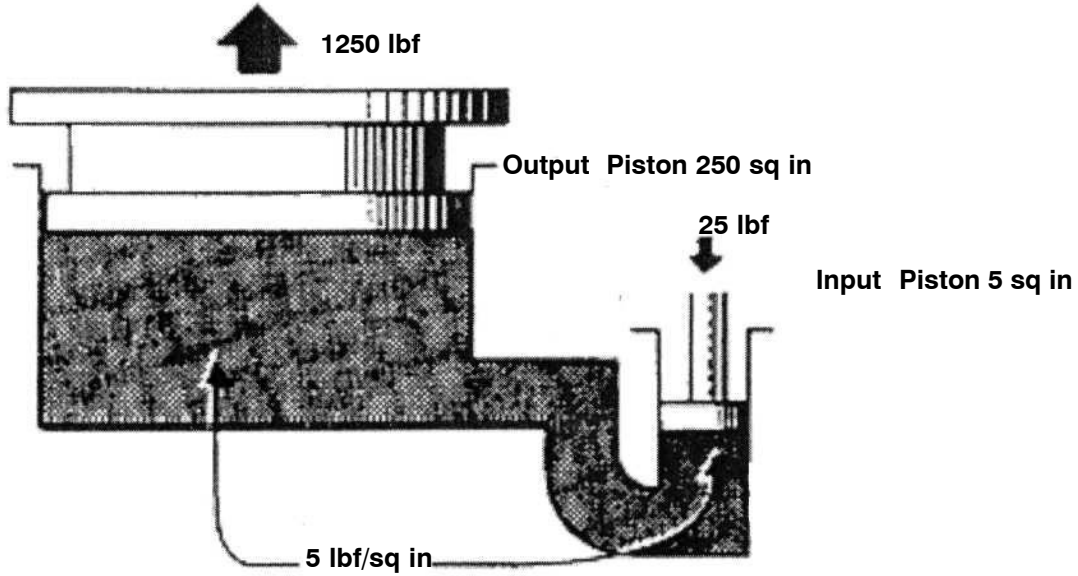


Figure 38 Hydraulic Jack

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Hydraulic Accumulator

An accumulator is a pressure storage reservoir in which hydraulic fluid is stored under pressure from an external source. The storage of fluid under pressure serves several purposes in hydraulic systems.

In some aircraft hydraulic systems it is necessary to maintain the system pressure within a specific pressure range for long periods of time. It is very difficult to maintain a closed system without some leakage, either external or internal. Even a small leak can cause a decrease in pressure. By using an accumulator, leakage can be compensated for and the system pressure can be maintained within an acceptable range for long periods of time.

Accumulators also damp out fluctuations in pressure due to the operation of services such as control surfaces and landing gear. They can supply extra pressure when all the hydraulic services are being operated at one time (flaps, control surfaces, landing gear etc.) and when the hydraulic pump is unable to cope. They can also be used in an emergency when all other hydraulic power pressure supplies (pumps etc) have failed. A large modern aircraft can be controlled on accumulator power alone, for up to an hour.

Accumulators also compensate for thermal expansion and contraction of the liquid due to variations in temperature. The accumulator consists of an air chamber, which is charged with air or nitrogen. This is called the pre−charge pressure and is usually about 1.000 psi. This pressure is measured when there is no hydraulic pressure. The air chamber is the under side of the piston (see diagram). With no hydraulic pressure, the air/nitrogen pressure will push the piston to the top of the accumulator to indicate the air/nitrogen pressure.

When the hydraulic pumps are switched on, the hydraulic pressure (acting on top of the piston, in opposition to the air/nitrogen pressure) begins to rise. When the hydraulic pressure exceeds the air/nitrogen pre−charge pressure (1.000 psi), the piston will begin to move down and further increases the air/nitrogen pressure.

At all times that the hydraulic pressure is above the air/nitrogen pre−charge pressure of 1.000 psi, the air/nitrogen and the hydraulic pressure are equal.

Thus when the hydraulic pressure has reached its working level of 3.000 psi, the air/nitrogen pressure is also 3.000 psi.

It is the additional pressure supplied to the air/nitrogen by the hydraulic pressure, which can be used to feed back the pressure to the hydraulic fluid if the hydraulic fluid pressure falls below that of the air/nitrogen. However, when the air/nitrogen gauge indicates 1.000 psi, the hydraulic pressure is zero, since the air/nitrogen has expanded back to its original pre−charge pressure.

Aircraft Technology

Many aircraft manufacurers calculate with US american units for the hydraulic system. So the normal pressure of an hydraulic system is 3.000 psi and the pre-charce pressure of an accumulator ist 1.000 psi.

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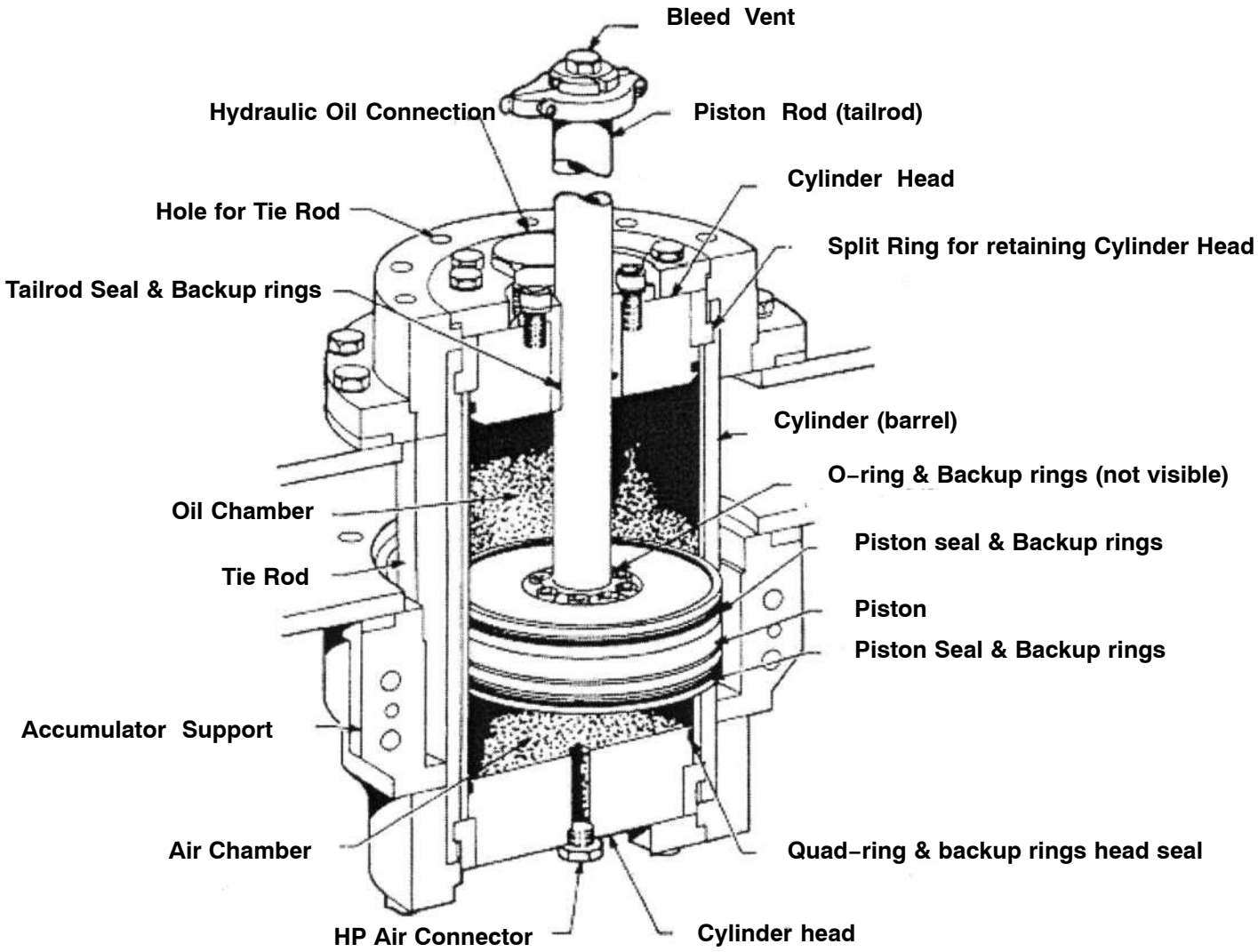


Figure 39 Hydraulic Accumulator

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Buoyancy in Liquids

The Archimedes Principle

The Archimedes Principle states that when an object is submerged in a liquid, the object displaces a volume of liquid equal to its volume and is supported by a force equal to the weight of the liquid displaced. The force that supports the object is known as the liquids “buoyant force”.

Liquids

If the object immersed has a specific gravity that is less than liquid, the object displaces its own weight of the liquid and floats.

Gases

The effect of buoyancy is not only present in liquids, but also in gases. Hot air balloons are able to rise because they are filled with heated air that is less dense than the air they displace.

Example

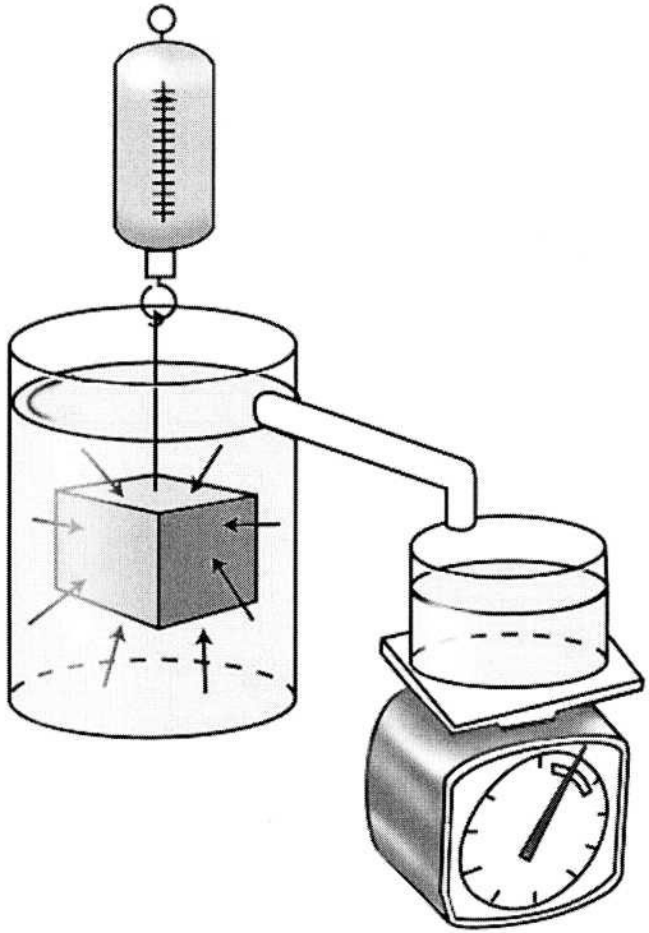
For example, when a 100 cubic centimeters block with the weight w = 10 N is attached to a spring scale and lowered into a full container of water, 100 cubic centimeters of water overflows out of the container.

The weight of 100 cm^2 of water is 0.98 N, therefore the buoyant force acting on the block is 0.98 N.

The spring scale reads 9.02 N.

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A body immersed in a fluid is buoyed up by a force equal to the weight of the fluid it displaces.

Figure 40 Archimedes Principle

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Buoyancy Details

Archimedes Principle Applied to Bodies that Float

A body will float in any fluid that has a weight density γ greater than the weight density of the body. For example a body of weight density 63.4 lb/ft^3 would float in ocean water (γ = 64.4 lb/ft^3) and sink in lake water (γ = 62.4 lb/ft^3).

When bodies float they can float “high” or “low”. The ratio of the weight density of the floating body relative to the weight density of the liquid determines exactly how high or low a body will float.

Example

In order to understand Archimedes Principle as applied to floating bodies, let us consider a submarine and imagine that a block of wood of density 48.3 lb/ft^3 and volume 2 ft^3 is thrust out of the hatch of a submarine into the ocean water. We know intuitively that this block of wood will rise to the ocean surface.

The weight of the block is 48.3 lb/ft^3 x 2 ft^3 = 96.6 lb. As long as the block is below the water surface (while it is rising to the top), it displaces 2 ft^3 of ocean water.

We know that:

Buoyancy Force = weight of displaced ocean water
= 64.4 lb/ft^3 x 2 ft^3
= 128.8lb

How far will the block rise?

It will rise until the BF exactly equals its weight. In our example it will rise until the BF has been reduced 96 lb (the weight of the block). The BF will be reduced as the block emerges from the water. In our example, it will rise until 25% of the blocks volume is above the water surface. It follows that 75% of 2 ft^3 (1.5 ft^3) will be below the water surface. When this occurs, the BF on the block is (64.4 lb/ft^3 x 1.5 ft^3) equals 96.6 lb. Note again that the BF equals the weight of the block while the block is floating.

The ratio of the weight density of the block (48.3 lb/ft^3) to the weight density of the ocean water (64.4 lb/ft^3) was 0.75. We recall that 75% of the floating block was under water. This is generally true and makes a much easier procedure to determine how low a block will float in a given liquid.

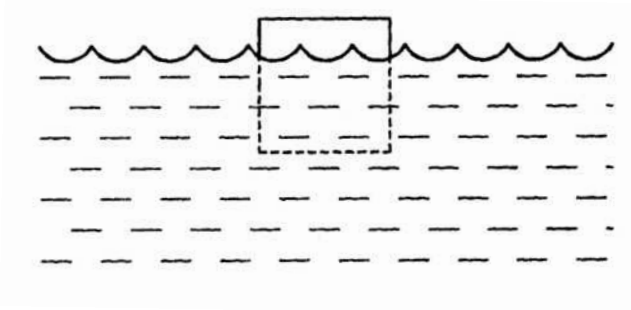


Figure 41 Floating Block of Wood

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Shape of Floating Bodies

In dealing with bodies that float, it is important to note that boats, made of materials more dense than water, are shaped in such a way that the total weight density is less than water. In order to understand this, consider the row boat with contents (people, lunch, fishing gear, etc.). Note in the diagram shown some of the boat is below the water surface. Suppose that the row boat floats in such a way that it displaces 8cu ft. of lake water. The weight of the displaced water is 8cu ft. times density of water 62.4 lb/ft^3 equates to 499 lb.

Therefore, the BF is 499 lb. The boat and contents must weigh 499 lb to float at this level. If the boat weighs 150 lb the contents must weigh 349 lb.

One final comment should be made regarding submarines. Submarines cruising at a definite depth in ocean water have a total weight density equal to the weight density of ocean water 64.4 lb/ft^3. This means that the total weight of the submarine (metal shell, air, crew, load, ballast, etc.) divided by the total volume is 64.4 lb/ft^3.

The ballast used in submarines is ocean water. These vessels can take on water or pump out water. If the submarine wants to descend, it takes on water. If it wants to rise towards the surface it pumps out water.

Example

A block of oak (Density = 45 lb/ft^3) is placed in a tank of benzene (Density = 54.9 lb/ft^3). The oak floats since its weight density is less than the weight density of benzene.

What percentage of the oak will be below the surface of the benzene?

We find the ratio of the two weight densities;

$$\frac{45 \text{ lb} / \text{ft}^3}{54.9 \text{ lb} / \text{ft}^3} = 0.82$$

We conclude that 82% of the oak block will be below the surface of the benzene.



Figure 42 Fisherman in a Boat

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M2.2.3 DYNAMICS

Mass

General

In physics the term for what we have up to now referred to as the amount of substance or matter is “mass”.

Mass is a SI basic quantity.

Atomic Mass Unit

A natural unit for mass is the mass of a proton or neutron. This unit has a special name the “Atomic Mass Unit” (amu). This unit is useful in those sciences which deal with atomic and nuclear matter.

In measuring the mass of objects which we encounter daily, this unit is much too small and therefore very inconvenient. For example, the mass of a bowling ball expressed in amus would be about 4,390,000,000,000,000,000,000,000,000 amu.

One kilogram equals 602,000,000,000,000,000,000,000,000 amu (6.02×10^{26}) Since one amu is the mass of a proton or neutron we know immediately that a kilogram of anything has this combined number of protons and neutrons contained in it.

Symbol and Unit

The symbol of the mass is *m*.

The kilogram (kg) is the SI unit of mass.

Imperial Unit

US-Americans use lb for “Pound“. The unit lb is derived from the latin word “libra“.

The conversion:

1 lb = 0,45359237 kg

Definition

The mass of an object is described as the amount of matter in an object and is constant regardless of its location.

For example, an astronaut has the same mass on earth as when in space. However, an astronaut’s weight is much less on the moon than it is on earth.

Another definition sometimes used for mass is the measurements of an objects resistance to change its state of rest to motion. This is seen by comparing the force required to move a big jet as compared to a small single engine aircraft.

Because the jet has a greater mass, it has a greater resistance to change.

Acceleration of Gravity

A realistic menas to find the mass of an object is the following: divide the weight of the object by the acceleration of gravity.

On earth, this acceleration is:

- 9.8 m/s^2 in the metric system
- 32.2 ft/s^2 in the imperial system.

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Figure 43 Astronaut on the Moon

WeR

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Force and Weight

FORCE

General

Work, power, force & motion are important concepts of physics.

As an aircraft maintenance technician, you must understand these concepts and be able to use the associated formulae to fully comprehend simple machines like pulleys, levers or gears.

Force

The word “force” generally denotes a **push or a pull**. When a body is acted upon by a resultant force it will begin to move. If the body is already moving a force may alter its speed, direction or bring it to rest. We therefore define force as follows:

Force is that which changes a body’s state of rest or of uniform motion in a straight line.

Symbol and Unit

The symbol for Force is typically *F*, from the english word “Force“.

The newton (N) is the SI unit of force.

Formula

Force = F

Mass = m

Acceleration = a

$$F = m \cdot a$$

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WeR

Figure 44 Force

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WEIGHT

General

Weight is defined as the gravitational pull of the earth on a given body. This is a force.

The direction of this force is regarded toward the geometrical center of the earth.

Physicists are very careful to distinguish between “mass & weight”.

- The mass of an object is the same wherever this object is in the universe. The mass of an astronaut is the same if he is on the earth, on the moon, in a spaceship or some place in the milky way galaxy.
- If the astronaut is standing on the earth surface, he has a weight.
- If the astronaut is not on the earth but is in a space station orbiting the earth, he is weightless.
- If the astronaut is on the moon, we speak of its “weight on moon”, the gravitational pull of the moon on the astronaut.

The greater the mass of an object on the surface of the earth, the greater is the weight of this object. These two quantities are approximately proportional to each other as long as the body remains on the earth’s surface. The word “approximately” refers to the fact that the pull of the earth on a body of a given mass varies slightly with the position of the body on the earths surface. The pull of the earth on the body is greater at the poles ($9.83\frac{m}{s^2}$) and slightly smaller at other places on the earth, like the equator ($9,78\frac{m}{s^2}$).

This is for three reasons:

- the earth is not a perfect shaped bullet
- the earth does not have the same density everywhere
- the earth rotates.

However, we usually neglect this slight difference and calculate with an average value of $9.81\frac{m}{s^2}$.

Symbol für Quantity and Unit

The symbol for this special force is typically *w*, for “Weight“.

The newton (N) is the SI unit of force.

Formula

Weight = w

Mass = m

Gravity = g

$$w = m \cdot g$$

Please not that this is special case for force.

The general formula for force is

$$F = m \cdot a$$

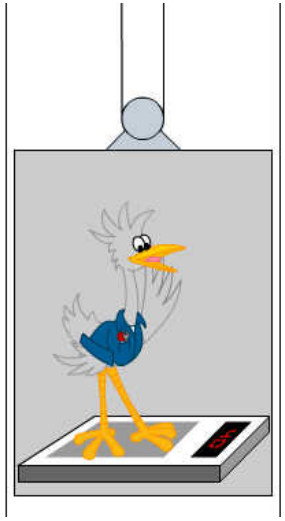
Example

For example, a body has a mass of 100 kg.

Its weight at the North Pole is 983,22 N and its weight at a place on the equator is 978,03 N.

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With ACCELERATION there is a change in force

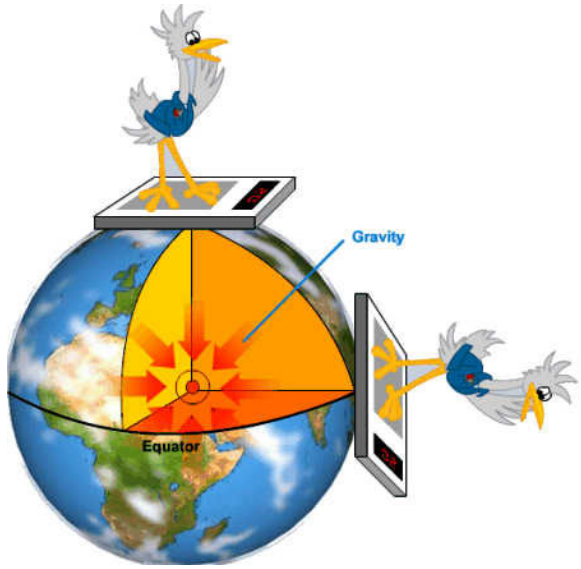
FORCE

FORCE = MASS · ACCELERATION
F = m · a[N]

The UNIT of FORCE is denoted by NEWTON [N]

$$1\ N = 1\ kg \cdot 1\ \frac{m}{s^2}$$

1 daN = 10 N



WEIGHT

WEIGHT = MASS · ACCELERATION DUE TO GRAVITY
WEIGHT = m · g[N]

The UNIT of WEIGHT is also denoted by

NEWTON [N]

Figure 45 Weight

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Friction

NATURE AND EFFECTS

When a body rests on a horizontal surface or is dragged or rolled on such a surface there is always contact between the lower body surface and the horizontal surface. This contact results in friction. Friction is work done as the surfaces rub against each other. This work heats the surface and always results in wasted work.

We need to define a force known as the normal force. A body resting on a horizontal surface experiences two forces, the downward force due to the gravitational pull of the earth on the body (weight of the body), and the upward push of the surface itself on the body (the normal force).

The weight (w) and the normal force (N) are equal to each other.

There are three kinds of friction:

- Starting friction
- Sliding friction
- Rolling resistance

Starting friction

It is present at the instant when a body, which has been at rest, just begins to move under the application of a force. Sometimes this instant when the body begins to slide is called “break away”.

Sliding friction

It is present as a body is sliding over another surface. Sliding friction is present when the surface of the body and the surface on which it slides are moving relative to each other.

ROLLING RESISTANCE

It is present between a rolling body and the surface on which it rolls. As in the case of sliding friction, the body and surface are moving relative to each other.

Equatation

In all three cases, the friction equation is the same.

$$F = \mu \cdot N$$

Symbol and Unit

The symbol μ (the Greek letter mu) is called the coefficient of friction.

There is no unit since it is just a coefficient.

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COEFFICIENT OF FRICTION

Every pair of flat surfaces has two different coefficients of friction.

Coefficients of Friction		
Material	**μ Start**	**μ Slide**
Steel on Steel	0.15	0.09
Steel on Ice	0.03	0.01
Leather on Wood	0.5	0.4
Oak on Oak	0.5	0.3
Rubber on dry Concrete	1.0	0.7
Rubber on wet Concrete	0.7	0.5

The coefficient of starting friction – μ_{start}

The coefficient of sliding friction – μ_{slide}

Coefficients of sliding friction are less than the coefficients of starting friction. This means that the force needed to start a body sliding is greater than the force needed to keep a body sliding with constant speed.

When we deal with a body that rolls over a flat surface, we have another coefficient of friction to consider, the coefficient of rolling friction.

The coefficients of rolling friction (μ_{roll}) are very small. Therefore rolling friction is much smaller than either starting or sliding friction.

Rubber tyres on dry concrete 0.02

Roller bearings 0.001 to 0.003

Example

A steel body weighing 450 N is resting on a horizontal steel surface. How many newtons of force are necessary to start the body sliding?

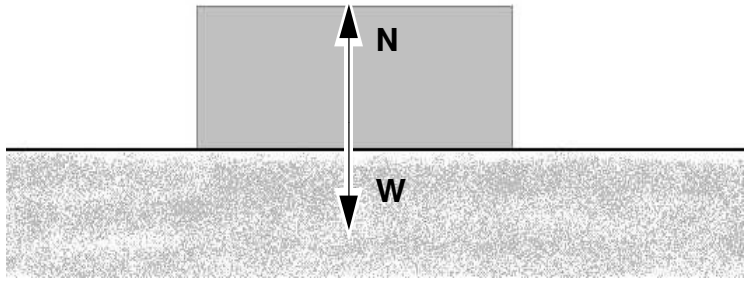
What force is necessary to keep this body sliding at constant speed?

$w = N = 450\ N$

$F = \mu \cdot N$

Force to start sliding motion $= 0.15 \cdot 450\ N = 68\ N$

Force to keep body sliding $= 0.09 \cdot 450\ N = 41\ N$



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Work

General

In ordinary conversation the word “work” refers to almost any kind of physical or mental activity, but in science and mathematics it has one meaning only. Work is done when a force produces motion. An engine pulling a train does work, so does a crane when it raises a load against the pull of the earth.

Similarly, a workman who is employed to carry bricks up a ladder and on to a scaffold platform also performs work.

Work is said to be done when the point of application of a force moves and is measured by the product of the force and the distance moved in the direction of the force.

Symbol and Unit

The symbol for Work is typically *W*, from the english word “Work“.

The Joule (J) is the SI unit of work.

One Joule is the work done by a force of one Newton acting through a distance of one meter.

Thus: 1 N m = 1 J

Imperial System

In the English system, work is typically measured in Foot–pounds. One foot–pound is equal to one pound of force applied to an object through the distance of one foot.

One pound is equal to 4.448 Newtons.

Formula

Work = W

Force = F

Distance = d

$$W = F \cdot d$$

Example 1

If you wish to calculate the work done by a man of mass 65 kg in climbing a ladder 4 m high, convert weight to Newtons by multiplying 9.81 m/s^2 (acceleration of gravity) and multiply this weight by the height.

$$W = (65 \times 9.8)\ N \cdot 4\ m$$

$$W = 2{,}548\ Joules$$

Example 2

You can see that an object with a force of 600 Newton is moved a distance of 30 meters.

The work is 600 Newton multiplied by 30 meters which is 18.000 Newton meters. This is 18.000 Joule.

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WORK

WORK = FORCE · DISTANCE

WORK = N · m

The WORK is denoted by JOULE [J] and has the Unit Nm

1J = 1N · 1m

Figure 46 Work

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Power

General

When you want to know the ability of a machine to do work in a certain time, you want to know its power. A strong steam engine will do more work in an hour than a horse.

Power is work over time or more specifically force multiplied by distance over time.

In the figure you can see that the object with a force of 600 Newton is moved a distance of 30 meters in 10 seconds.

The power is 600 Newton multiplied by 30 meters divided by 10 seconds which is 1 800 watts or 1.8 kilowatts.

Symbol and Unit

The symbol for Force is typically *P*, from the english word “Power“.

The Watt (W) ist the SI unit of power.

One Watt is one Joule per second.

Thus: $1W = 1\frac{J}{s}$

Old Unit

You probably know the term horse power. When steam engines were first used their power was compared to the power of horses because they were used for work which was previously done by horses.

Formula

Power = P

Work = W

Time = t

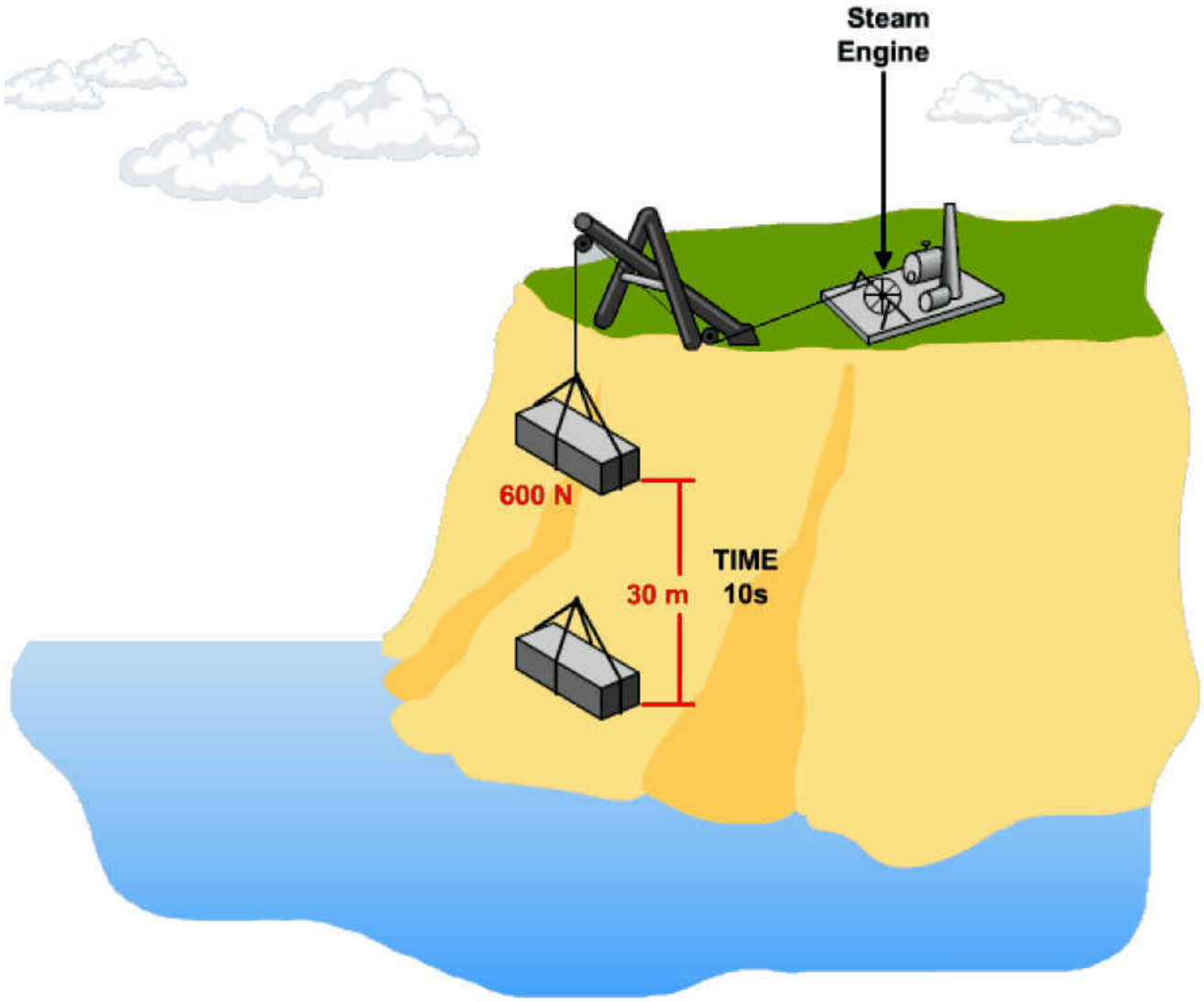
$$P = \frac{W}{t}$$

Reminder

$$W = F \cdot d$$

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POWER

$$\text{POWER} = \frac{\text{FORCE} \cdot \text{DISTANCE}}{\text{TIME}}$$

$$\text{POWER} = \frac{600\text{N} \cdot 30\text{m}}{10\text{ s}}$$

$$\text{POWER} = 1800\ \frac{\text{Nm}}{\text{s}}$$

$$\text{POWER} = 1800\text{ W}$$

$$\text{POWER} = 1.8\text{ kW}$$

Figure 47 Power

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Levers

General

A lever is a device used to gain a mechanical advantage.

In its basic form, the lever is a seesaw that has a weight at each end. The weight on one end of the seesaw tends to rotate the board counter−clockwise while the weight on the other end tends to rotate the board clockwise. Each weight produces a moment or turning force. The moment of an object is calculated by multiplying the objects weight by the distance the object is from the balance point or fulcrum.

A lever is balanced when the algebraic sum of the moments is zero.

The symbol for moment is commonly denoted M.

Example

An object with the weight w = 10 N is located two meters to the left of a fulcrum causes a moment M of negative 20 N m.

An object with the weight w = 10 N located two meters to the right of a fulcrum has a moment of positive 20 N m.

Since the sum of the moments is zero, the lever is balanced.

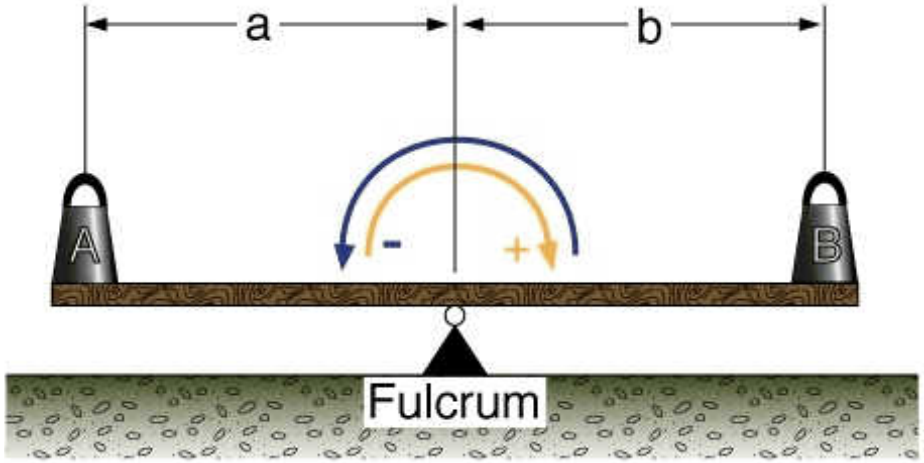


Figure 48 Lever I

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FIRST–CLASS LEVER

The figure illustrates a practical application of a first–class lever.

The end of a bar with a length of 4 meters is placed under a 100 N weight, so the fulcrum is 0,5 meters from the weights centre of gravity. This leaves 3.5 meters between the weight and the point at which the force, or effort is applied.

When the force F is applied, it acts in the direction opposite the weights movement. To calculate the amount of force F required to lift the weight, you must calculate the moments on each side of the fulcrum.

This is done using the formula:

$$\frac{L}{l} = \frac{R}{F}$$

Where:

L = length of effort arm

l = length of resistance arm

R = resistance (here: weight of the object)

F = force

$$\frac{3.5m}{0.5m} = \frac{100N}{F}$$

$$3,5\ m \times F = 0,5\ m \times 100\ N$$

$$F = \frac{(0,5 \times 100)}{3,5} N$$

$$F = 14,28\ N$$

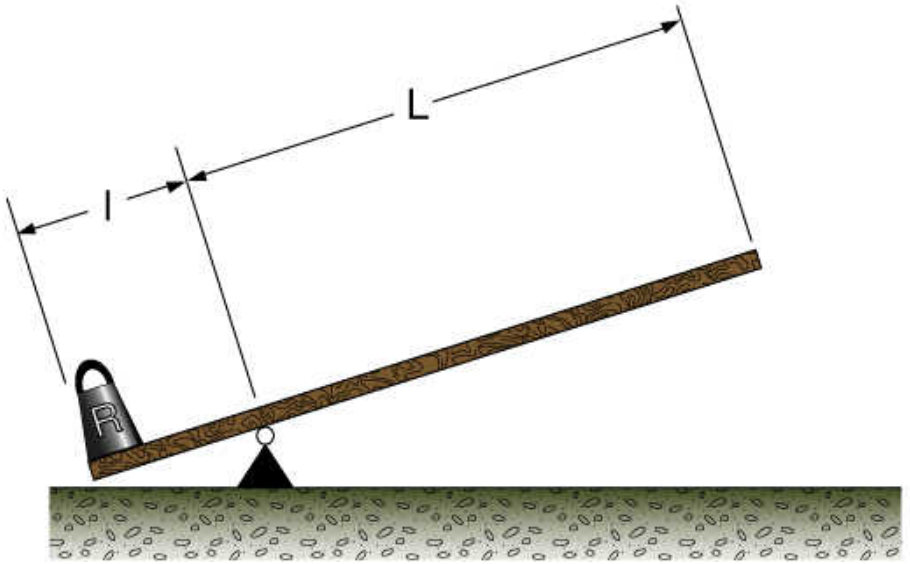
Although less effort is required to lift a 100–newton weight, a lever does not reduce the amount of work done.

Remember, work is the product of force and distance therefore, when you examine the ratio of the distances moved on either side of the fulcrum, you notice that the effort arm must move 7 cm to move the resistance arm 1 cm.

The work done on each side is the same.

0,01 m x 100 N = 0,07 m x 14,28 N

300 N = 300 N



l = 0,5m

L = 3,5m

R = 100N

$$\frac{L}{l} = \frac{R}{F}$$

$$\frac{3.5m}{0.5m} = \frac{100N}{F}$$

RuF

Figure 49 Lever II

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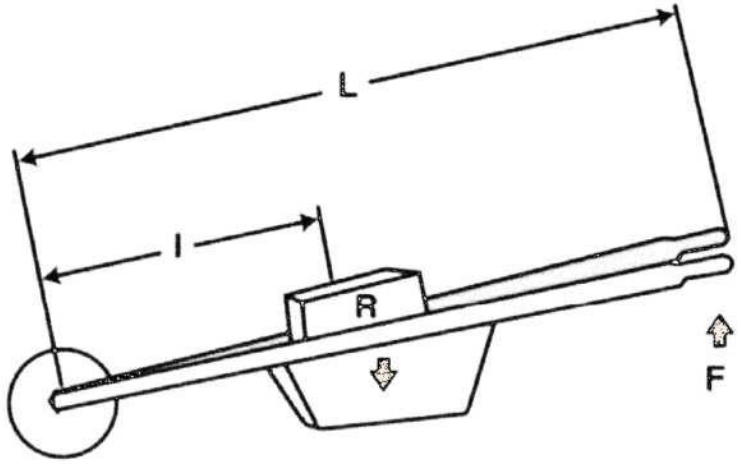
SECOND–CLASS LEVER

Unlike the first class lever, the second class lever has the fulcrum at one end of the lever and effort is applied to the opposite end.

The resistance, or weight, is typically placed near the fulcrum between the two ends. The most common second class lever is the wheelbarrow. When using a wheelbarrow, the lever, or handle, is used to gain mechanical advantage to reduce the force required to carry a load.

For example, if a wheelbarrow has 200 pounds of weight concentrated 12 inches from the wheel axle and effort is applied 48 inches from the axle, only 50 pounds of force F is needed to lift the weight. You can calculate this by using the same relationship derived for a first class lever.

The mechanical advantage gained using a second class lever is the same as that gained when using a first class lever. The only difference is that the resistance and force on the second class lever move in the same direction.



I = 12 INCHES
R = 200 POUNDS
L = 48 INCHES

$$\frac{L}{I} = \frac{R}{E}$$

$$\frac{48\text{ in}}{12\text{ in}} = \frac{200\text{ lb}}{F}$$

$$48F = 2{,}400$$

$$F = 50 \text{ POUNDS}$$

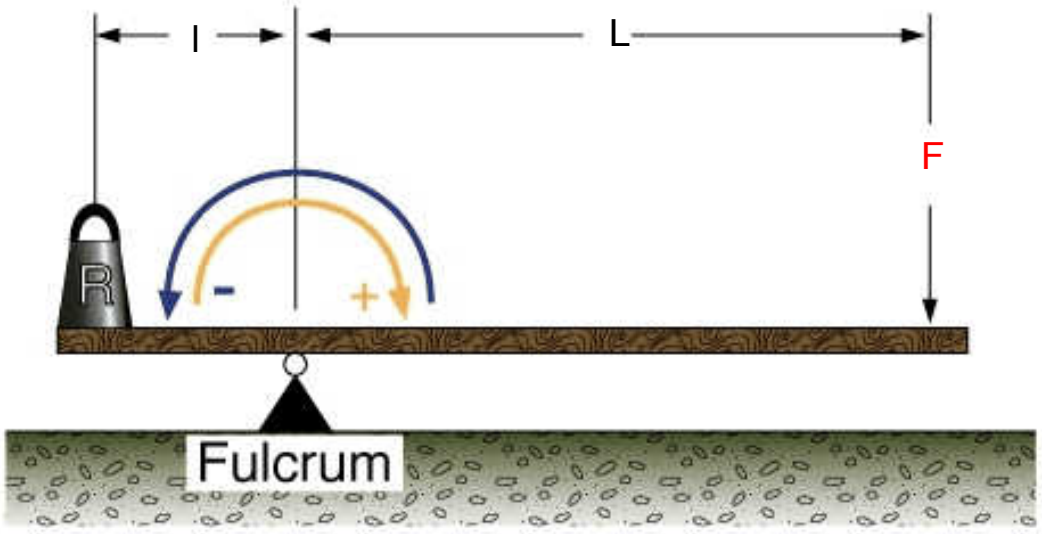
$$\text{FORCE RATIO} = \frac{50}{200} = \frac{1}{4}$$

$$\text{DISTANCE RATIO} = \frac{12}{3} \text{ OR } \frac{4}{1}$$

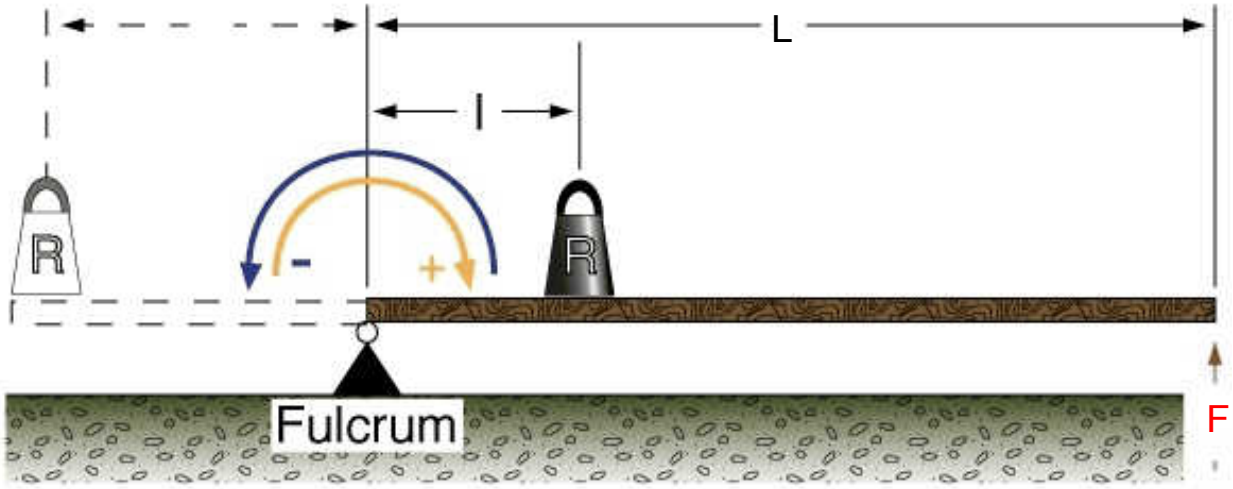
Figure 50 Lever III

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First Class Lever



Second Class Lever

Figure 51 Levers (Class I and II)

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THIRD–CLASS LEVER

In aviation, the third class lever is primarily used to move a resistance a greater distance than the force applied.

This is accomplished by applying the effort between the fulcrum and the resistance.

However, when doing this, a greater effort is required to produce movement.

An example of a third class lever is a landing gear retracting mechanism. The effort required to retract the landing gear is applied near the fulcrum while the resistance is at the opposite end of the lever.

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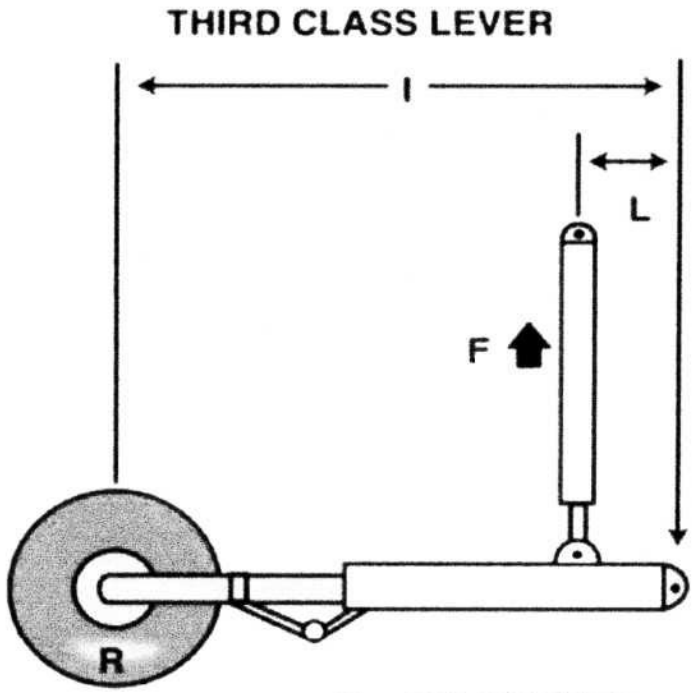


Figure 52 Lever (Class III)

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Inclined Planes

General

Another way to gain mechanical advantage is through the inclined plane.

An inclined plane achieves an advantage by allowing a large resistance to be moved by a small effort over a long distance.

Formula

The downhill-slope force (F) required is calculated through the formula:

$$F = w \times \frac{h}{d}$$

from:

$$\frac{d}{h} = \frac{w}{F}$$

$$\frac{d}{h} \times F = w$$

$$d \times F = w \times h$$

Where:

d = length of the ramp

h = height of the ramp

w = weight or resistance of the object

F = force required to raise or lower the object

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Example

Determine the amount of effort required to roll a barrel with a weight of 500 N up a 12 meters inclined plane to platform that is 4 meters high.

Where:

l = length of the ramp

h = height of the ramp

w = weight or resistance of the object

F = force required to raise or lower the object (downhill-slope force)

By using an inclined plane, 500 N of resistance is moved by an effort of 166.7 N. The mechanical advantage gained is the ratio of the ramp to the height of the platform 3:1.

$$\frac{12m}{4m} = \frac{500N}{x}$$

$$12m \times x = 500N \times 4m$$

$$12m \times x = 500N \times 4m \quad | :m$$

$$12 \times x = 500N \times 4$$

$$12 \times x = 2000N \quad | :12$$

$$x = 166,7N$$

w = 500 Newton

l = 12 meters

h = 4 meters

F = x Newton

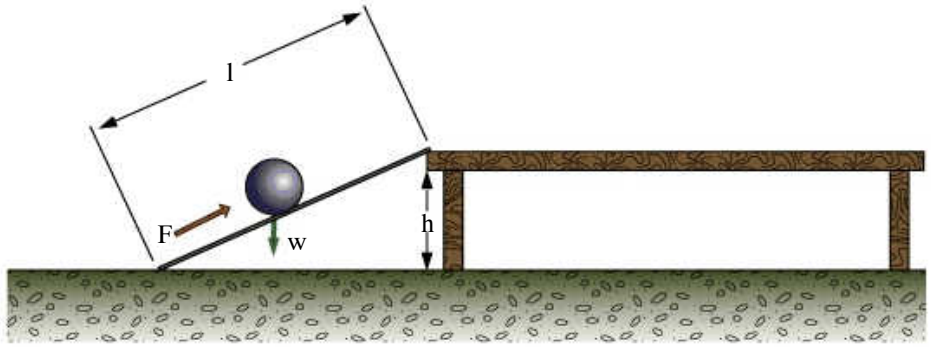


Figure 53 Inclined Plane

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Newton's Laws

Introduction

The rapid advance in aviation in the first half of the last century can be attributed in large part to a science of motion which was presented to the world three centuries ago by Sir Isaac Newton, a British physicist. Newton's treatise on motion, the "Philosophiae Naturalis Principia Mathematica" (in short: Principia), published in 1687, showed how all observed motions could explain on the basis of three laws. The application of these laws have led to great technological advances in the aerodynamics, structure and powerplant of aircraft. It is safe to say that any future improvements in the performance of aircraft will be based on these laws of motion.

NEWTON'S FIRST LAW

The old magicians trick of pulling a cloth out from under a full table setting is not only a reflection of the magicians skill but also an affirmation of a natural tendency which dishes and silverware share with all matter. This natural tendency for objects at rest to remain at rest can be attested to by any child who ever tried kicking a large rock out of the path.

It is also a well known fact that once a gun is fired, the command "stop" has no effect on the bullet. Only the intervention of some object can stop or deflect it from its course. This characteristic of matter to persist in its state of rest or continue in whatever state of motion it happens to be in is called inertia. This property is the basis of a principle of motion which was first enunciated by Galileo in the early part of the 17th century and later adopted by Newton as his first law.

The first law is called the law of inertia. It states:

A body at rest remains at rest and a body in motion continues to move at a constant velocity unless acted upon by an unbalanced external force.

The importance of the law of inertia is that it tells us what to expect in the absence of forces: either rest (no motion) or straight line motion at constant speed. A passenger's uncomfortable experience of being thrown forward when an aircraft comes to a sudden stop at the terminal is an example of this principle in action. A more violent example is the collision of a vehicle with a stationary object. The vehicle is often brought to an abrupt stop.

Unbelted passengers continue to move with the velocity they had just prior to the collision only to be brought to rest (all too frequently with tragic consequences) by surfaces within the vehicles (dashboards, windshields, etc.).

NEWTON'S SECOND LAW

A Learjet accelerates down the runway a distance 1,000 m, takes off and begins its climb at 6,000 ft/min quickly reaching a cruising altitude of 35,000 ft, where it levels off at a speed of 260 knots.

Subsequently, the aircraft may have to perform a variety of manoeuvres involving changes in heading, elevation and speed. Every aspect of the aircraft's motion is governed by the external forces acting on its wings, fuselage, control surfaces and powerplant. The skilled pilot using his controls continually adjusts these forces to make the aircraft perform as desired.

The interplay between force and motion is the subject of Newton's second law. An understanding of this law not only provides insight into the flight of an aircraft, but allows us to analyze the motion of any object.

Newton's second law states:

The rate of change of momentum of a body is proportional to the applied force and takes place in the direction in which the force acts.

$$\text{Force}_{net} = \text{Mass} \cdot \text{Acceleration} = F = m \cdot a$$

An increase in velocity with time is measured in the metric system in m/sec. In the Imperial system it is measured in ft/sec. This is an important relationship when working with the acceleration of gravity. For example, if a body is allowed to fall freely under the effect of gravity, it accelerates uniformly at 32.17 ft/s every second it falls.

The second law states that a net or unbalanced force acting on an object equals the mass of the object times the acceleration of that object.

Inertial Mass

Inertial mass is the mass of an object measured by its resistance to acceleration. To achieve a given acceleration denoted with a, you need more force for a bigger mass.

According to Newton's second law, you can use this formula: $m = \frac{F}{a}$.

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NEWTON'S THIRD LAW

Newton's third law is sometimes referred to as the law of action and reaction. This law focuses on the fact that forces, the pushes and pulls responsible for both the stability of structures as well as the acceleration of an object, arise from the interaction of two objects.

A push, for example, must involve two objects, the object being pushed and the object doing the pushing.

Newton's third law states:

Every action has an equal and opposite reaction.

The thirds law states that no matter what the circumstances, when one object exerts a force on a second object the second must exert an equal and oppositely directed force on the first.

An apple hanging from a tree is pulled by the earth with a force which we call its weight. Newton's third law tells us that the apple must pull back on the earth with an exactly equal force. The weight of the apple is a force on the apple by the earth, directed downward.

The force which the apple exerts back on the earth, is a pull on the earth directed upward. Another force acting on the apple is the upward pull exerted by the branch. The law of action and reaction tells us that the apple must be pulling down on the branch with the same magnitude of force.

People are often confused by this principle because it implies, for instance, that in a tug of war the winning team pulls no harder than the losing team. Equally enigmatic is how a horse and wagon manage to move forward if the wagon pulls back on the horse with the same force the horse pulls forward on the wagon. We can understand the results of the tug of war by realizing that the motion of the winning team (or losing team) is not determined exclusively by the pull of the other team, but also the force which the ground generates on the team members feet when they "dig in".

Recall, it is the net force, the sum of all the acting forces which determine the motion of an object.



Figure 54 Sir Isaac Newton

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Energy

General

The concept of energy is one of the most important concepts in all of physical science. We often hear of energy sources, alternate energy, shortage of energy, conservation of energy, light energy, heat energy, electrical energy, sound energy, etc. So what is the meaning of the word “energy”?

Energy is defined as the “Capacity to do Work”. This definition is only a partial definition. However, it has the advantage of immediately relating the concept of energy to the concept of work. These two ideas are intimately related to each other.

KINETIC ENERGY

Kinetic energy is a quality that a body has after work has been done on this body. Once work has been done on a body of mass (m) this body has energy. The body can then do work on other bodies.

Study the following situation.

A body of mass (m) was resting on a table. A player exerted a horizontal force (F) on this mass through a distance (s). Since the angle between the force and the displacement was zero degree angle, the work done this body was simply Fs.

At the instant the player removed his cue from the billard ball we note two facts.

- The body accelerated while the force (F) was acting on the body and the body has acquired a velocity (v) during this time of acceleration (a).
- The body has moved through a distance (s) in time (t).

Symbol and Unit

The symbol for Kinetic Energy is typically E_k.

The Joule (J) is the SI unit of energy.

Formula

Kinetic Energy = E_k

Mass = m

Velocity = v

$$E_K = \tfrac{1}{2}\, m \cdot v^2$$

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Figure 55 Kinetic Energy

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POTENTIAL ENERGY

Another equally important situation where an agent easily can do work on a body occurs when the agent raises a body vertically in a gravitational field, at the surface of the earth. In this case, the work done on the body again equals the force applied multiplied by the distance the body is raised.

$W = F \cdot s$

W = Weight of Body x Distance Raised

here the force F has the same amount as the weight w.

We recall the formula for weight which is a force: w = m x g.

Also since distance is a vertical distance we use the symbol “h” for height. In our discussion we will assume that the symbol “h” always represents the vertical distance of the body above the surface of the earth.

Therefore, we write:

$W = m \cdot g \cdot h$

Again we have a case where an agent did work on a body and the body has acquired “energy”. This type of energy is known as gravitational potential energy.

Symbol and Unit

The symbol for Potential Energy is typically *PE*.

Sometimes, *U* is used.

The Joule (J) is the SI unit of energy.

Formula

Potential Energy = PE

Mass = m

Gravity = g

Height = h

$PE = m \cdot g \cdot h$

Summary

If we neglect air resistance (which results in loss of energy to heat), we note that there is a conservation of kinetic and potential energy of a body moving in a gravitational field.

As a body falls from a height (h) and moves closer to the surface of the earth, its potential energy decreases and its kinetic energy increases while it is falling.

Therefore, there is an easy way of finding the speed of a falling body during any instant of its fall.

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Example

A body of mass, 10 kg falls to the earth from a height of 300 m above the surface of the earth.

What is the speed of this body just before it touches ground?

$$PE = E_k$$

$$m \cdot g \cdot h = \tfrac{1}{2} m \cdot v^2$$

$$10\,kg \cdot 9.81\,\frac{m}{s^2} \cdot 300\,m = \frac{1}{2} \cdot 10\,kg \cdot v^2$$

$$29430\,\frac{kg \cdot m^2}{s^2} = 5\,kg \cdot v^2 \qquad | : 5\ kg$$

$$5886\,\frac{m^2}{s^2} = v^2 \qquad | \sqrt{\ }$$

$$v = 76.7\,\frac{m}{s}$$

The kinetic energy that the body has just before it reaches the ground immediately changes to sound energy and heat energy on impact. It may also “squash” anybody in its path or make an indetation in the earth, this is strain energy (energy to deform).

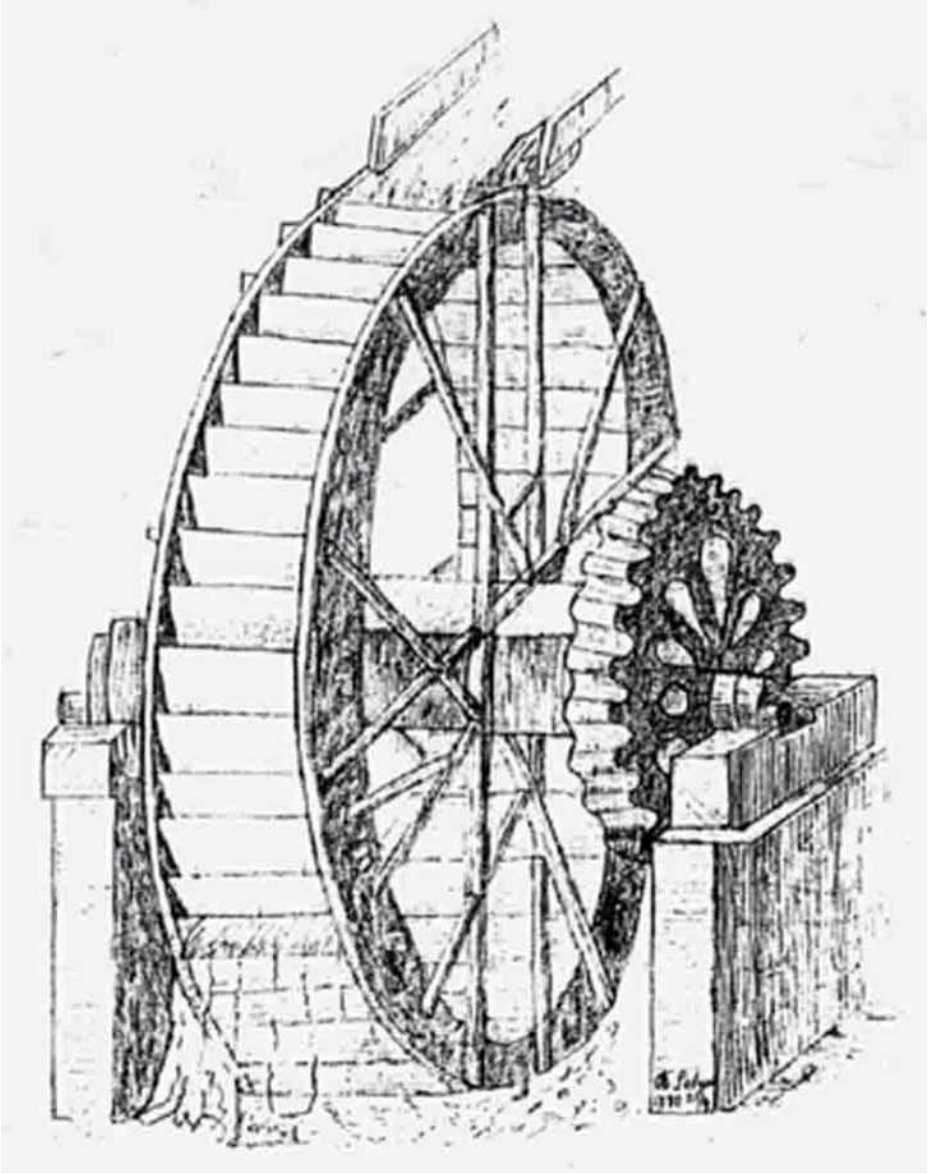


Figure 56 Water Wheel

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HEAT

General

Heat is a kind of energy. Normally we think of the thermal energy which increases with its temperature.

In physics, we talk of thermodynamic temperature.

Thermodynamic Temperature is a SI basic quantity.

Symbol and Unit

The symbol for Quantity is T.

The Kelvin (K) is the SI unit of Thermodynamic Temperature.

Thermodynamic

In simple terms, thermodynamic processes start as soon as two bodies with a different thermodynamic temperature can interact.

In the most common way, this happens when two bodies have contact with each other. As an example, you can see that a radiator has a different temperature than the surrounding air. This starts a heat transfer which is called thermodynamic process.

The total amount of energy transferred through heat transfer is conventionally abbreviated as Q.

Since this is energy, its unit is Joule (J).

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Figure 57 Heat

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TOTAL ENERGY

A body of any mass may have various energies:

- Kinetic Energy
- Potential Energy
- Heat Energy
- Electromagnetic Energy.

There are even some more kinds of energy.

Total Energy is just the sum of all these energies in a body.

Example

A cannon ball may have the kinetic energy from the cannon fire and potential energy when the cannon is standing on a hill.

It may have more energies like heat or magnetism.

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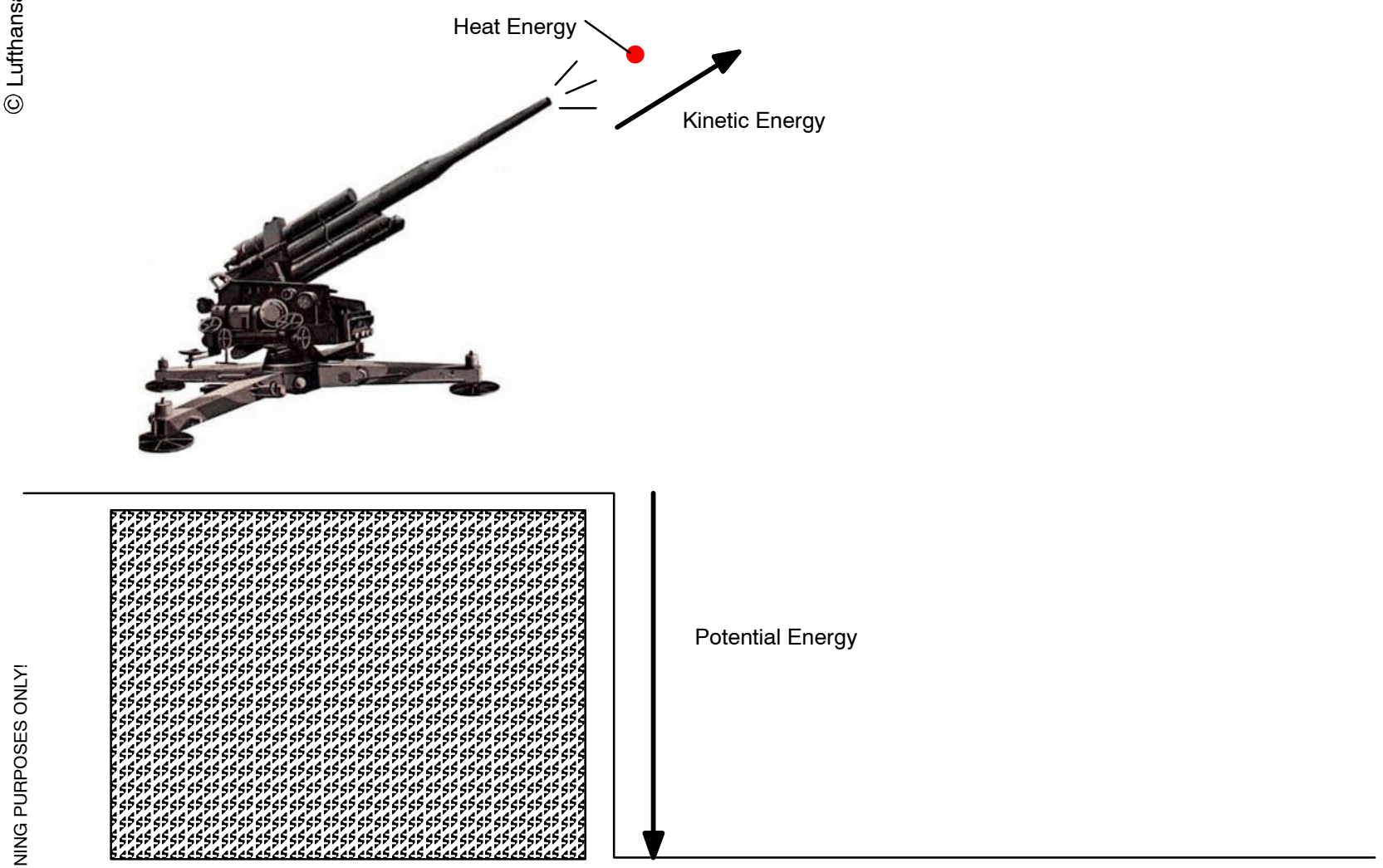


Figure 58 Cannon

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Efficiency

General

The efficiency of energy conversion is the ratio between the input into a mechanism and the useful output of the mechanism.

The useful output may be electric power, mechanical work, or heat.

For example, fuel is burned in an engine. What we want is force to cause a motion. What we do not want is heat. However, heat will be produced and a radiator is necessary.

Even though the definition includes the notion of usefulness, efficiency is considered a technical or physical term. Goal or mission oriented terms include effectiveness and efficacy.

Dimension Unit

Generally, energy conversion efficiency is a dimensionless number between 0 and 1.0, or 0% to 100%. Efficiencies may not exceed 100%, e.g., for a perpetual motion machine.

However, other effectiveness measures that can exceed 1.0 are used for heat pumps and other devices that move heat rather than convert it. This is causes by the heat caused by friction in the bearings.

Symbol for Quantity

The symbol for efficiency is η.

This is no quantity which can be counted, and so there is no unit.

Formula

The formula is as follows:

$$\eta = \frac{P_{out}}{P_{in}}$$

$$P_{out} = P_{in} - loss$$

Example:

When a cart is pulled, but the bearings of the wheels are not good, heat will be produced because of the friction. So the power will be converted not only to kinetic energy but also to some heat energy. By this, we have less kinetic energy.

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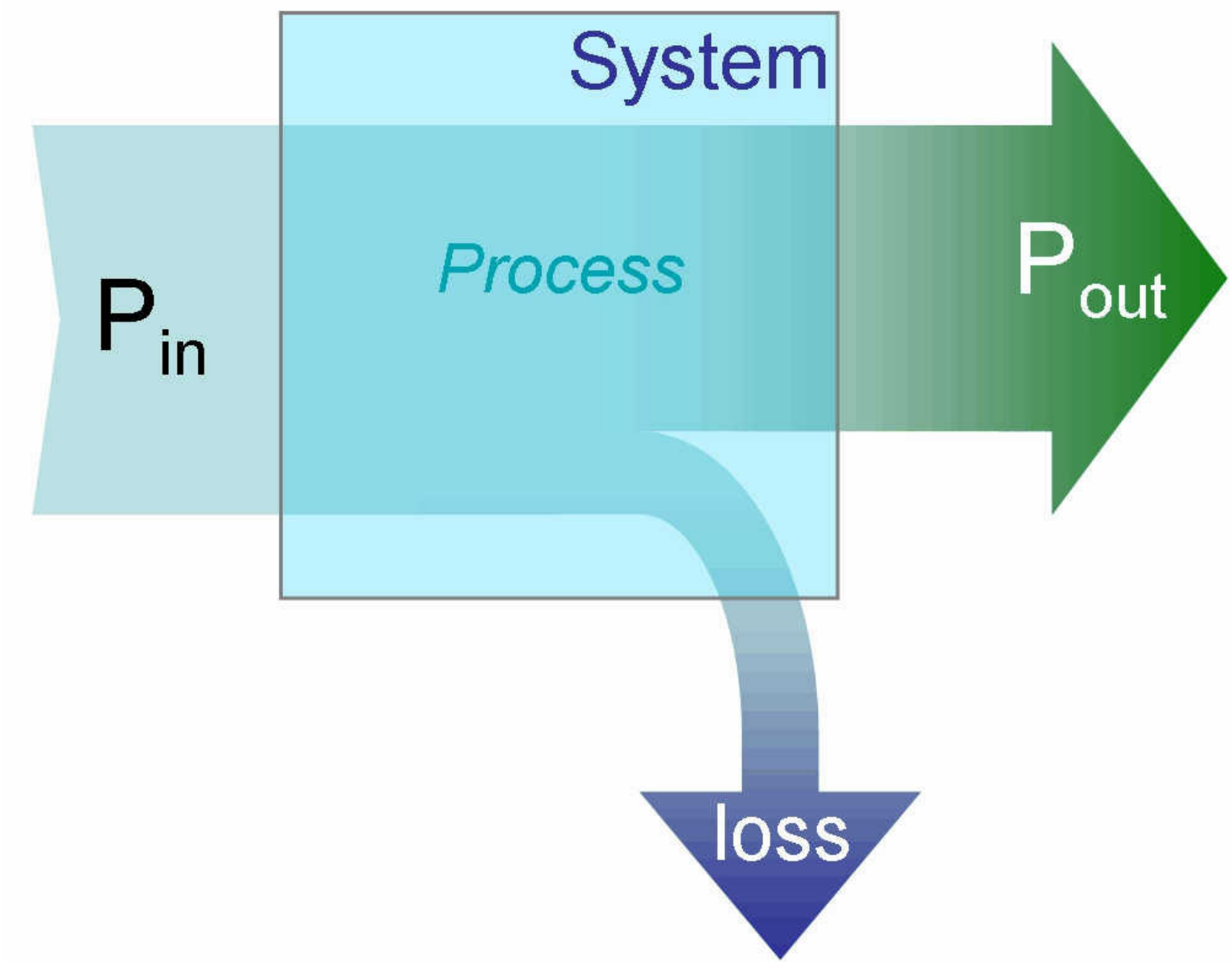


Figure 59 Efficiency

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Momentum

Definition of Momentum

Momentum is a vector quantity defined as the product of mass times velocity. Note that velocity (v) is also a vector quantity.

We write the defining equation as:

$$\text{Momentum} = m \cdot v$$

Momentum is a very important quantity when we are dealing with collisions, because it is conserved in all such cases.

CONSERVATION OF MOMENTUM

In a collision, there are always at least two bodies that collide.

We will deal only with collisions of two bodies. We will also limit our discussion to collisions occurring in one dimension. Such collisions are called “head–on” collisions.

At this time, we need to recall two of newtons laws. We need Newton’s second law: $F = m \cdot a$,
and newton’s third law, which tells us that if two bodies collide, the force that the first body exerts on the second body is equal in magnitude and opposite in direction to the force that the second body exerts on the first body. Also recall that the acceleration (a) equals the change in the velocity divided by the time.

Let us visualize two bodies of masses, M_1 and M_2 on a one dimensional track.

If these two bodies collide, we have four different velocities to consider. We name these velocities very carefully.

$v_{1'}$ = the velocity of body one before the collision.

$v_{1''}$ = the velocity of body one after the collision.

$v_{2'}$ = the velocity of body two before the collision.

$v_{2''}$ = the velocity of body two after the collision.

By using Newtons two laws we can derive the following equation.

The equation tells us that the total momentum before the collision is equal to the total momentum after the collision. Sometimes we say simply that “Momentum is Conserved”.

$$m_1 \cdot v_1' + m_2 . v_2' = m_1 . v_1' + m_2 \cdot v_2''$$

The simplest example of the conservation of momentum is in recoil problems.

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Example

A boy and a man are both on ice skates on a pond.

The mass of the boy is 20 kg and the mass of the man is 80 kg. They push on each other and move in the opposite directions.

If the recoil velocity of the boy is 80 m/s, what is the recoil of the man?

First we note that both the man and boy are at rest before the collision occurs.

$$
\begin{array}{llll}
m_1 \cdot v_1' & + m_2 \cdot v_2' & = m_1 \cdot v_1' & + m_2 \cdot v_2'' \\
20 \cdot 0 & + 80 \cdot 0 & = 20 \cdot 80 & + 80 \cdot v_2'' \\
 & 0 & = 1600 & + 80 \cdot v_2'' \quad \mid -1600 \\
 & -1600 & = 80 \cdot v_2'' & \mid : 80 \\
 & -20 \text{ m/s} & = v_2'' &
\end{array}
$$

The negative sign indicates that the man recoils in the opposite direction from the boy.

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Impulse

Collision Problems

Whenever two bodies collide, momentum is always conserved. This is simply the result of applying Newtons second and third laws as we have done in the preceding discussion.

Sometimes kinetic energy is also conserved in a collision. This happens when the bodies are so hard that there is very little deformation of the bodies in the actual collision process. Billiard balls are a good example. These collisions are known as elastic collisions. We will derive a formula for determining the velocities of the bodies after the collision has occurred.

Another type of collision that we will discuss is the perfectly inelastic collision. In this type of collision, the bodies are deformed so much that they actually stick together after the collision. An example would be the collision of two masses of putty. We will also do some problems for this type of collision.

INELASTIC COLLISIONS

We use the conservation of momentum for dealing with this type of collision.

As we have said, the colliding bodies stick together after impact.

Therefore, the equation is simply:

$$m_1 . v_1' + m_2 . v_2' = (m_1 + m_{2)} . v''$$

Note that we use the symbol v" for the common velocity of the two bodies (which are now one body) after the collision.

It is important to include the signs of the velocities of the bodies in setting up momentum equations. As usual, we use a positive sign for east and a negative sign for west, a positive sign for north and a negative sign for south.

Example

A truck with a mass of 1550 kg is moving east at 60 m/s. A car with a mass of 1250 kg is travelling west at 90 m/s the vehicles collide and stick together after impact.

What is the velocity of the combined mass after the collision has occurred?

$$m_1 . v_1' + m_2 \cdot v_2' = (m_1 + m_{2)} . v''$$

$$1550\ kg \cdot 60\ m/s + 1250\ kg \cdot -90\ m/s = (1550\ kg + 1250\ kg) \cdot v''$$

$$-19500\ kgm/s = 2800\ kg \cdot v''$$

$$v'' = -6.96\ m/s$$

Since the calculated velocity has a negative sign, we conclude that the combined mass is travelling west after the impact occurred.

Our answer is that the wreckage starts to move west with a speed of 6.96m/sec. Sometimes the principle of conservation of momentum in the case of an inelastic collision can be used by the police to determine the speed of a vehicle engaged in a head–on collision.

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Figure 60 Inelastic Collision

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ELASTIC COLLISIONS

Elastic collisions are collisions that occur between bodies that deform very little in the collision. Therefore we assume that no energy is lost. An example of such a collision is the collision between pool balls.

In elastic collisions, both kinetic energy and momentum are conserved. In an ordinary elastic collision problem, we know the masses and the velocities of two bodies that will collide. We want to predict, by mathematical calculation, the velocities the bodies will have after the collision has occurred, the two unknowns.

If we write the two conservation equations, we have two equations in these two unknowns. It is possible to solve these two equations for these two unknowns. However, one of the conservation equations, the energy equation, is a “second order” equation. A “second order” equation contains the squares of the unknowns. This makes the solution more difficult. Instead, we will use an algebraic trick! The two conservation equations can be solved together producing a third equation. This third equation and the momentum conservation equation provide the two first order equations that we will use in solving elastic collision problems.

The following two equations have been obtained algebraically and must be used for carrying out elastic collision calculations.

(1) $m_1 \cdot v_1' + m_2 \cdot v_2' = m_1 \cdot v_1'' + m_2 \cdot v_2''$

(2) $v_1' - v_2' = v_2'' - v_1''$

Example

A billiard ball of mass 2 kg is moving east at 3 m/s and undergoes an elastic collision with another billiard ball of mass 3 kg moving west at 4 m/s. Find the velocities of the two balls after the collision.

$m_1 = 2$; $v_1' = 3$ (east)
$m_2 = 3$; $v_2' = -4$ (west)

Substitute in equation (1):

$$2 \cdot 3 + 3 \cdot -4 = 2 \cdot v_1' + 3 \cdot v_2''$$

(3) $$-6 = 2 \cdot v_1' + 3 \cdot v_2''$$

Substitute in equation (2):

$$3 - (-4) = v_2'' - v_1''$$

(4) $$7 = v_2'' - v_1''$$

Rewrite equations (3) and (4) putting the unknowns in the left members and in order.

(3) $2 v_1' + 3 v_2'' = -6$

(4) $-v_1'' + v_2'' = 7$

We now have two equations and two unknowns. There are several methods of solving such a system of equations. We will use the method of addition. In this method we multiply either or both of the equations by constants to make the coefficient of one of the unknowns in the one equation a positive number and to make the coefficient of this same unknown in the other equation a negative number of the same magnitude.

We then add the two equations to eliminate one of the unknowns. We then solve for the other unknown by substituting in either equation.

Multiply **(4)** by the number 2

(5) $-2 \cdot v_1'' + 2 \cdot v_2'' = 14$

Add **(3)** and **(5)**

$$\begin{aligned} 2 \cdot v_1'' + 3 \cdot v_2 + 6 &= 2 \cdot v_1 - 2 \cdot v_2 + 14 && | -2v_1 \\ 3 \cdot v_2 + 6 &= -2 \cdot v_2 + 14 && | +2v_2 \\ 5 \cdot v_2 + 6 &= 14 && | -6 \\ 5 \cdot v_2 &= 8 && | \div 5 \\ v_2'' &= 1.6 \frac{m}{s} \end{aligned}$$

Substitute this value back into **(4)**

$$\begin{aligned} -v_1'' + 1.6 &= 7 && | -1.6 \\ -v_1'' &= 5.4 && | \cdot (-1) \\ v_1'' &= -5.4 \frac{m}{s} \end{aligned}$$

We note that we interpret a positive sign for the velocity as motion east and negative sign as motion west.

Our final result is that the 2 kg ball is moving west with a speed of 5.4 m/s after the collision and the 3 kg ball is moving east with a speed of 1.6 m/s after the collision.

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Figure 61 Elastic Collision

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Gyroscopic Principles

General

Gyroscopes or gyros in short are fascinating to study and a great deal of material is available on them.

For the most part, we will be connected with only two of the properties of the spinning gyros.

Gyros are used to detect turns around the x, y or z axis of an aircraft.

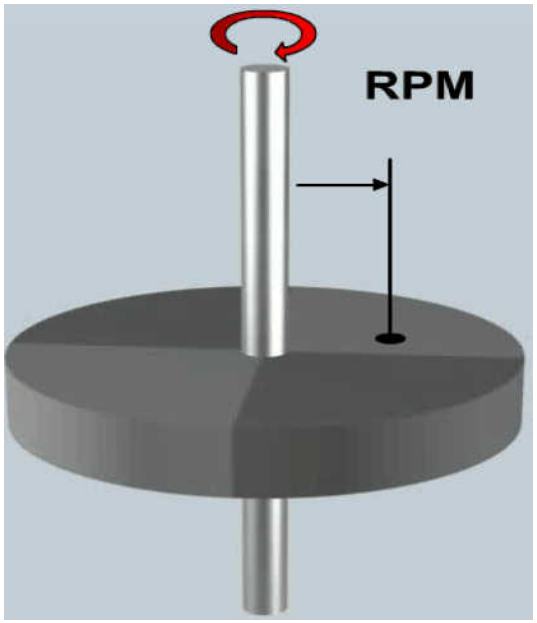
Rigidity in Space

The first is the tendency of a spinning gyro to remain fixed in space if it is not acted upon by outside forces such as bearing friction. This is the property of rigidity.

Rigidity is used in gyros to show the direction (Horizontal Situation Indicator or HSI) and attitude (Attitude Director Indicator or ADI) of an aircraft.

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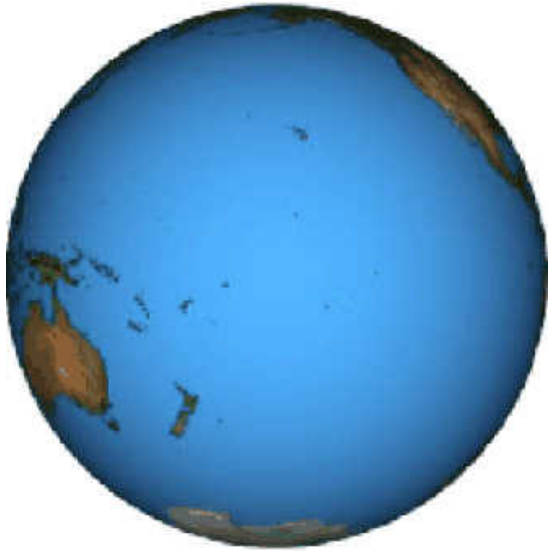


Figure 62 Rigidity in Space

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Precession

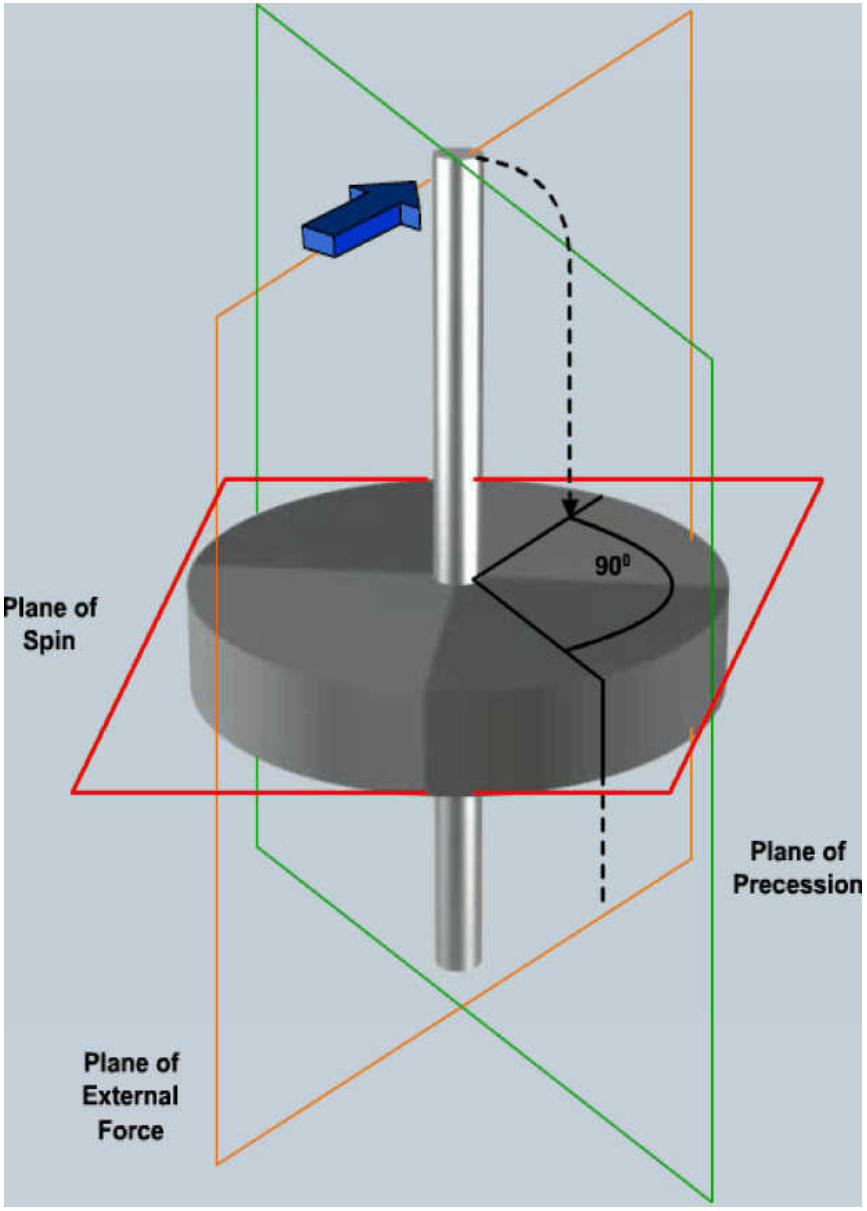
The other property of a spinning gyro that concerns us is its right angle obstinacy. It never goes in the direction that you push it, but off to one side. The diagram below illustrates this obstinate characteristics. The rules for anticipating the actual direction of motion from a given applied force are shown below.

Whichever way you apply the force to the axis of a gyro, it will move in a direction 90° (in the direction of rotation) to the force. The speed at which it moves is proportional to the force applied. This action is called precession.

The force of precession is used in rate gyros, such as those in a turn and slip indicator, where the speed of turn is measured by the force that the precessing gyro exerts on a spring.

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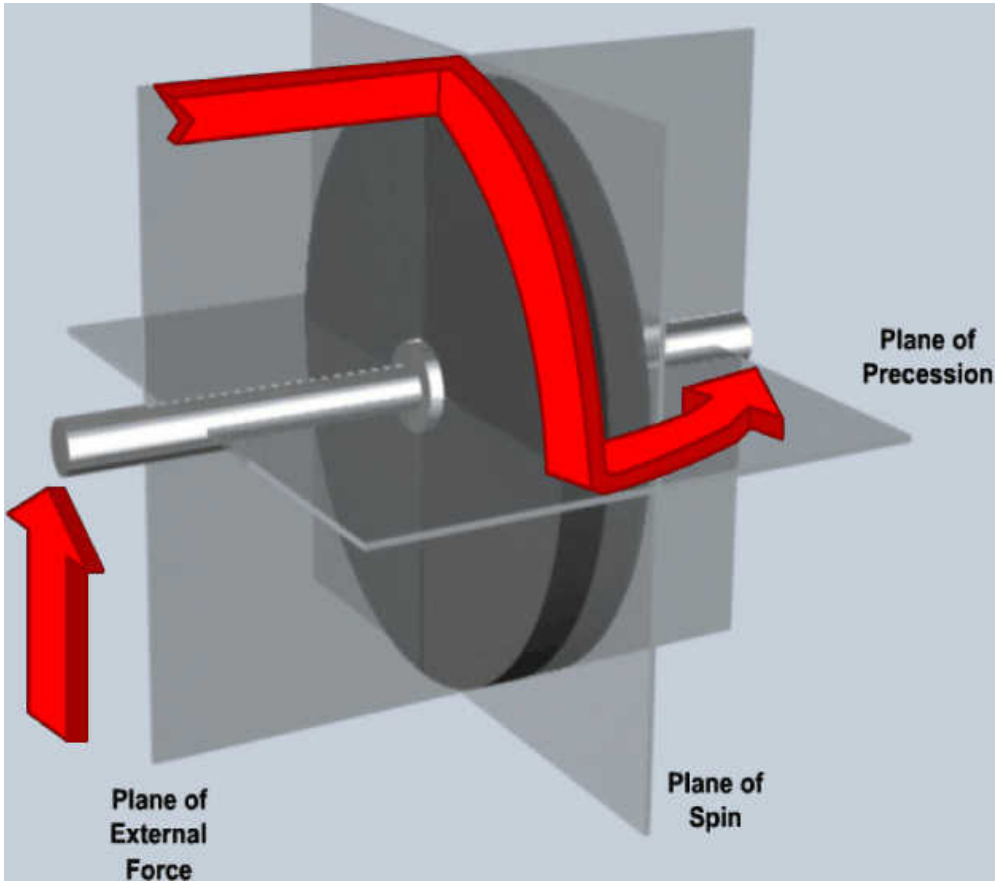


Figure 63 Gyro Precession

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M2.2.4 FLUID DYNAMICS

Specific Gravity and Density

DENSITY

Equal volumes of different substances vary considerably in their mass.

For instance aircraft are made chiefly from aluminium alloys which, volume for volume, have a mass half that of steel, but are just as strong. The lightness or heaviness of a material is referred to as its **density**.

The density of a substance is its mass per unit volume. The density of solids and liquids varies with temperature. However, the density of a gas varies with temperature and pressure. To find the density of a substance, divide the mass of the substance by its volume.

Symbol and Unit

The symbol for quantity is ρ (greek small rho).

The kilogram per cubic meter (kg/m^3) is the SI unit of density.

Formula

Density = ρ

Mass = m

Volume = V

$$\text{Density } (\rho) = \frac{Mass}{Volume} \text{ kg/m}^3 \text{ or g/cm}^3$$

Other algebraic forms of this same equation are:

$$m = \rho V \quad \text{or} \quad V = \frac{m}{\rho}$$

Example

The liquid which fills a certain container has the mass of 326,4 t and weighs 3.2 MN (Meganewton).

The container is 4 m long, 3 m wide and 2 m deep. Therefore its volume is 24 cubic meters.

Based on this the liquids density is 13 600 kg/m^3

$$13\ 600 \text{ kg/m}^3 = \frac{326400\ kg}{24\ m^3}$$

Because the density of solids and liquids vary with temperature, a standard temperature of 4 °C is used when measuring the density of each. Although temperature changes do not change the volume of a substance through thermal expansion or contraction. This changes a substances weight per unit volume.

When measuring the density of a gas, temperature and pressure must be considered. Standard conditions for the measurement of gas density is established as 0 °C and a pressure of 1013 hPa (29.92 inches of mercury column) which is the average pressure of the atmosphere at sea level.

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SPECIFIC GRAVITY

It is often necessary to compare the density of one substance with that of another. For this reason, a standard is needed from which all other materials can be compared. The standard when comparing the densities of all liquids and\solids is water at 4 °C.

The standard for gases is air.

In physics the word “specific” refers to a ratio. Therefore, specific gravity is calculated by comparing the weight of a definite volume of substance with the weight of an equal volume of water. This is why “Specific Gravity“ is also called “Reative Density“.

Symbol

The symbol for quantity is *RD*.

Formula

The following formulas are used to find specific gravity (sp. gr.) of liquids and solids.

$$RD = \frac{\text{Weight of a Substance}}{\text{Weight of equal volume of Water}}$$

$$RD = \frac{\text{Density of a Substance}}{\text{Density of Water}}$$

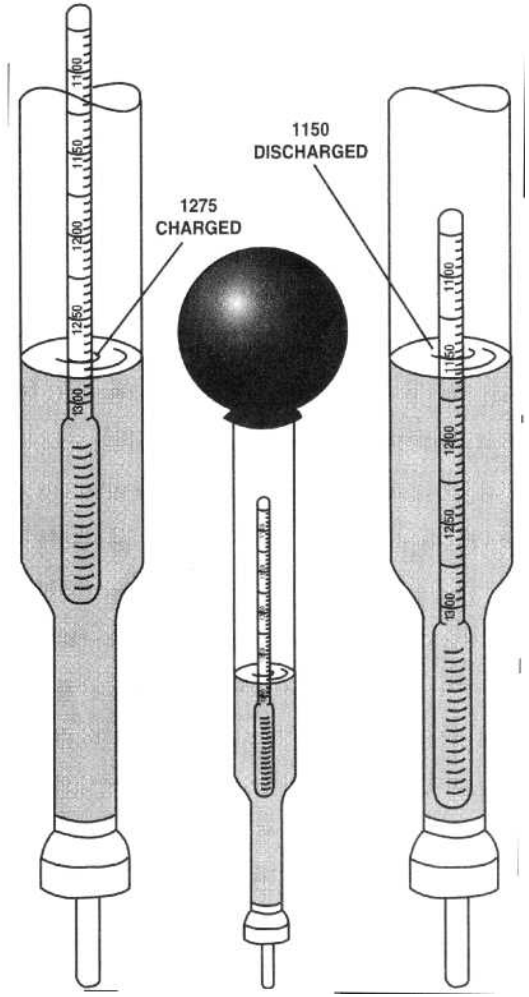
The same formulas are used to find the density of gases by substituting air for water. Specific gravity is not expressed in units, but as a pure number.

Hydrometer

A device called a hydrometer is used to measure the specific gravity of liquids. This device has a tubular shaped glass float contained in a larger glass tube.

The float is weighted and has a vertically graduated scale. The scale is read at the surface of the liquid in which the float is immersed. A reading of 1000 is shown when the float is immersed in pure water.

When filled with a liquid having a density greater than pure water, the float rises and indicates a greater specific gravity. For liquids of lesser density, the float sinks below 1000.



The specific gravity of a liquid is measured with a hydrometer.

Figure 64 Hydrometer

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Density and Specific Weight Tables

Density

The table shows some examples for the density ρ of various materials.

Liquids	kg/m³	slug/ft³
Water	1000	1.940
Sea Water	1030	2.00
Benzine	879	1.71
Alcohol	789	1.53
Gasoline	680	1.32
Kerosene	800	1.55
Sulpuric Acid	1831	3.55
Mercury	13600	26.3

Metals	kg/m³	slug/ft³
Aluminium	2700	5.25
Cast Iron	7200	14.0
Copper	8890	17.3
Gold	19300	37.5
Lead	11340	22.0
Nickel	8850	17.2
Silver	10500	20.4
Steel	7800	15.1
Tungsten	19000	37.0
Zinc	7140	13.9
Brass	8700	16.9

Woods	kg/m³	slug/ft³
Balsa	130	0.25
Pine	480	0.93
Maple	640	1.24
Oak	720	1.4
Ebony	1200	2.33

Non–Metals	kg/m³	slug/ft³
Ice (32°F, 0°C)	922	1.79
Concrete	2300	4.48
Glass	2,600	4.97
Granite	2700	5.25

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Specific Weight

The table shows some examples for the specific weight γ of various materials.

Weight Densities at 20°C/ 68°F		
Liquids	**kN/m³**	**lbf/ft³**
Water	9,807	62.4
Ocean Water	10,100	64.4
Benzene	8,620	54.9
Carbon Tetrachloride	15,630	99.5
Ethyl Alcohol	7,740	49.3
Gasoline	6,670	42.5
Kerosene	7,850	49.9
Lubricating Oil	8,830	56.2
Methyl Alcohol	7,770	49.4
Sulfuric Acid 100%	17,960	114.3
Turpentine	8,560	54.5

Weight Densities at 20°C / 68°F		
Nonmetallic Solids	**kN/m³**	**lbf/ft³**
Ice	9,040	57.5
Concrete	22,600	144
Earth, packed	14,700	94
Glass	25,500	160
Granite	26,500	169

Weight Densities at 20°C / 68°F		
Solid Metals	**kN/m³**	**lbf/ft³**
Aluminum	26,500	169
Cast Iron	70,600	449
Copper	87,200	555
Gold	189,300	1,205
Lead	111,200	708
Magnesium	17,100	109
Nickel	86,800	553
Silver	103,000	656
Tungsten	186,000	1,190
Zinc	70,000	446

Weight Densities at 20°C / 68°F		
Woods	**kN/m³**	**lbf/ft³**
Balsa	1,270	8
Pine	4,700	30
Maple	6,300	40
Oak	7,100	45

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Pressure

General

Pressure is defined as the force divided by the area on which the force acts. For example, the pressure exerted on the ground by a body depends on the area of the body in contact with the ground. A person wearing ice skates will exert a far greater pressure than a person wearing shoes.

Formula

The equation defining presssure is:

$$Pressure = \frac{Force}{Area} \text{ or } Force = Pressure \times Area$$

Example

On a day when the atmosphere pressure is 1020 hPa, what is the force acting on a desk top having an area of 2,5 m^2 ?

$Force = Pressure \times Area$ = 1020 hPa x 2,5 m^2

Force = 102 kPa x 2,5 m^2

F = 102 kN/m^2 x 2,5 m^2

F = 102 kN x 2,5

F = 255 kN

The molecules making up a gas are in ceaseless motion. They collide and rebound from any solid surface which they encounter. These collisions result in a net push or force on the surface. As we have said, this force, divided by the area of the surface over which it is exerted, is called pressure.

Atmospheric Pressure

On our earth, we live under a blanket of air. The density of air decreases with altitude.

At sea level, the average atmospheric pressure is 101,3 kPa, commonly written as 1013 hPa. This is 14.7 lbf/in^2. Various types of barometers are used to measure atmospheric pressure.

The mercury barometer is a narrow vertical glass tube which is inverted in a dish of mercury. The small space above the mercury column is a perfect vacuum. As the air molecules bombard the surface of the mercury in the dish, they balance the mercury in the column since there are no bombarding molecules above the mercury in the column. The height of the mercury column varies slightly from day to day as the atmospheric pressure changes.

At standard pressure (14.7 lbf/in^2) the mercury column is 760 mm high. In the English system the height of the mercury column is 29.92 inches. Sometimes we use the height of mercury (Hg) column as a unit for stating pressure.

We can say:

1 Atmosphere = 1013 hPa = 14.7 lbf = 760 mmHg = 29.92 inHg

NOTE: Since mercury expands with an increase in ambient temperature, the barometer must be corrected to that which it would read at the accepted value of room temperature 20 °C or 68 °F

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Absolute & Gauge Pressure

All of the pressure measuring instruments which the aircraft mechanic is likely to use are designed to register the extent to which the pressure being measured differs from the ambient pressure. The term “ambient pressure” refers to the pressure in the area immediately surrounding the object under study.

For example, a tyre gauge registering 32.0 psi is telling us that the pressure inside the tyre is 32.0 psi greater than the pressure outside the tyre. On a day when the atmospheric pressure is 1006 hPa (14.6 psi), the actual pressure the gas is exerting on the inner walls of the tyre is 46.6 lbf/in^2 (32.0 + 14.6).

The actual pressure the gas is exerting on the walls of its container is called the absolute pressure. The general relation which connects gauge pressure, absolute pressure and atmospheric pressure is:

$$P_{abs} = P_g + P_{atm}$$

The zero on the absolute pressure scale is the pressure exerted by a perfect vaccuum.

Let assume that the atmoshepric pressure on a certain day is 15 psi (15 $lbf/in^{2)}$. The table below gives the gauge pressure and the absolute pressure for several different examples.

The equation $P_{abs} = P_g + P_{atm}$ is satisfied in each entry.

	Absolute Pressure lbf/in^2 (psi)	**Gauge Pressure lbf/in^2 (psi)**
Inside a tyre	49	34
Pressure cooker	35	20
Outside air	15	0
Cabin pressure of an a/c	11	–4
Perfect vacuum	0	–15

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Static, Dynamic and Total Pressure

General

Gravity, applied forces and atmospheric pressure are static factors that apply equally to fluids at rest or in motion, while inertia and friction are dynamic factors that apply only to fluids in motion.

STATIC PRESSURE

The mathematical sum of gravity, applied force, and atmospheric pressure is the static pressure obtained at any one point in a fluid at any given time.

Static pressure exists in addition to any dynamic factors that may also be present at the same time.

DYNAMIC PRESSURE

Remember, Pascal's Law states that a pressure set up in a fluid acts equally in all directions and at right angles to the containing surfaces. This covers the situation only for fluids at rest or practically at rest. It is true only for the factors making up static head.

Obviously, when velocity becomes a factor it must have a direction, and as previously explained, the force related to the velocity must also have a direction, so that Pascal's law alone does not apply to the dynamic factors of fluid power.

TOTAL PRESSURE

The dynamic factors of inertia and friction are related to the static factors. Velocity head and friction head are obtained at the expense of static head.

However, a portion of the velocity head can always be reconverted to static head.

Force, which can be produced by pressure or head when dealing with fluids, is necessary to start a body moving if it is at rest, and is present in some form when the motion of the body is arrested; therefore, whenever a fluid is given velocity, some part of its original static head is used to impart this velocity, which then exists as velocity head.

Example 1

In the figure below, you see the static air pressure which lasts on the roof of a house. This is caused by the gravity which pulls on the air which is directly above the house.

Since there is also air inside the house, there is a counterpressure.

If there was a vacuum inside the house, the column of air would bend the roof downwards. The mass of the air column is about 10 000 kg on one square meter.

Example 2

Imagine a hermit crab housing in a snail shell.

The static pressure on his house is caused by the water column above.

Since there is also water inside the shell and inside the crab's body, there is a counterpressure.

When animals are pulled out of the deep sea, they explode because the static pressure is decreased rapidly around them.

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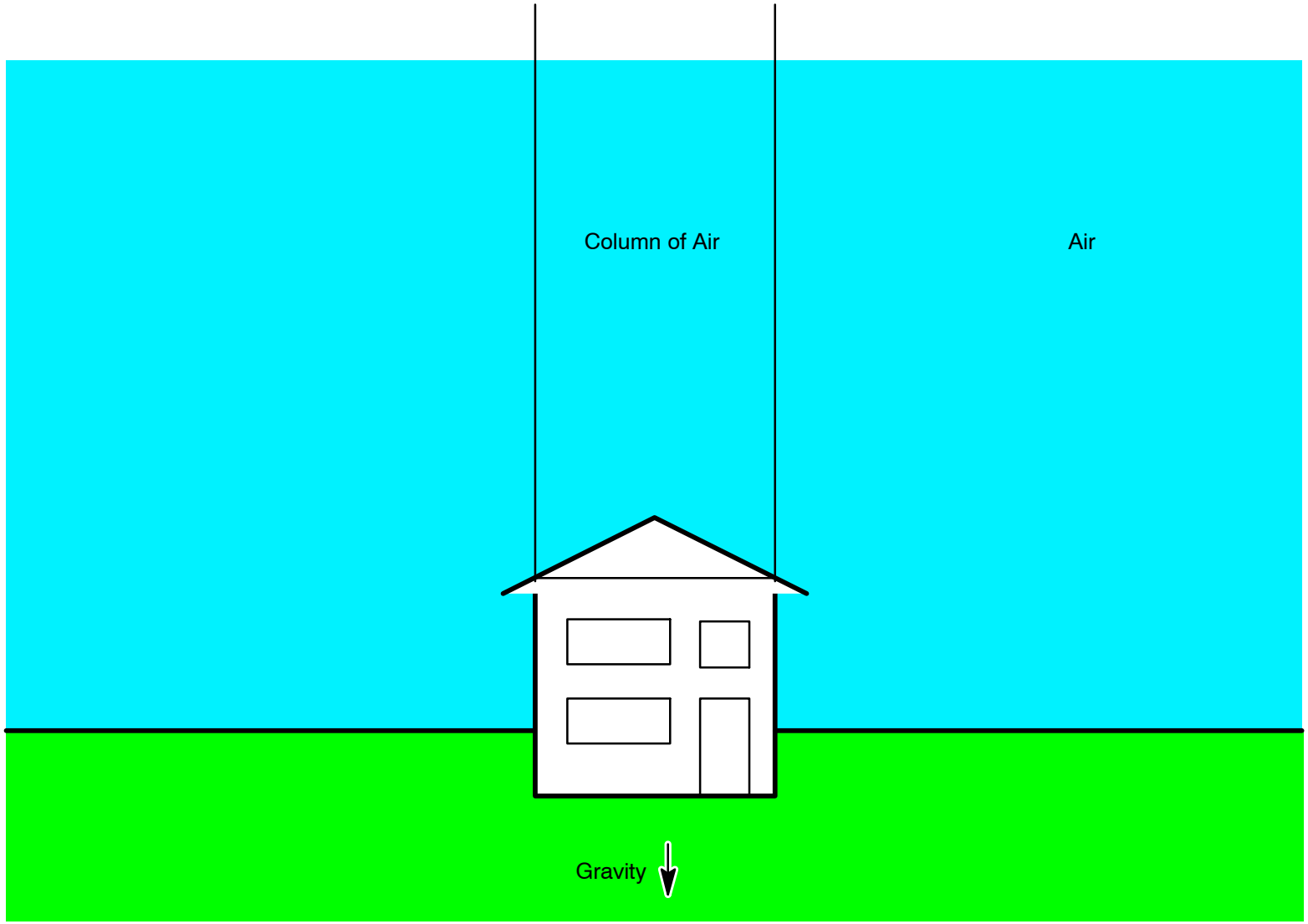


Figure 65 Static Pressure

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Effects of Compressibility on fluids

General

The term compressibility is used when an increase in pressure will result in a decrease of volume of the affected material.

In fluids, however, the compressibility is extremely low. Thus, an increase of pressure in fluids will have nearly no change in volume.

Pressure in Fluids

There are two ways to increase the pressure of fluids:

- A kind of vat.

  Gravity pulls all molecules of the fluid down. The lower the portion which is looked at, the higher is the pressure. Example: an ocean is a big vat.
- A closed container and a force which tries to decrease the volume of that container.

  Example: a cylinder and an appropriate piston within.

Compressibility

For each fluid, there is a contant factor to calculate the volume change caused by pressure. This is the compressibility.

Symbol and Unit

The symbol for Compressibility is typically β (in Germany, the symbol is κ).

The unit is m^2/N or 1/Pa.

Formula

With the help of the compressibility, the change of volume caused by a change of pressure is calculated like this:

$$-\Delta V = \beta \times V \times \Delta p$$

The negative value is due to the decrase of volume when the pressure increases.

Example 1

A cylinder is filled with fluid. When a piston is moved downwards with the force F, the piston will move the distance d.

When you know the diameter of the cylinder, you can calculate the change in volume. This is ΔV.

Example 2

When you know the compressibility of the fluid, the total volume and the change in pressure, you can use the formula. Then you also get ΔV.

With ΔV calculated and knowing the diameter of the cylinder, you can calculate the distance d.

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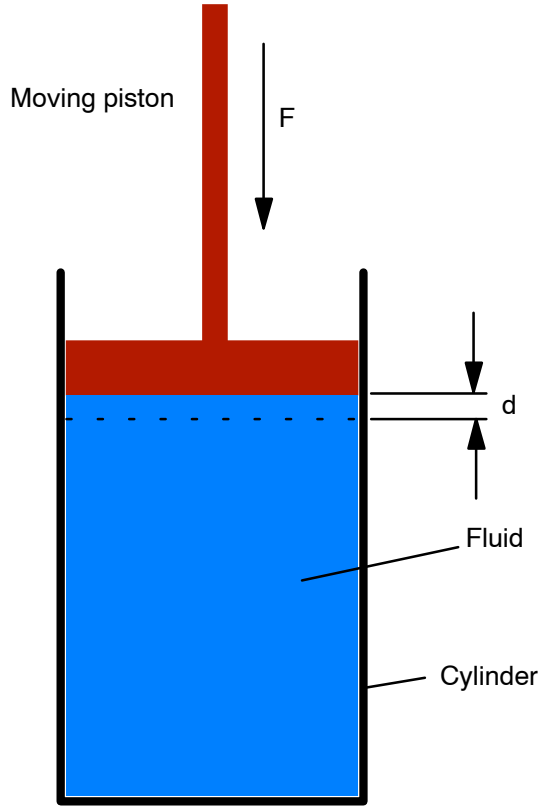


Figure 66 Compression of Fluids

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Viscosity

General

The factor which most affects the behavior of a fluid in motion is the viscosity of the fluid. This is the fluid's own resistance to flow and is due to internal friction within the fluid. In a liquid this internal friction is caused by intermolecular attraction and in a gas it is caused by the interchange of molecules between the different layers.

The viscosity of the fluid will be influenced by the temperature, normally the hotter the liquid becomes, the lower the viscosity. This is called a positive coefficient of viscosity.

A few materials have a negative coefficient of viscosity and increase their viscosity with temperature.

Fluid Flow

The fluid can flow in different ways depending on the shape of the duct in which it is contained and on the viscosity of the fluid.

If the flow is disorderly then the speed and direction of the particles passing a particular point will be constantly changing, this is known as **Turbulent Flow**.

If the flow is steady then all the particles passing a particular point will have the same direction and speed. This is known as **Steady Flow**.

Laminar Flow

This is an example of a type of steady flow where the particles of a particular streamline all travel at the same speed but each adjacent streamline is travelling at a different speed. This is due to the viscosity of the fluid. For example, if a fluid is flowing next to the skin of an aircraft then the layer of air next to the skin will not be moving at all relative to the skin. The next layer will be moving at a low velocity, the next layer slightly faster and so on until the full, free stream velocity is reached. This arrangement is normally the most desirable on an aircraft because it causes the least air resistance (drag) on the aircraft. For this reason, the aircraft is made with a smooth shape to encourage laminar flow, this smoothing of the shape is called **streamlining**.

In the diagrams below we can see examples of laminar flow inside a duct. The effect of the fluid's viscosity can be seen as the layer immediately adjacent to the wall of the duct is not moving at all and each subsequent layer is moving a little faster. The more viscous the fluid then the greater this effect would be.

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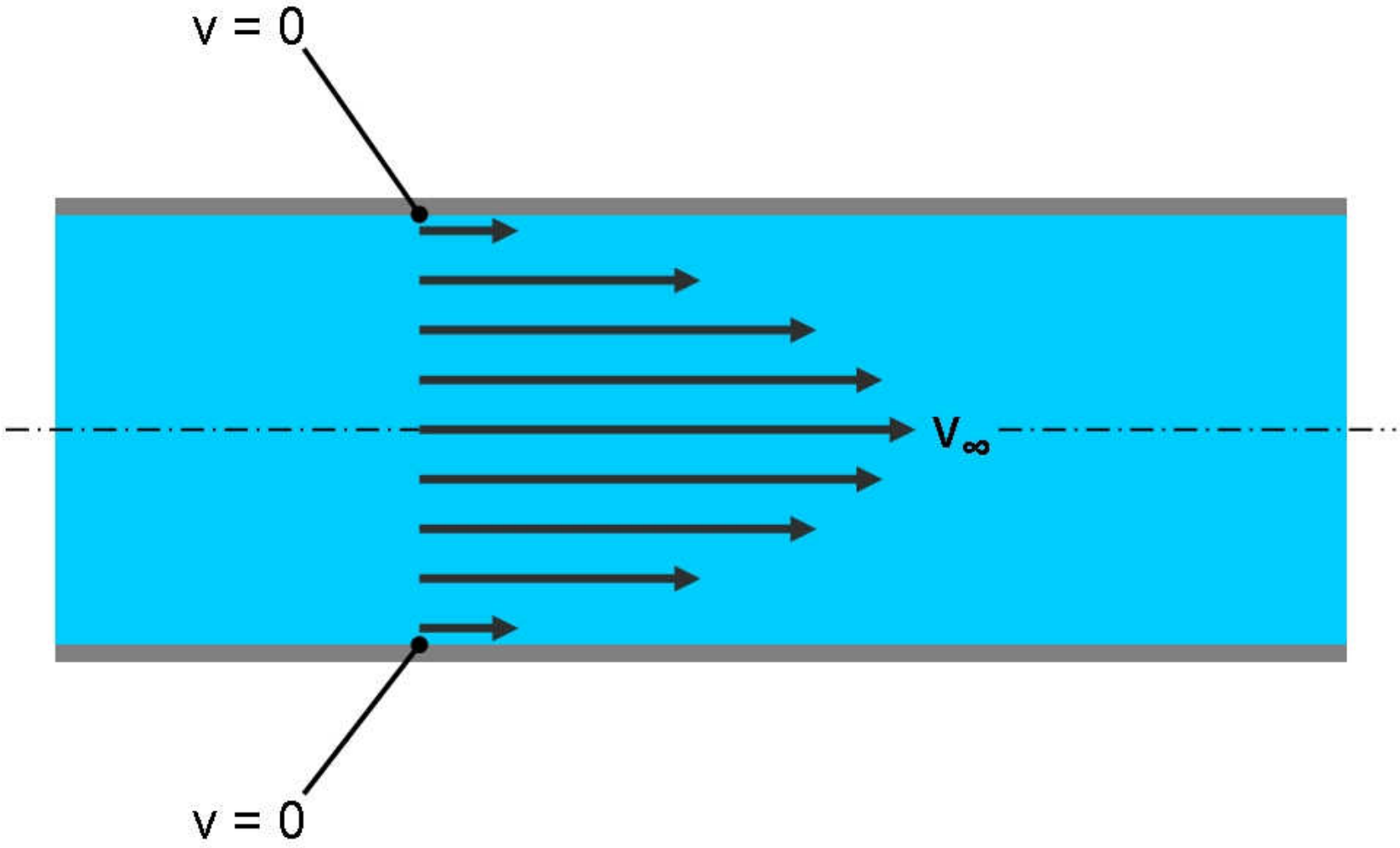


Figure 67 Longitudinal Cut of Fluid Flow Showing Laminar Flow in a Circular Duct

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Fluid Resistance and Effects of Stramlining

General

When a car is on the highway, its speed is not only limited by speed limits. The maximum speed is reached when the engine performs maximum power, but the forces of friction and drag have the same value. Thus, further acceleration is not possible.

In this case, drag is the air resistance.

FLUID RESISTANCE

On a ship or a submarine, speed is also limited by the drag.

In this case, drag is the fluid resistance.

In fluids, the following factors are important for the calculation of fluid resistance:

- size of the object
- form of the object
- density of the fluid

Additionally, the drag incrases with the square of velocity.

Symbol and Unit

Fluid resistance is a kind of force. The symbol for quantity is F_d.

The newton (N) is the SI unit of force.

Formula

To calculate the force of drag F_d you need the following factors:

- size of the object (reference area) **A**
- form of the object which results in a coefficient of drag $\mathbf{C_d}$
  This is a dimensionless parameter and thus it has no unit.
- density of the fluid ρ
- speed of fluid or object in fluid **v**

With everything in a correct relation the formula is as follows:

$$F_d = \frac{1}{2} \cdot \rho \cdot v^2 \cdot C_d \cdot A$$

STREAMLINING

Normally, a sports car is stramlined and an old van is not. The reason is, that a sports car is bought by people who want to drive fast. For a given engine power, a low drag is a means to increase the maximum speed.

The drag depends on the size and the shape of the car.

Thus, when the size of an object is given, the drag can be reduced by streamlining its hull.

The same is true for ships and submarines and any other objects in fluids.

The coefficient of drag C_d is a reslult of the shape of the object.

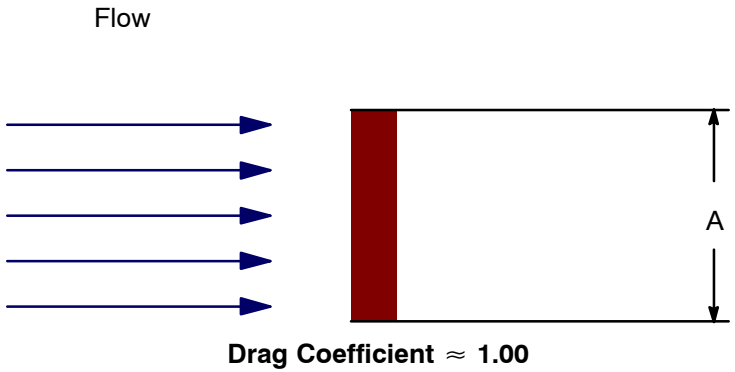
A kind of wall has a great resistance. The resistance is not only caused by the front, but also by the rear. This is because the form of the rear determines the strength of turbulances.

Examples

In the figure below, you see various objects and their drag coefficient.

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Drag Coefficient ≈ 0.28
(Manufacturer: Rumpler, 1928)



Drag Coefficient ≈ 0.3
(Manufacturer: Porsche, 2007)



PT Boat

Figure 68 Drag Coefficient

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Bernoulli's Principle

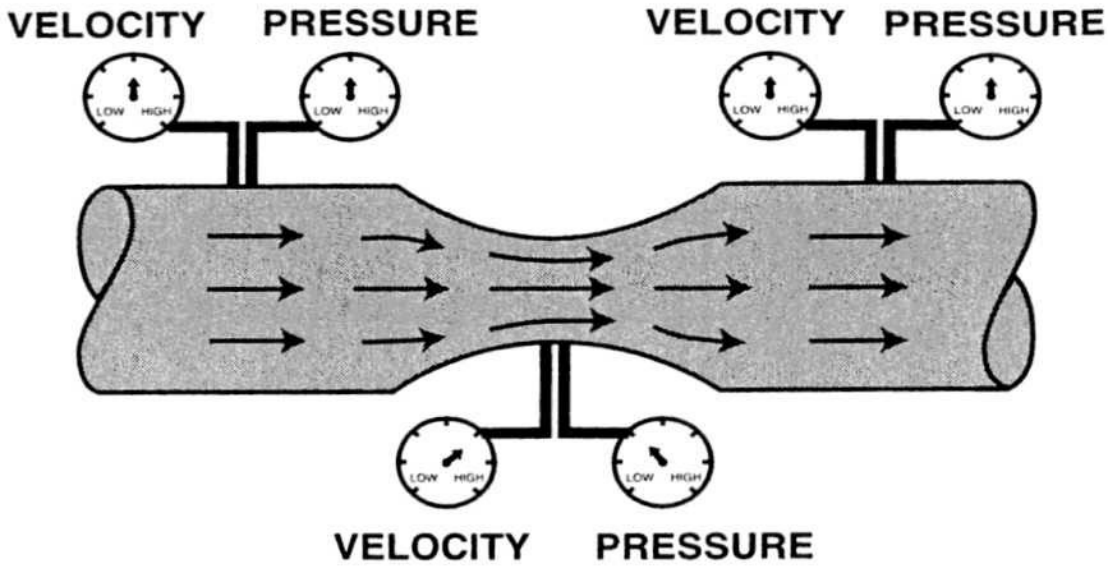
General

The Swiss mathematician and physicist Daniel Bernoulli developed a principle that explains the relationship between potential and kinetic energy in a fluid. As discussed earlier, all matter contains potential energy and/or kinetic energy. In a fluid, the potential energy is that caused by the pressure of the fluid, while the kinetic energy is that caused by the fluids movement.

Although you cannot create or destroy energy, it is possible to exchange potential energy for kinetic energy or vice versa.

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Bernoulli's principle states that when energy is neither added to nor taken from a fluid in motion, the potential energy, or pressure decreases when the kinetic energy or velocity increases.

Figure 69 Bernoulli's Principle

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VENTURI

A venturi tube is a specially shaped tube that is narrower in the middle than at the ends.

As fluid enters the tube, it is travelling at a known velocity and pressure. When fluid enters the restriction, it must speed up, or increase its kinetic energy. However, when the kinetic energy increases, the potential energy decreases. Then as the fluid continues through the tube, both velocity and pressure return to their original values.

A venturi tube is a tube constructed in such a way that the cross–sectional area of the tube changes from a larger area to a smaller area and finally back to the same larger area. As a fluid flows through this tube the velocity changes from a lower velocity to a higher velocity and finally back to the same velocity. We note that, if the rate (volume per second) of fluid flow is to remain constant, the fluid must flow faster when it is flowing through the smaller area.

The height of the fluid column in the vertical tubes at the three places shown in the figure below, is an indication of the fluid pressure. As we expect from Bernoulli's Principle, the pressure is greater where the velocity is lower and vice versa. Venturi tubes in different shapes and sizes are often used in aircraft systems.

If we consider the types of energy involved in the flowing fluid, we find that there are three types – potential (gravitational), pressure and kinetic energies. Consider only the two positions in the venturi, the wide part (1) and the narrow section (2), and consider the conservation of energy principle.

Potential Energy at 1		Potential Energy at 2
+		+
Pressure energy at 1	=	Pressure Energy at 2
+		+
Kinetic Energy at 1		Kinetic Energy at 2

The above is assumed since the total energy in the fluid cannot change, only transferred from one form to another. This is the basis for Bernoulli's Formula.

Since the Venturi in this case is horizontal, there is no change in potential energy, and so the potential energies can be cancelled from the formula;

Pressure energy at 1		**Pressure Energy at 2**
+	**=**	**+**
Kinetic Energy at 1		**Kinetic Energy at 2**

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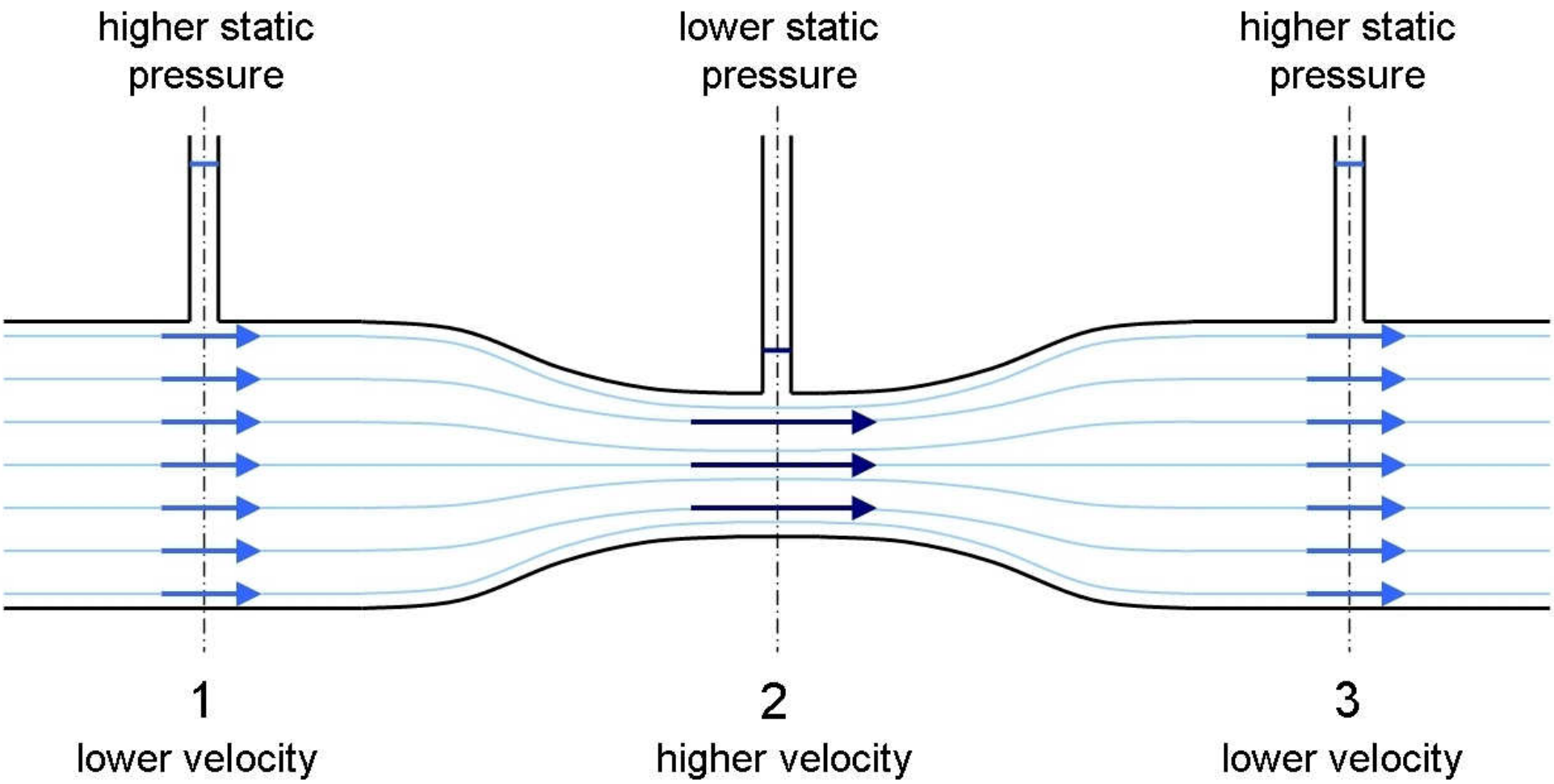


Figure 70 Venturi Tube

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Formula

Since kinetic energy is $\frac{1}{2}mv^2$

where

m = mass of fluid,

v = velocity of fluid

and pressure energy is $m\frac{P}{\rho}$

where

P = pressure,

ρ = density of fluid

Thus:

$$m\frac{P_1}{\rho} + \frac{1}{2}mv_1^2 = m\frac{P_2}{\rho} + \frac{1}{2}mv_2^2$$

note that the mass, m has no suffix since mass flow rate is constant regardless of the area of flow. The density ρ, is also a constant since the fluid is considered incompressible (even air, providing its velocity is subsonic).

Cancelling the mass, m from the equation and multiplying each term by the density, ρ gives:

$$P_1 + \frac{1}{2}\rho v_1^2 = P_2 + \frac{1}{2}\rho v_2^2$$

This is the standard mathematical form of the Bernoulli's equation. It can be rearranged to give the pressure difference.

For example the difference between the upper and lower surfaces of a wing.

$$P_1 - P_2 = \frac{1}{2}\rho v_2^2 - \frac{1}{2}\rho v_1^2$$

Factorizing

$$P_1 - P_2 = \frac{1}{2}\rho\left(v_2^2 - v_1^2\right)$$

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M2.3 THERMODYNAMICS

Temperature

General

Our common notion of hot and cold has its precise expression in the concept of temperature. As objects are heated their molecules move faster. In a solid the molecules vibrate more rapidly. In liquids and gases the molecules move all over in the container at a faster rate of speed. These variations in speed of the molecules cause objects to expand when they are heated.

This expansion can be used to construct instruments called thermometers. The ordinary mercury thermometer uses the expansion of a volume of mercury contained in a bulb to indicate temperature.

Temperature is a SI basic quantity.

Symbol and Unit

The symbol for Temperature is *T*.

The Kelvin (K) is the SI unit of temperature.

TEMPERATURE SCALES

Celsius and Fahrenheit

A number of temperature scales are currently in use.

The metric scale is the Celsius or centigrade scale. On this scale the freezing point of water is zero and the boiling point is 100 °C.

The Fahrenheit scale is used in the imperial system. On this scale the freezing point of water is 32 °F and its boiling point is 212 °F.

Kelvin and Rankin

Two other temperature scales are used by engineering and experimental scientists. In both of these scales the zero of the scale is placed at absolute zero, the coldest possible temperature. These scales are the metric Kelvin scale and the English Rankin scale.

Absolute Zero

In theory, if we cool any substance enough, we can cause all molecular motion to cease. We call this lowest possible temperature “absolute zero”. Ordinary gases like air would be rock soild at this temperature. Low temperature physicists have never been able to reach this extremely low temperature in their laboratories. However, they have come close to a fraction of a centigrade degree. Absolute zero is a limiting temperature which can never be reached. Because to reach it we would need a cooling agent which is colder as zero Kelvin, or “absolute zero“.

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Conversion from Celsuis to Fahrenheit

There are formulas that enable us to change from the Celsius reading to a Fahrenheit reading and vice versa.

These formulas are:

$$C = \frac{5}{9}(F - 32)$$

and in reverse

$$F = \frac{9}{5} + 32$$

Unit	Boiling point of Water	Freezing point of Water	Absolute zero
Celsius	100 deg	0 deg	–273 deg
Kelvin	373	273	0
Fahrenheit	212 deg	32 deg	–460 deg
Rankin	672 deg	492 deg	0 deg

Conversion from Celsuis to Kelvin

There are also formulas that change from a Celsius reading to a Kelvin reading and from a Fahrenheit reading to a Rankin reading.

These formulas are very important to us at this time since we will have to use absolute temperatures in the gas laws.

These formulas are:

K = °C + 273

and in reverse

R = °F + 460

NOTE: Kelvin has no ° sign in front of the K. The accurate conversion factor for °C to K is + 273.15.

Example

20 °C = 293,15 K

Conversion from Fahrenheit to Rankin

The conversion factor for °F to R is: plus 460.

Example

32 °F = 492 R

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Expansion

General

The temperature of a body is a measure of the average kinetic energy of the molecules of that body. It follows that molecules of warm liquids and gases move around faster in their containers than molecules of cool liquids and gases. As a solid is heated its molecules vibrate faster about their equilibrium positions. As a result of this increased motion of molecules as they are heated, solids and liquids expand as the temperature is raised.

If temperature is a measure of how fast things are moving, when a solid heats up, the molecules vibrate about their positions.

At higher temperatures, the molecules vibrate more and the material actually grows in size. When a material is cooled, the molecules do not move as much and the material shrinks.

Jam Jar Lid

Let's look at what happens to materials when they change temperature. For instance, you have a jam jar that's lid is stuck and you want to remove it. One common way is by running the jar under hot water so that the jar lid expands and can come off the jar.

Strip of Metal

If we look at a long strip of metal, with length L_o, we might want to find out what its change in length is under certain conditions. This is important, for instance, in building roads that must undergo temperature extremes. Experimentally, we find that the change in length is directly related to the change in temperature and to the initial length of the bar.

The dependence on the initial length of the bar comes about because there are that many more molecules moving, so the change in length will be greater than that of a shorter bar.

Coefficient

Think back to our jam jar scenario, when you heat the lid, you are also heating the glass, too. Glass does expand but, not at the same rate as the material from which the lid is made. This means that we somehow have to account for the fact that different materials expand or contract by different amounts under the same temperature change.

The way we account for different rates of different materials in our equation is via the "Coefficient of Linear Expansion" (α). α has units of /°C (pronounced per degree Celsius).

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Linear Expansion

A rod of a substance will increase its length for a given temperature change. The increase in length depends on the original length of the rod, the temperature change, and the material of the rod. The increase in size of the object comes about by the fact that an increase in temperature results in an increase in kinetic energy of the molecules or atoms which make up the material. Increasing the movement of the molecules forces it to occupy more space.

We define alpha (α), the coefficient of linear expansion. Tables of values for various substances are found in handbooks of physics.

Formula

The formula is:

$$\Delta L = \alpha \, x \, Lo \, x \, \Delta T$$

In this formula,

Lo = The original length of the rod

α = The coefficient of linear expansion

ΔL = The change in length of the rod

ΔT = The change in temperature

Coefficient of Linear expansion α	
Substance	**per ° C**
Aluminum	23×10^{-6}
Brass	18.4×10^{-6}
Concrete (varies)	10×10^{-6}
Copper	$16{,}5 \times 10^{-6}$
Glass (pyrex)	3.2×10^{-6}
Ice	51×10^{-6}
Iron	12.2×10^{-6}
Lead	29.3×10^{-6}
Steel	13×10^{-6}

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Expansion Details

AREA EXPANSION

Two dimensional solid bodies experience thermal area expansion.

The formula is as follows:

$$\Delta A = 2\,\alpha\,Ao\,\Delta T$$

In this formula,

Ao = The original area of the rod

α = The coefficient of linear expansion

ΔA = The change in area of the body

ΔT = The change in temperature

VOLUMETRIC EXPANSION

Three dimensional solid bodies experience volume expansion.

The formula is as follows:

$$\Delta V = 3\,\alpha\,Vo\,\Delta T$$

In this formula,

Vo = The original volume of the rod

α = The coefficient of linear expansion

ΔV = The change in volume of the body

ΔT = The change in temperature

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Liquids and Gases

General

Our expression for the thermal expansion of solids only works for solids.

Neither liquids or gases have a fixed shape when left on their own. The expression also fails if you have to consider the expansion of a solid in all directions.

Liquids

Liquids also experience thermal expansion. Normally, liquids expand more than solids. For this, there is a coefficient.

Coefficient

Beta (β) is called the coefficient of volume.

For solids, β is approximately equal to 3α. This is true only when the change in volume is small compared to the original volume. The problem is that for liquids and gases, β is very large and this formula sometimes will not work.

Formula

$$\Delta V = \beta \, Vo \, \Delta T$$

Table

There are also tables of the coefficient of volume expansion.

Coefficient of Volume Expansion	
Liquids	**per K**
Mercury	0.182×10^{-3}
Methanol	1.1×10^{-3}
Benzene	1.06×10^{-3}
Gasoline	0.95×10^{-3}

Gases

Generally liquids expand more than solids, and gases much more than liquids, for any given change in temperature. This is because the molecules of liquids are not tied to each other and have more room and freedom to vibrate than do the molecules or atoms in solids.

The molecules of gases of course are completely free to move, and will move much more vigorously when heated than either solids or liquids.

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The Interesting Case of Water

Most materials expand when heated and contract when cooled. Water is an exception. between 0 °C and 4 °C, water actually expands when cooled. Above this range, it behaves normally. Water therefore has its greatest density at 4 °C. This turns out to be quite important for things that live underwater. In the winter, you notice that the top of the pond always freezes first. As the temperature decreases, there is a temperature gradient in the water.

The top will cooler than the bottom because it is in contact with the cold air. When the water on top of the lake reaches 4 °C, it becomes denser and sinks to the bottom of the lake, being replaced by warmer water from the bottom. The water that is now on top cools to 4 °C, and so on, until the whole lake is at 4 °C.

The surface water cools even more, but now it is less dense than the water below it, so it stays on top of the lake and turns to ice (which is even less dense than cold water). If the ice sank instead of floating, the lake would freeze all the way through and pretty much everything inside would die. The layer of ice additionally acts as an insulator, keeping the rest of the water away from the surface and the colder environment.

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Heat Definition

General

We recall that temperature is a measure of the average kinetic energy, and therefore the average velocity, of the molecules of the substance whose temperature is being measured.

Energy

Heat is a measure of the total energy of molecular motion. The more molecules that are moving, the greater is the heat energy.

Example 1

Let us compare a teaspoon of water at 90 °C with a cup of water at 50 °C. The molecules of water in the teaspoon are moving faster than the molecules of water in the cup. However, since we have so many more molecules in the cup, the heat energy in the cup is greater than the heat energy in the teaspoon.

If the teaspoon of water is placed on a large block of ice and the cup of water also placed on the this block of ice, the cup of water at 50 °C would melt more ice than the teaspoon of water at 90 °C.

Example 2

In the figure below, you see some objects. They have all the same temperature.

But when they have a different mass, then the objects with the bigger mass have more heat.

Symbol and Unit

The symbol for Heat is *Q*.

The Joule (J) is the SI unit of heat.

Reminder

One Joule is the work done by a force of one Newton acting through a distance of one meter.

Thus: 1 Nm = 1 J

Other Units

There are older units for measuring heat energy.

The units are the Btu (British Thermal unit) and the metric units are Calorie (C).

1 British Thermal unit (Btu) = the amount of heat needed to raise the temperature of 1lb of water 1 °F

1 Calorie = the amount of heat needed to raise the temperature of 1 kilogram of water 1 °C.

(Note: 1 Calorie = 1 Kcal = 4186 J, 1 Btu = 0,252 Cal)

1 calorie = the amount of heat needed to raise the temperature of 1 gram of water 1 °C 1 Celsius Heat Unit (CHU) = the amount of heat needed to raise the temperature of 1lb of water 1 °C

NOTE: The CHU is a mix of English and Metric units and is rarely used

When we talk about the heat content of fuel (which must be burnt to be released) commonly called the heat of combustion, we talk about Calories per lb of fuel, or Btu per lb of fuel, or Joules per kg of fuel.

Since 1 Btu = 252 calories and

1 cal = 4.186 Joules,

there are 1055 joules in 1 Btu.

Since 1 lb = 0.454 kg,

1 Btu/lb = 480 J/kg.

We note that the calorie is the famous dietary Calorie. The body stores excess food as fat and we measure the Calories in a certain foodstuff by burning these foodstuffs and measuring the heat produced.

In the solution to heat problems, we will limit our discussion to the English system, since this is the system that is most often used in our society.

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Figure 71 Objects with Heat

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Heat Capacity and Specific Heat

General

As heat is added to a body its temperature increases. However, the same amount of heat added to a piece of aluminium and a piece of copper will not produce the same temperature change.

Aluminium and copper have different “specific heats”.

Since there are two equations, (depending on whether you are using Imperial or Metric units) there are also two sets of Specific Heat capacity constants.

It is important to note that the equation deals with substances that are not changing their states of matter. Another equation will deal with heat added or lost as body changes from one state (solid, liquid or gas) to another.

Metric Equation

$$Q = m\,C\,\Delta T \text{ (metric)}$$

In this equation:

Q = heat gained or lost (J)

m = mass of the body (kg)

C = the specific heat of the substance (J/kg ˚C)

ΔT = the temperature change (˚C or ˚K)

Imperial Equation

The important equation is the following:

$$Q = w\,C\,\Delta T \text{ (imperial)}$$

In this equation:

Q = heat gained or lost (Btu)

w = weight of the body (lb)

C = the specific heat of the substance (J/kg ˚F)

ΔT = the temperature change (˚F or ˚R)

Example

How much heat must be supplied to raise the temperature of 2 kg aluminium fitting from 20 ˚C to 30 ˚C?

$$Q = m\,C\,\Delta T$$

Q = 0,912 kJ/kg x 2 kg x 10 ˚K

Q = 18,24 kJ.

A difference of 1 ˚C is the same as a difference of 1 K.

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Specific Heat Capacities		
Liquids	**kJ/kg K**	**Btu/lb F**
Acetic Acid	2.13	0.51
Alcohol	2.93	0.70
Ammonia	0.47	0.11
Paraffin	2.14	0.51
Petroleum	2.09	0.50
Turpentine	1.98	0.33
Fresh Water	4.19	1.00
Sea water 4C	3.94	0.93

Specific Heat Capacities		
Metals	**kJ/kg K**	**Btu/lb F**
Aluminium	0.912	0.212
Copper	0.389	0.093
Gold	0/130	0.031
Iron	0.460	0.110
Lead	0.130	0.031
Mercury	0.138	0.033
Nickel	0.452	0.108
Platinum	0.134	0.032
Silver	0.234	0.056
Tin	0.230	0.055
Zinc	0.393	0.094
Solids		
Asbestos	0.84	0.20
Ashes	0.84	0.20
Asphalt	0.80	0.19
brick	0.92	0.22
Carbon	0.71	0.17
Coal	1.31	0.314
Coke	0.85	0.203
Concrete	1.13	0.27
Cork	2.03	0.485
Glass	0.84	0.20
Granite	0.75	0.18
Ice	2.11	0.504
Wood	2.3 – 2.7	0.55 – 0.65

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Heat Transfer

General

When warm bodies and cool bodies are mixed heat exchange occurs. The heat lost by the hot body equals the heat gained by the cold body:

Heat Lost = Heat Gained

On each side of this equation there is a $Q = w\,C\,\Delta T$ term. In writing an expression for ΔT, we always express this change as the larger temperature minus the smaller temperature.

Example

If 5 000 kg of water at 38 °C are mixed with 7000 kg of water at 4 °C, what is the final temperature of the mixture?

Note, if the final temperature is T, the temperature 38 °C is more than T and the temperature 4 °C is less than T. Therefore the temperature change of the first amount of water water is (38 – T) and the temperature change of the other is (T – 4).

Heat Lost = Heat Gained

In setting up $w\,C\,\Delta T$ left and right members of the above equation, we will not include the units. However, we will note that the weights must be in kg and the temperature changes in Celsius degrees (C).

5 000 x (38 – T)	= 7000 x (T – 4)	
190 000 – 5000 T	= 7000 T – 28 000	| + 28 000
218 000 – 5000 T	= 7000 T	| + 5000 T
218 000	= 12 000 T	| : 12 000
18.17	= T	

The temperature of the mixture is about 18.2 °C.

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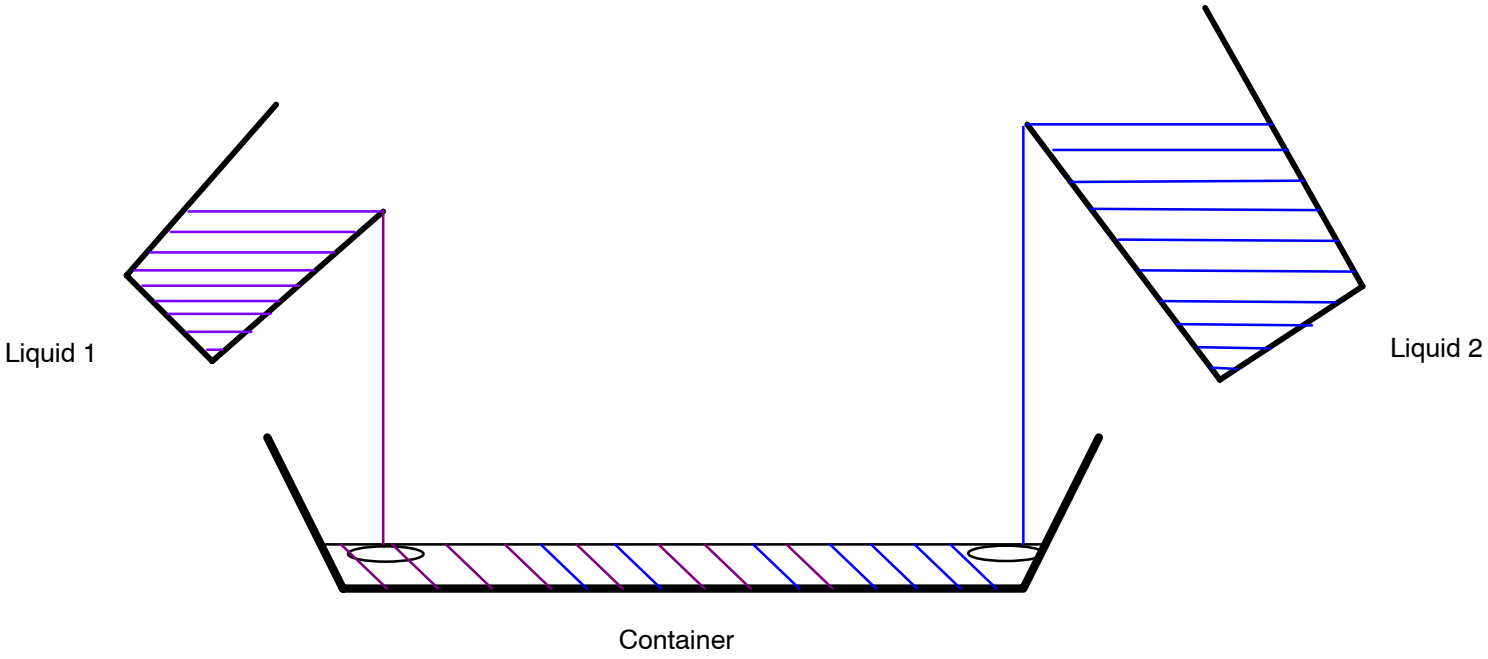


Figure 72 Mixture

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Convection, Radiation and Conduction

General

Heat can be transferred from one place to another by one or more of the following processes:

- Convection
- Conduction
- Radiation.

Convection

Convection is the transfer of heat energy in a gas or liquid by movement of currents.

Examples:

Heat leaves a coffee cup as the currents of steam and air rise.

Think of air and water currents (it can also happen in some solids, like sand). The heat moves with the fluid.

Consider this; convection is responsible for making macaroni rise and fall in a pot of heated water. The warmer portions of the water are less dense and therefore, they rise. Meanwhile, the cooler portions of the water fall because they are denser.

Conduction

Conduction is the transfer of energy through matter from particle to particle. It is the transfer and distribution of heat energy from atom to atom within the substance.

Example:

A spoon in a cup of hot soup becomes warmer because heat from the soup is conducted along the spoon. Conduction is most effective in solids, but it can happen in fluids.

Have you ever noticed that metals tend to feel cold? They only feel cold because they conduct heat away from your hand. You perceive the heat that is leaving your hands as cold.

Radiation

Radiation is electromagnetic waves that directly transport energy through space.

Example:

Sunlight is a form of radiation that is radiated through space to our planet at the speed of light without the aid of fluids or solids. The energy travels through nothingness. Because there is no solids touching the sun and our planet, conduction is not responsible for bringing heat to Earth. Since there are no fluids in space, convection is not responsible.

Thus, radiation brings heat to our planet.

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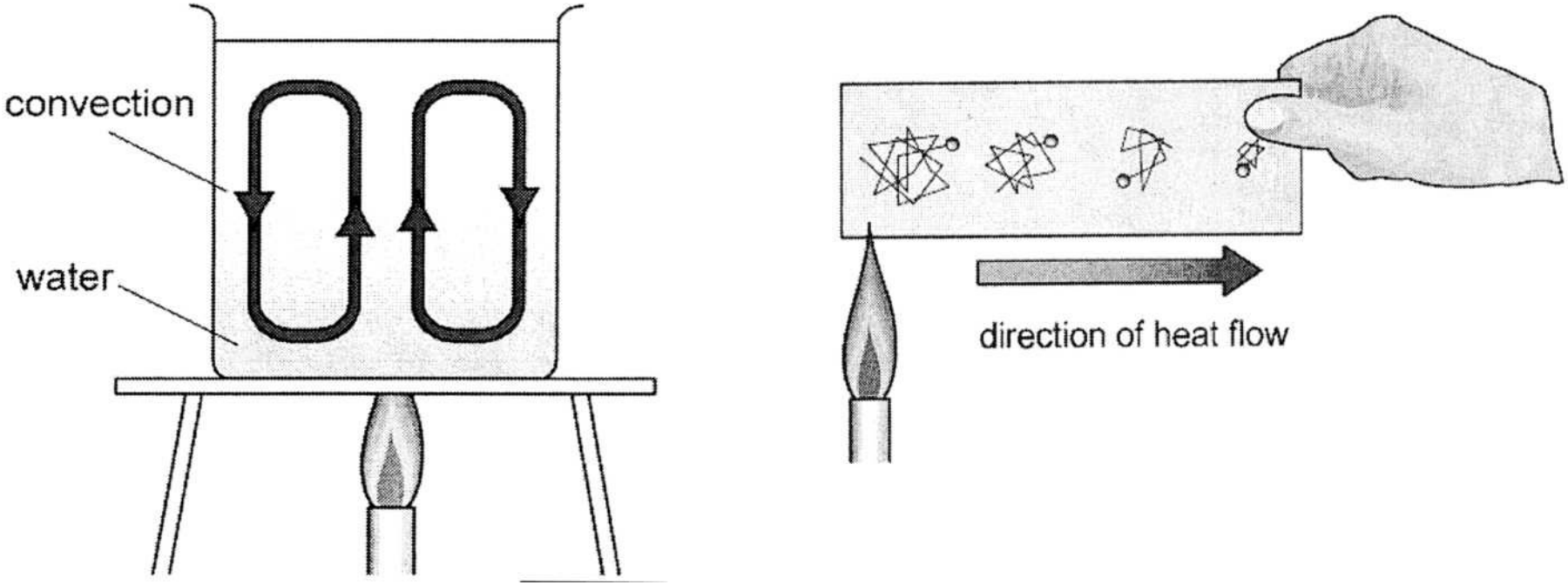


Figure 73 Heat Transfer

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Thermal Conductivity

General

We know that heat flows through insulting materials from the warm side to the cool side. It is possible to predict how many Joule will flow through a given insulator in a given amount of time.

The thermal conductivity differs between the materials.

Pressure and environmental temperature can have influence on the thermal conductivity of many materials.

Symbol and Unit

The symbol is κ (kappa).

The unit is watts per kelvin per meter and is written W/(m K). $\frac{W}{m \cdot K}$

Please remember that 1 W = 1 J/s

Calculation

This equation is less difficult than it seems at first. We will carefully define each symbol.

Q = heat flow in J (Joule)

t = time in hours

A = the surface area of the insulation in square meters

ΔT = the temperature difference in K (Kelvin)

d = the thickness of the insulation in meters

κ = the thermal conductivity of the material from which the insulation is made

Formula

The equation is:

$$\frac{Q}{t} = \frac{(\kappa A \Delta T)}{d}$$

This formula is more simple than it appears.

Example

An outside wall of a house has total cross–sectional area of 200 m^2.

The thickness of the fibreboard insulation is 5 cm.

The inside temperature is 20 °C and the outside temperature is 10 °C.

What is the heat loss per hour through this outside wall?

$$\frac{Q}{t} = \frac{(\kappa A \Delta T)}{d} =$$

$$= \frac{0.03\,J \cdot 200\,m^2 \cdot 10\,K}{s\,m\,K \cdot 0.05\,m}$$

Units reduced:

$$= \frac{0.03\,J \cdot 200 \cdot 10}{s \cdot 0.05}$$

$$\frac{Q}{t} = 1200\,\frac{J}{s} \qquad |\cdot 3600$$

$$= 4\,320\,000\ \text{J/h} = \underline{4320\ \text{kJ/h}}$$

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Examples for Thermal Conductivities

Thermal Conductivity in W / m · K	
Air	0,0262
Vacuum	0
Wood *	0,15
Wool	0,035
Isolation Polystyrene *	0,036
Isolation Polyurethane *	0,03
Glaswool *	0,04
Concrete	2,1
Clay *	0,7
Water	0,556
Iron	80
Silver	429

*depending on consistency

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First Law of Thermodynamics

General

The work of James Prescott Joule and others may be summed up in a statement as the first law of thermodynamics:

Energy can be neither be created nor destroyed but can only be transformed from one form to another.

In simple terms:

$$ENERGY_{in} = ENERGY_{out}$$

In mathematical terms:

$$Q = W + \Delta U$$

ΔU = the change in internal energy of the system

Q = net heat flow into the system during the process

W = net work done by the system during the process

States of a Substance

The state of a substance can be defined by any two of the following variables:

- Temperature
- Pressure
- Specific Volume
- Internal Energy
- Enthalpy
- Enthropy.

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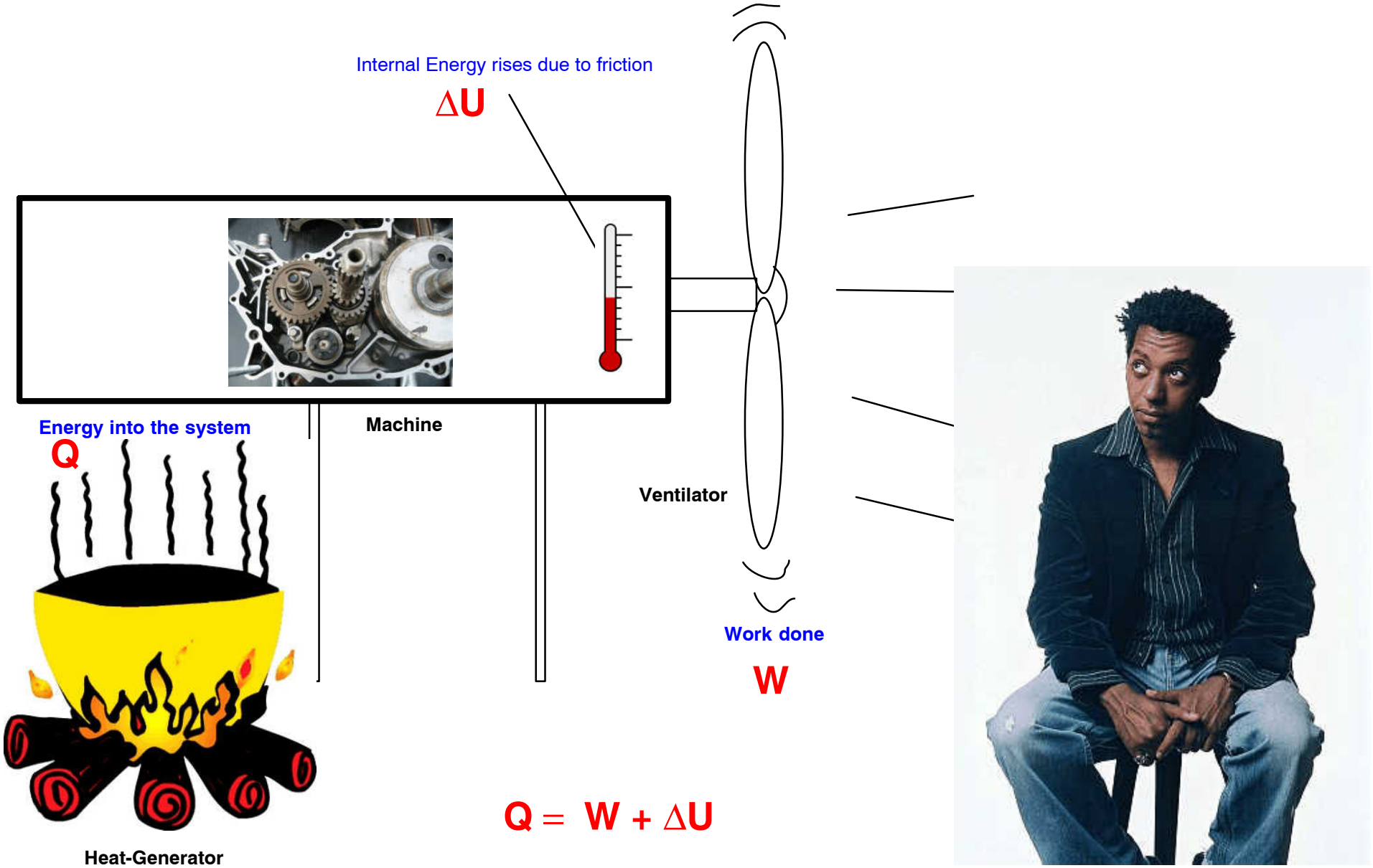


Figure 74 First Law of Thermodynamics

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Thermodynamic Cycles

General

There are two types of thermodynamic cycle:

- **Open Cycle** – Working fluid is taken in and then discarded as in gas turbine engines which will be considered later.
- **Closed Cycle** – Working fluid never leaves the system. The working fluid undergoes a series of processes and returns to it initial state such as a refrigeration cycle which we will see later.

Five Basic Elements of a Thermodynamic Cycle

1. Working Substance – A medium receives, stores and transports the energy.
2. Heat Source – Supplies thermal energy to the working fluid.
3. Heat Receiver – Absorbs the heat (or thermal energy) from the working substance.
4. Pump – Moves the working substance from the low pressure side to the high pressure side of the cycle.
5. Engine – Converts the thermal energy to work (mechanical energy).

Essential Elements of Closed & Open Cycles

There are two basically different types of engine cycles:

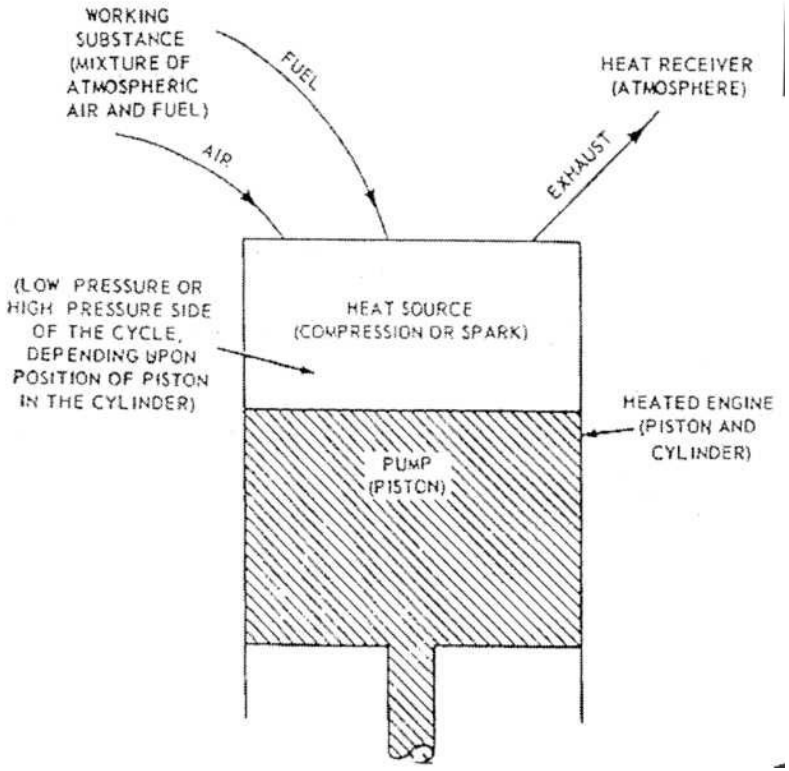
- Heated Engine Cycle
- Unheated Engine Cycle.

In the heated engine cycle, heat is added in the engine itself (i.e internal combustion engine).

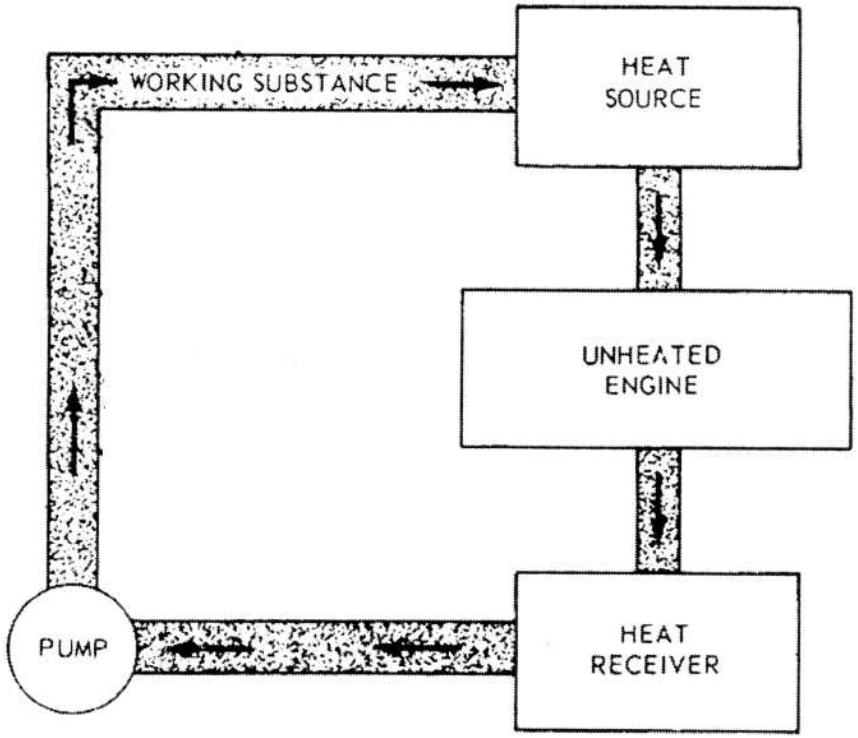
In the unheated engine cycle, the working substance receives its heat in a device that is separate from the engine.

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Heated Engine Cycle



Unheated Engine Cycle

Figure 75 Engine Cycles

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Thermodynamic Process

General

A thermodynamic process is classified by the type of working substance flow. There are two types:

- **Non–Flow** – Working fluid does not flow into or out of its container (i.e internal combustion engines and reciprocating steam engines).
- **Steady Flow** – Working fluid flows steadily and uniformly through some device (i.e boilers and turbines).

State Changes of a Working Substance

- Isobaric – the pressure remains steady during the thermodynamic process (i.e boilers and condensers).
- Isenthalpic – Enthalpy of the working fluid does not change during the process (i.e turbine throttling).
- Isothermal – temperature of the working fluid remains the same (i.e ideal pumps).
- Adiabatic – no heat transferred to or from a working fluid (i.e compressors).
- Isochoric – volume of the working fluid remains the same.

Enthalpy (H)

Enthalpy is a means to measure the internal energy of a thermodynamic system.

Enthalpy is a combination of:

- Internal energy U
- Flow work is p · V, where p is pressure and V is volume.

Symbol and Unit

The symbol for the enthalpy of a system is *H* .

The Joule is the unit of the enthalpy an is written *J* .

Mechanical energy is necessary to maintain a steady flow.

Flow work = p · V

so, H = p · V + U

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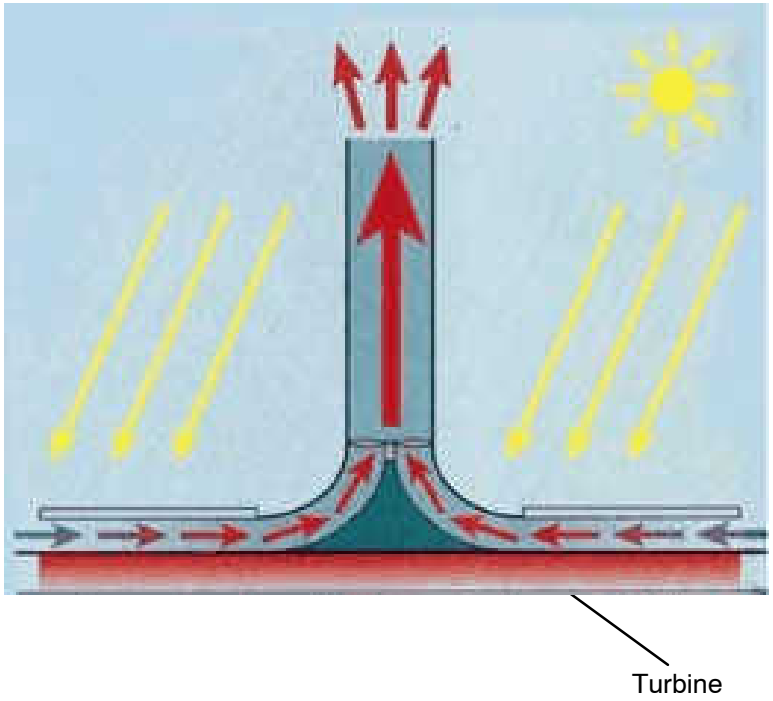


Figure 76 Solar Chimney Power Plant

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Second Law of Thermodynamics

General

Before talking about the second law, we must talk about reversibility. Think of the following situations:

- Adding heat to water on a oven.
- Shaft rotating heating the bearings.
- Warming your hands by rubbing them.

In the previous examples we see the direction the energy flows.

Reversibility in thermodynamics is a process in which the reverse could be performed transforming all energy back to its original state without any losses.

There is no such process as reversibility

No process is possible where you can remove energy from a reservoir and produce an equal amount of work from that energy, but mechanical work can be totally converted to heat.

What does all this mean?

There is no perfect engine where energy can be converted back without some input.

Entropy

Entropy is an index of unavailability of energy.

In other terms, entropy can be thought of as the amount of energy that can not be reversed from mechanical energy to heat energy. Entropy always increases for a thermodynamic system.

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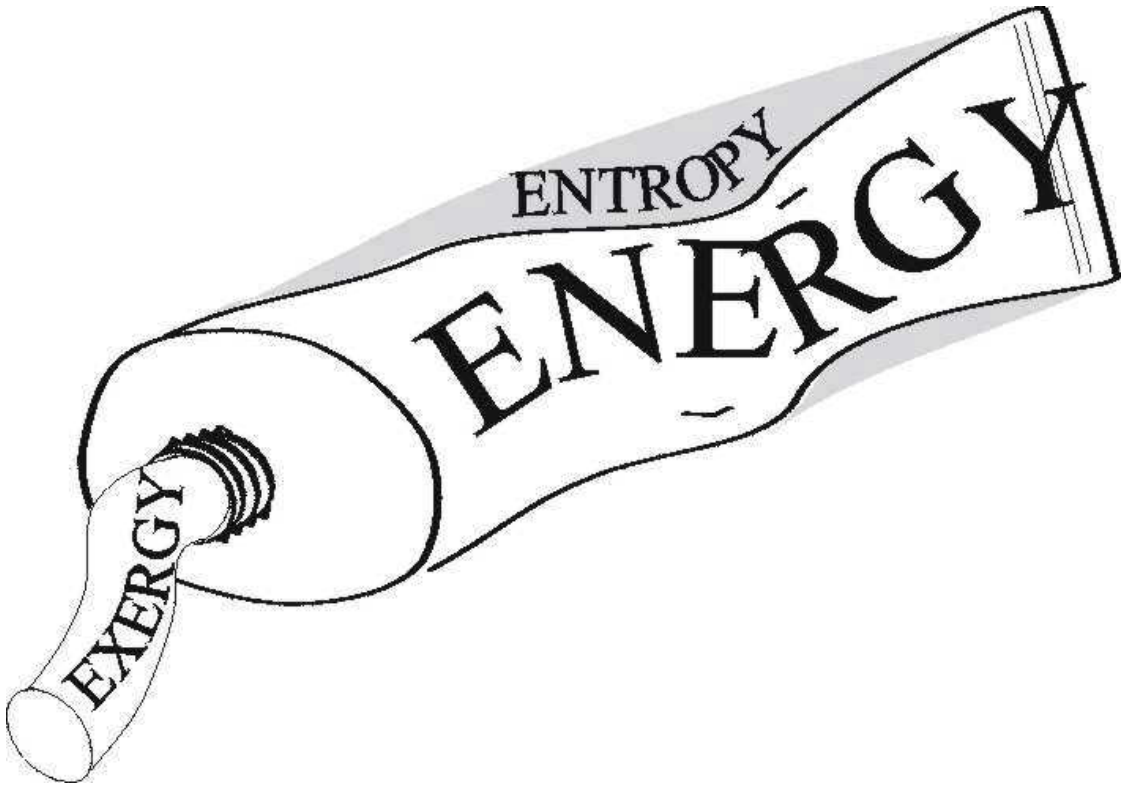


Figure 77 Entropy

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Gas Laws

General

Normally we talk about a gas when a matter is gaseous in normal temperatures. Of course, gas can be an element or a compound.

For the phenomena of gas physics, there are various gas laws.

Ideal Gas

In theory, an ideal gas would be gaseous down to a temperature of zero Kelvin.

The idea of an ideal gas is needed to understand the basic behavior of gases. In reality, there are some variations between the different gases.

In an ideal gas, the diameter of an particle is much smaller than the distance between two particles. Any contact with the inside wall of the container would result in a full “elastic collision“.

The particles do not influence each other (gravity or other forces).

During collisions the particles behave like solid matter during an elastic collision.

BOYLE-MARIOTTE LAW

Robert Boyle and Edme Mariotte found out that when you decrease the volume of gas in a container, the pressure of the gas will increase.

The pressure multiplied by the volume is constant.

Gas in a container means, that the mass of gas is constant.

This law is universally valid when the temperature is constant.

Formula

p = pressure

V = volume

$$p \cdot V = \text{const.}$$

Example

When you inflate a balloon with air, the hull will give a resistance. When the balloon is inflated, the elasticity of the rubber will try to decrease the volume. Thus, the pressure inside the balloon is bigger than the surrounding atmosphere.

When the forces of elasticity on one hand and the forces of pressure difference inside / outside the balloon on the other hand are in balance, the volume of the balloon remains constant.

The girl in the figure successfully inflated a balloon.

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Edme Mariotte



Robert Boyle



Figure 78 Gas Volume and Pressure

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Gas and Temperature

As for most materials, the volume of an amount of gas will increase when the temperature increases.

An increase of temperature may have different reasons:

- heating from outside with flames
- heating by the sun
- chemical reactions.

GAY-LUSSAC'S LAW

Joseph-Louis Gay Lussac found out that when you increase the temperature of a gas, the volume of the gas will also increase.

This is only universally valid when the gas has the possibility to expand.

For a temperature change of 1 K, all gases will increase their volume by the same amount.

Formula

V = volume

T = temperature

$$\frac{V}{T} = \text{const.}$$

AMONTONS' LAW

Guillaume Amonton found out that when you increase the temperature of gas in a container, the pressure of the gas will increase.

This is only universally valid when the gas has no possibility to expand.

Formula

p = pressure

T = temperature

$$\frac{p}{T} = \text{const.}$$

Example

When an airship flies, the sun beams can heat up the hull. As a result, the pressure in the gas container increases until the containers burst.

To prevent this, the hull of airships is painted with silver, sun rays reflecting color.

By the way: airships use the effect of buoyancy to compensate the weight of the airship and its freight.

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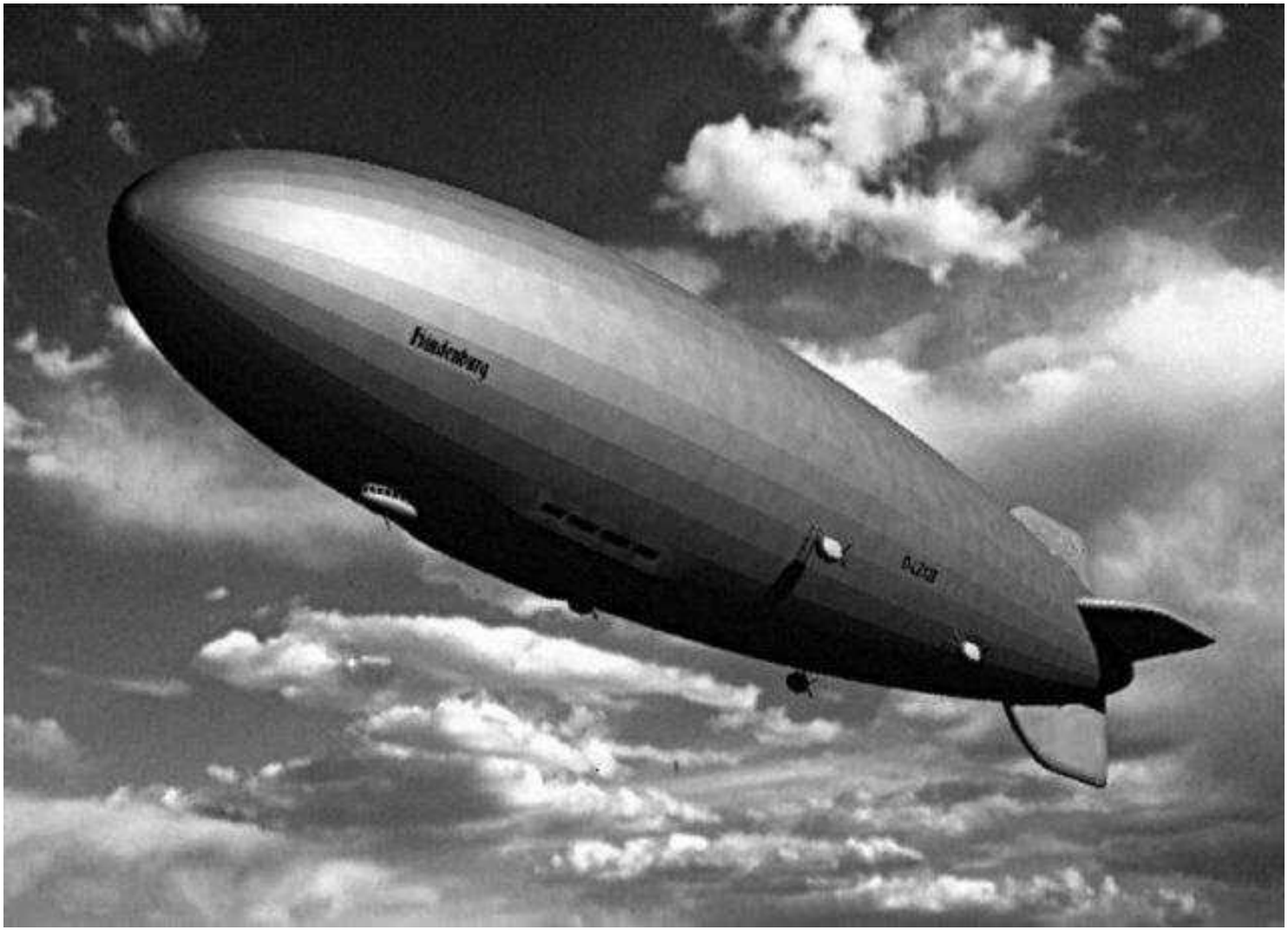
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Gay-Lussac



Amonton



LZ-129

Figure 79 Airship

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Specific Heat of Gas

General

Concerning gas, some relations are constant. This is stated in the gas laws by Boyle/Mariotte, Gay-Lussac and Amonton.

Amedeo Avogadro found a relationship between the mass of an element and the number of atoms of this mass.

BOLTZMANN CONSTANT

When the knowledge of volume, pressure and temperature is combined, we find that the following statement is true:

$$\frac{p \times V}{T} = \text{const.}$$

or

p x V = constant x T

For a fixed number of particles (N), Ludwig Boltzmann found a constant.

Symbol and Unit

The symbol for the Boltzmann constant is k_B.

The Joule per Kelvin (J/K) is the SI unit of the Boltzmann constant.

The value is $1.38 \cdot 10^{-23}$ J/K

Formula

p = pressure

V = volume

T = temperature

N = number of particles

k_B = Boltzmann constant

$p \cdot V = N \cdot k_B \cdot T$

SPECIFIC HEAT

When thermal energy is given to a gas, it will increase its volume and its specific heat.

When the container is not flexible, the volume is constant and the specific heat will increase. Thus, in a closed container less heat energy is needed to change the temperature of the gas.

Work done by Expanding Gas

General

Gas will expand when it is heated from outside the container or when there is an exothermal reaction. This happens, when a gas is “explosive“.

In other words, a heat source like a spark will start a chemical reaction. The result of the chemical reaction, the resulting compound, absorbs the energy of the combustion process and increases its thermodynamic temperature.

According to Amonton’s Law, the pressure of the gas will increase.

As an example, a cylinder and a piston form a container.

Remember the definition for Work:

$$W = F \times d$$

When the temperature *T* of gas in a container is increased, the pressure *p* also increases.

Remember the formula for pressure:

$$p = \frac{F}{A}$$

or

$F = p \cdot A$

When we combine these formula, we get:

$W = p \cdot A \cdot d$

p = pressure

A = the area of the piston

d = the distance the piston moves.

When the piston moves with a low pressure, only little work is done.

In other words: when the piston has to move a lot of resistance, it needs high pressure to move it.

Summary

For a given cylinder and piston you can calculate the needed temperature change of the gas to achieve the needed pressure.

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Ludwig Boltzmann

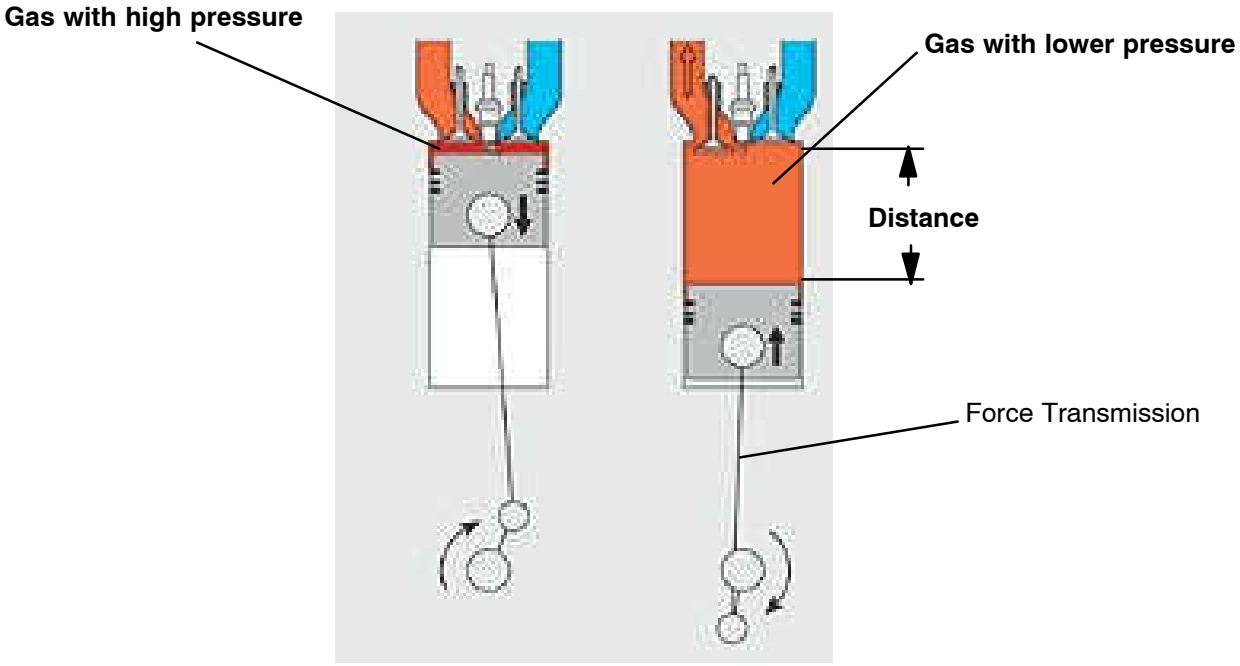


Figure 80 Work of Expanding Gas

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Isothermal Process

General

Isothermal process menas, that there is an heat exchange between a container and the environment, but the heat inside the container remains constant.

Example

Mr. and Mrs. Smith live in a hut. During the cold winter, they want a constant temperature of 20°C.

The hut loses heat due to its bad isolation. But the oven produces the same heat amount.

So the temperature in the hut will not change.

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Figure 81 Isothermal Process

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Adiabatic Process

General

Adiabatic process menas, that in a machine temperature is changed without heat exchange with the environment.

There are two kinds of adiabatic process:

- compression
- expansion

ADIABATIC COMPRESSION

When a gas is compressed it will heat up.

You must apply some force to achieve a compression.

ADIABATIC EXPANSION

When a gas is free to expand it will cool down.

No force is needed.

Expanding gas can perform work.

Reality

In reality, machines do not have perfect adiabatic processes because there is no perfect thermal isolation. An engine should keep the heat in the combustion chamber and relief some heat via the exhaust system. But the metal of the engine will heat up and requires cooling.

This is the reason why radiators are used in most cars.

Example

Rudolf Diesel developped an engine where air is compressed in a cylinder.

The compressed air will become very hot.

When fuel is added to this air, for example via an injection, this mixture of fuel and air will ignite because of the high temperature of the air.

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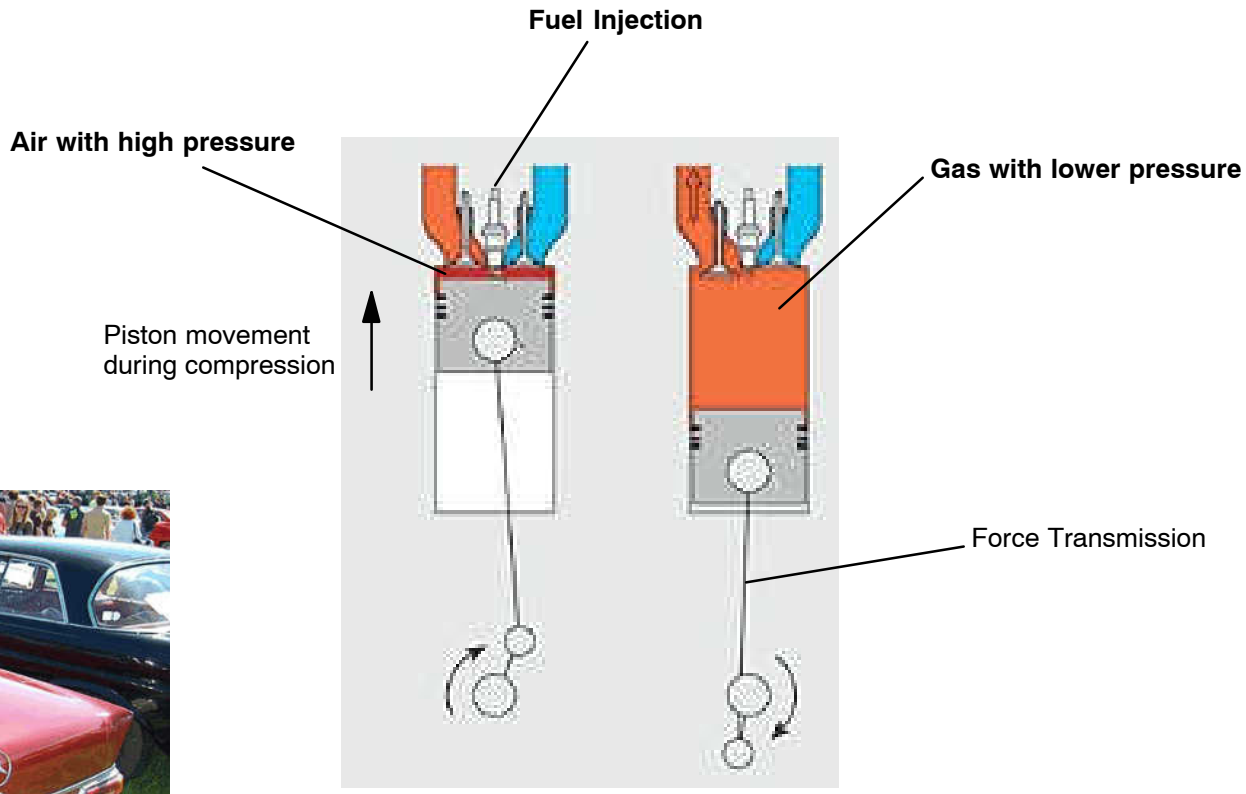
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Rudolf Diesel



Famous Car with Diesel Engine



Diesel Engine

Figure 82 Adiabatic Process

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Engine Cycles

General

When the air passes through an operating gas turbine engine, the air pressure, the temperature and the volume change. After the air has passed through the engine, the air pressure, the temperature and the volume go back to their original condition.

This full process, where the end condition of the air is equal to the start condition, is called the working cycle of an engine.

The best way to understand the working cycle of a gas turbine is to compare it with the process in a four stroke piston engine.

In both engines, the air passes through four different working steps beginning with the induction, then compression, combustion and exhaust.

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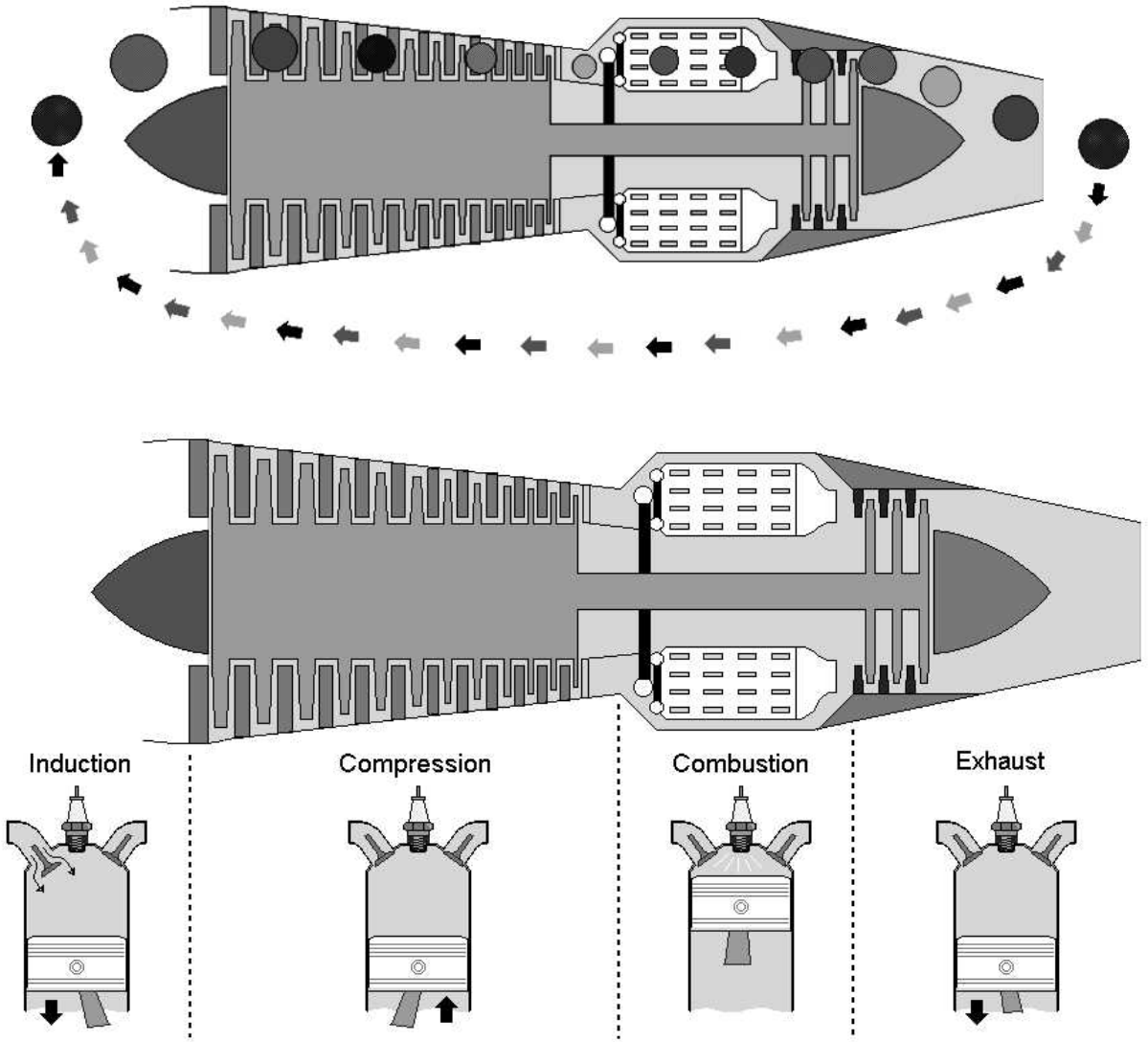


Figure 83 Engine Cycles

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Refrigeration

General

Refrigeration is the name given the process of reducing the temperature of a body. Normally we associate the process with domestic refrigerators in which we keep food fresh but the same principle is used in air conditioning of buildings, cars and aircraft.

Basic principles

A refrigeration unit has a closed system containing a refrigerant which is a liquid with a very low boiling point, often below zero degree Celsius. The fluid is generally referred to as Freon irrespective of the manufacturer's product name. A refrigerator has two heat exchangers, one inside and one outside.

As you will recall from our earlier discussion on the changes between different states of matter, the process of evaporation from requires the addition of energy. This energy comes from the relatively warm air inside the fridge and, as this energy is absorbed into the freon, the temperature inside the fridge drops.

Working Cycle

The diagram below shows a simple refrigeration system.

Starting at the bottom, the compressor compresses warm freon gas and causes it to become a hot, high pressure gas which passes to the left into the coils of the condenser.

Compression of the gas is essential to the operation of the refrigerator for two reasons, firstly the temperature of the refrigerant must be raised above the ambient temperature to allow some heat energy to be given up to the surrounding air. Secondly, the refrigerant is forced to become a liquid because of the pressure and temperature in the condenser.

The condenser is the matrix of tubes which is visible on the back of a domestic refrigerator.

In the condenser the freon gives up some of it's heat to the surrounding air and becomes a warm liquid.

This liquid is then expanded through the expansion valve where it loses a large amount of heat in the transition from liquid to gas and we now have a very cold gas in the coils of the evaporator. The energy for this evaporation, as stated above, comes from the air surrounding the evaporator and consequently the air is cooled. At the end of the evaporator coil the warm freon gas is then compressed by the compressor and the cycle continues.

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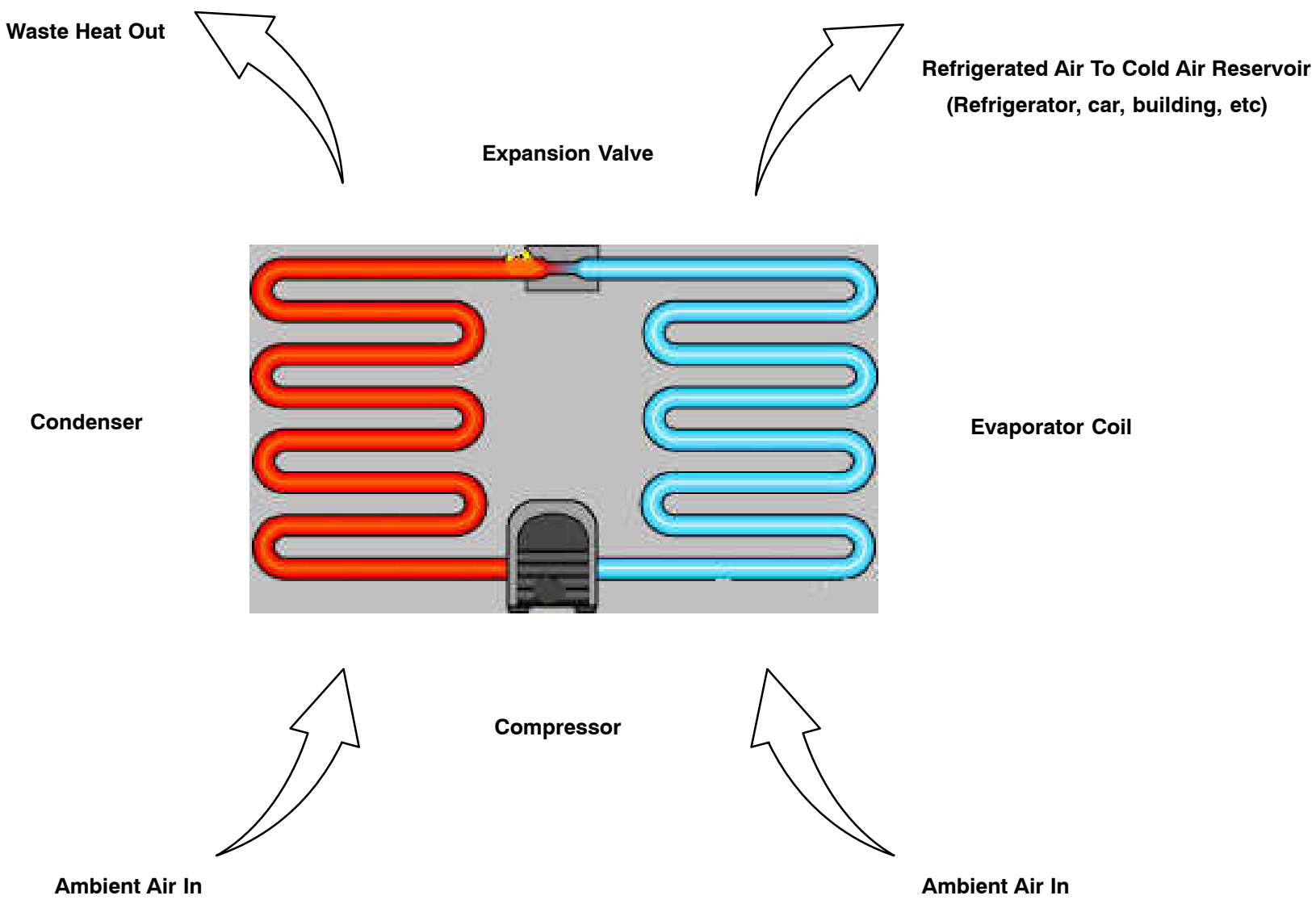


Figure 84 Simple Refrigeration Unit

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Heat Pumps

General

The refrigeration principle explained on the previous page can be used in reverse to create a warming effect. These are used for the cabin heating on some small aircraft.

As you can see from the figure below, the components are much the same as for a refrigeration unit but the air is used in a different way.

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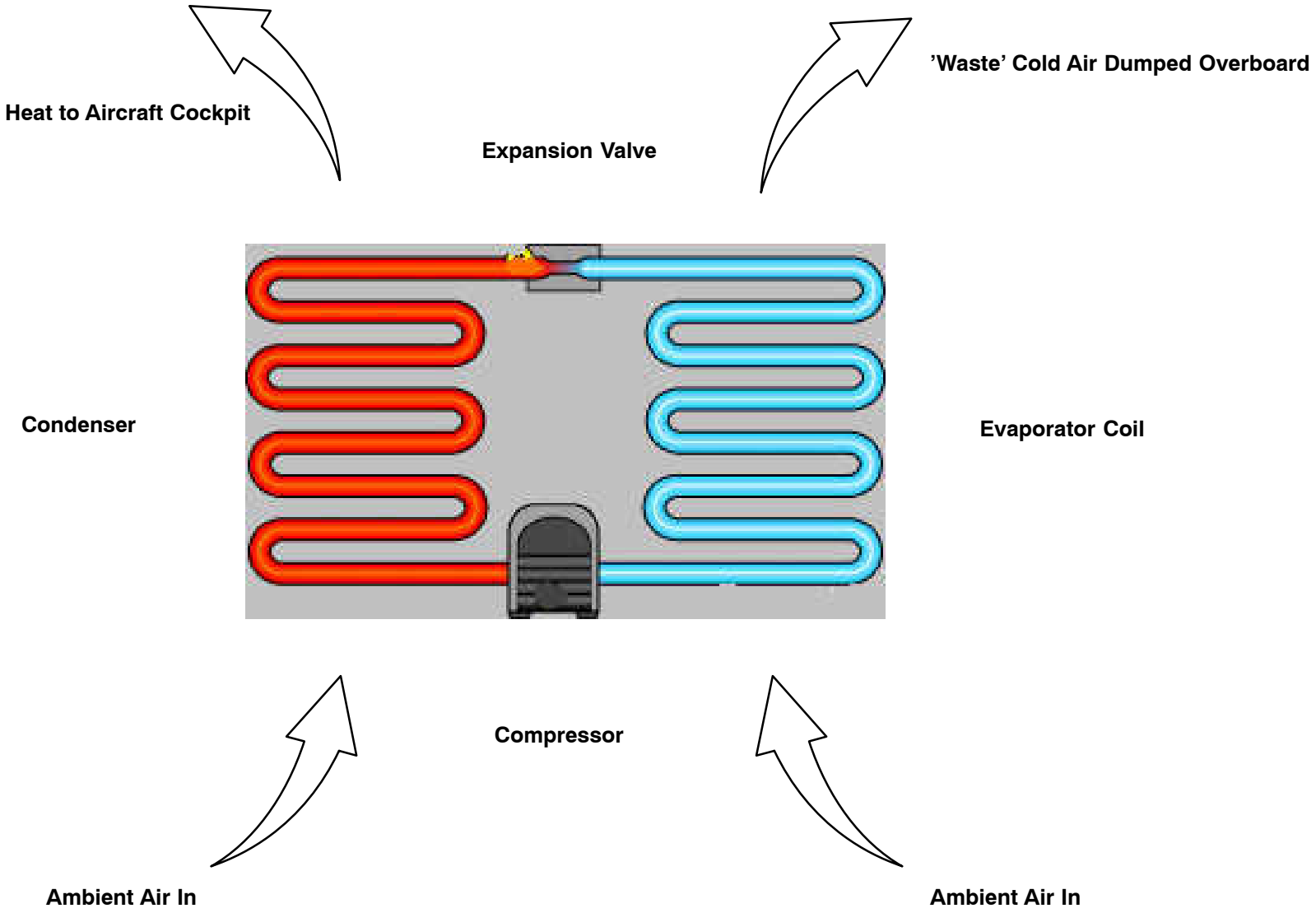


Figure 85 Simple Heat Pump for a Small Aircraft

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Heat of Combustion

General

The heat of combustion is the energy released as heat when a material undergoes complete combustion with oxygen.

The chemical reaction is typically a hydrocarbon reacting with oxygen to form the following result:

- carbon dioxide
- water
- heat.

Reality

In reality, the material does not react with pure oxygen, but with air. By this, also other compounds will be produced.

Heating Value

When we regard the chemical characteristic of a substance, we can find out the maximum possible heating value. This is true only when all products of combustion are gaseous.

In this case we talk about a “Higher Heating Value“ (HHV).

When we consider that some products will fall back to a liquid form, which takes thermal energy, the remaining energy is lower.

In this case we talk about “Lower Heating Value“ (LHV).

Unit

The unit for the heating value is Megajoule per Kilogram (MJ/kg)

For gases, Megajoule per cubic meter (MJ/m^3) can also be used.

Examples for Heating Values

	HHV	LHV
Hydrogen	143	120
Gasoline	47	44
Diesel	45	42
Methane	56	50

Example

On the picture, you can see a container for oil which is burning.

The Lower Heating Value should be used to calculate the heat gained.

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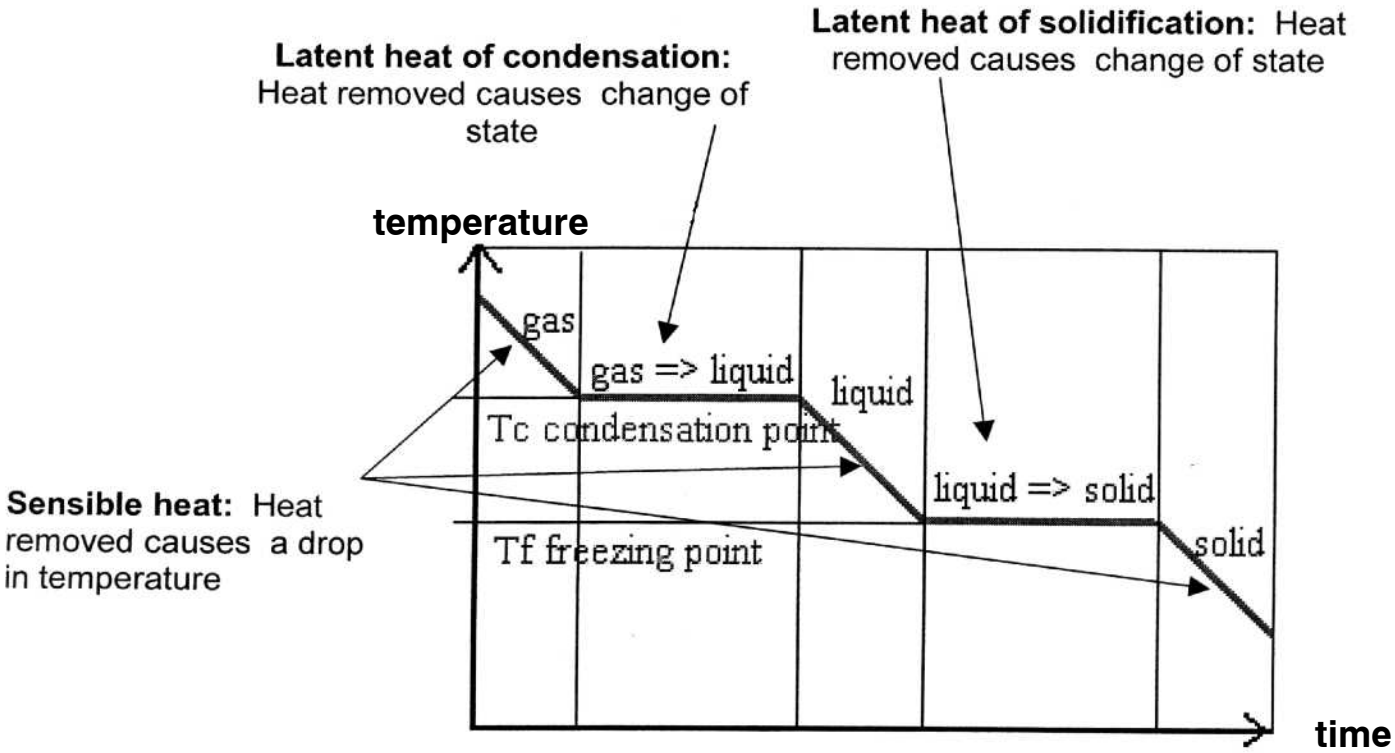


Figure 86 Combustion

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Latent Heats



Note: The temperature stays constant during the state changes of condensing and freezing.

A cooling curve summarizes the changes:

gas –> liquid –> solid

Figure 87 Cooling Curve

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NOTE: The temperature stays constant during the state changes of melting and boiling.

Since “fusion” (to melt) is the opposite of “solidification”, the Latent Heat of Fusion is the same as the Latent Heat of Solidification. Also, since “vaporization” is the opposite of “condensation”, the Latent Heat of Vaporization is the same as the Latent Heat of Condensation.

A heating curve summarizes the changes:

solid –> liquid –> gas

The principle of latent heat (especially of vaporization) is what is behind the operation of fridge and air conditioning system, water injection of gas turbine engines, and the cooling effect you feel when you perspire.

That principle is that if you make a fluid vaporize, it extracts heat (latent heat) to cause it to vaporize, but the fluid does not change temperature.

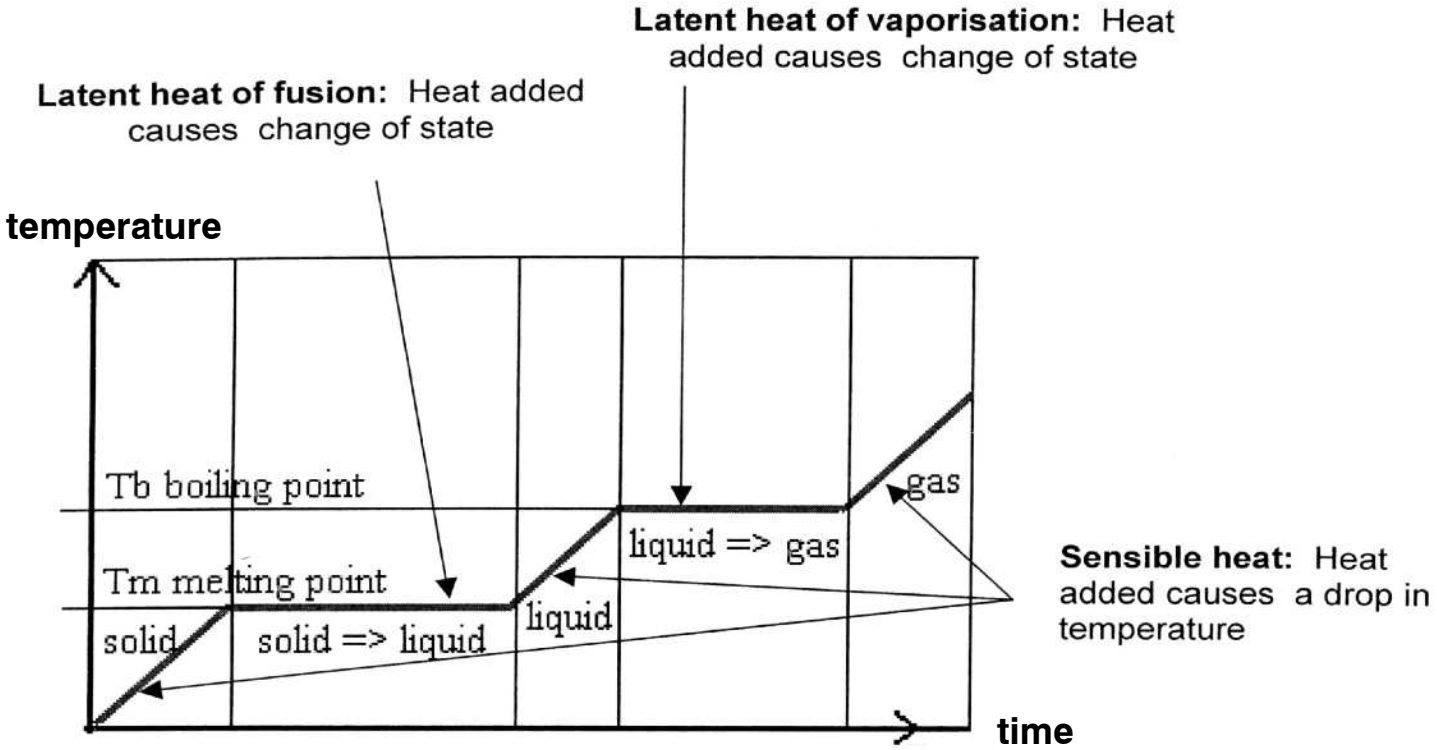


Figure 88 Heating Curve

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M2.5 WAVE MOTION AND SOUND

Transverse & Longitudinal Waves

General

There are many types of waves; light waves, sound waves, radio waves, etc. In our first discussion of waves, we will deal with that type which is called “mechanical wave”.

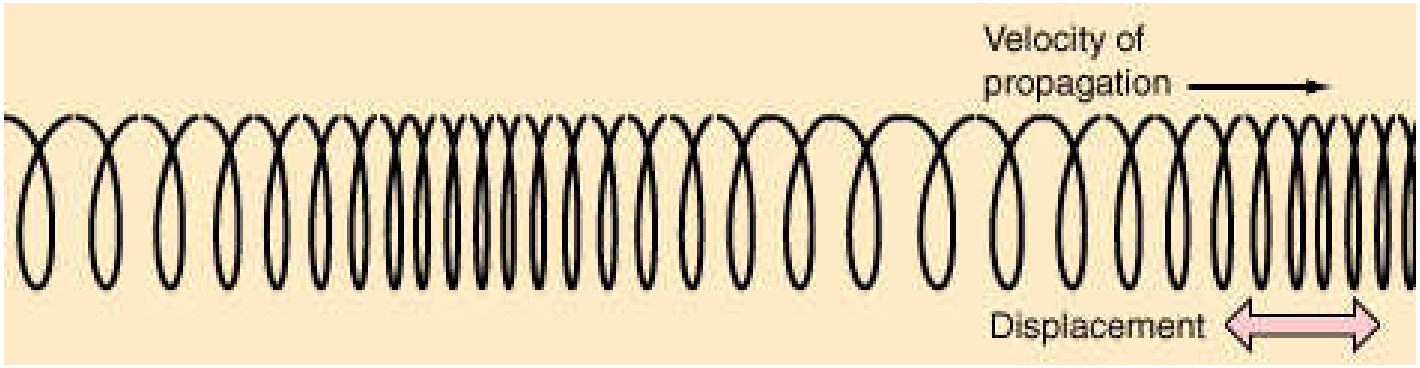
Mechanical waves are waves that need a medium such as water or air to travel (magnetical waves are the opposite and need no medium to travel) and can be categorized into two distinct categories.

The Primary, or P-Wave, is a longitudinal wave that forms alternating areas of compression and rarefaction as it travels through a medium. An example of a longitudinal wave is a sound wave.

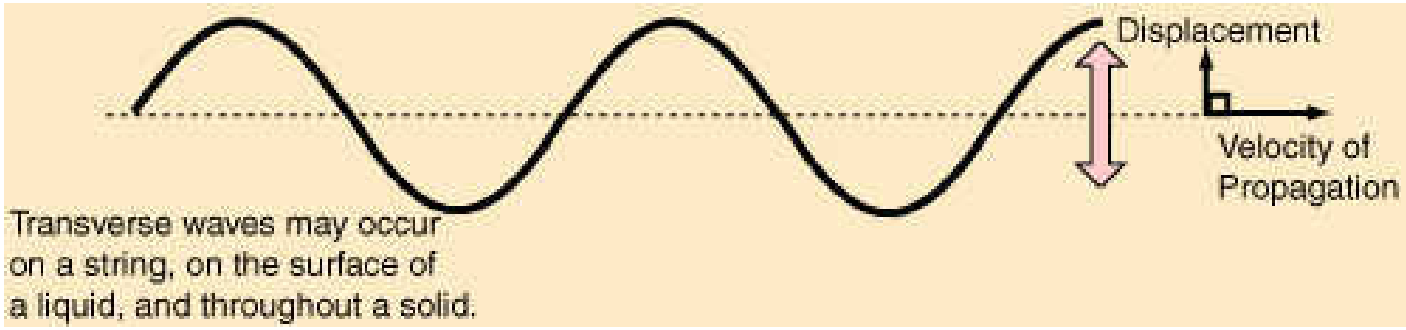
The Secondary or S-Wave is a transverse wave, which is also known as a shear wave. A typical example of a transverse wave is a ripple on a pond.

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A Longitudinal Wave



A Transverse Wave

Figure 89 Wave Forms

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Progressive & Stationary Waves

General

When a wave propagates, for example when a stone is dropped in a pond, then the wave appears to move outward from the point of disturbance. The moving wave travels across the surface of the water and is known as a progressive wave. If the progressive wave is reflected back from the shoreline, then it can interact with waves that are still travelling outwards. If the correct speed and frequency are generated then the resultant wave will appear to be stationary. Such a stationary wave is known as a standing wave.

Here we shall consider both types.

Progressive Waves

Let us assume that a stone is thrown into the middle of a large, calm pond on a day when there is no wind. If there is a perpendicular plane surface cutting the water surface through a point where the stone hits the water, an observer would see the water surface disturbed in such a way that a curve would be visible.

This curve would have a shape as shown in the figure below.

Standing Wave

In the figure below it is important to note that the pattern of crests and troughs is moving. If the stone hits the water surface at the point (P), the pattern is moving to the right. Of course, the entire pattern is moving out from point (P) in all directions, but we are looking in only one direction. We should also note that the pattern is moving with a definite speed, called the wave speed.

The amplitude (A) of the wave is the greatest displacement from the rest position.

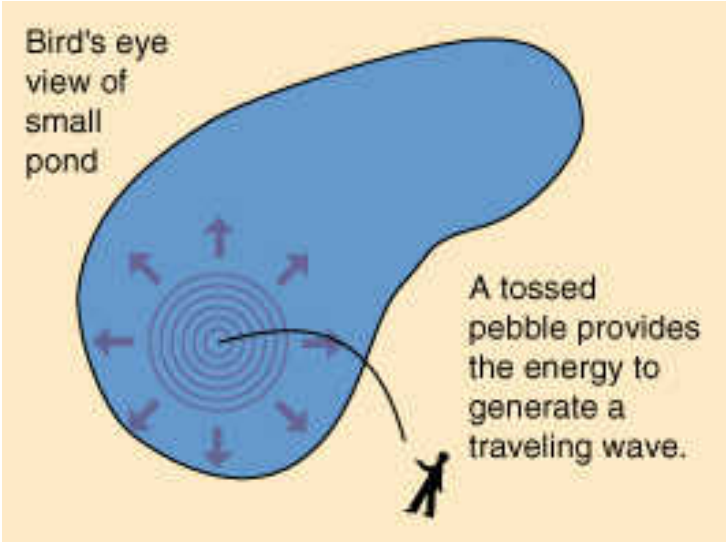
Wavelength

Another distance that we will need in our discussion of waves is the wavelength, λ (Greek letter lambda). The wavelength is defined as the distance from one point on the wave pattern to the next point in a similar position. The distance from the top of a crest to the top of the next crest is a wavelength. Also the distance from the bottom of one trough to the bottom of the next trough is also the same distance, one wavelength.

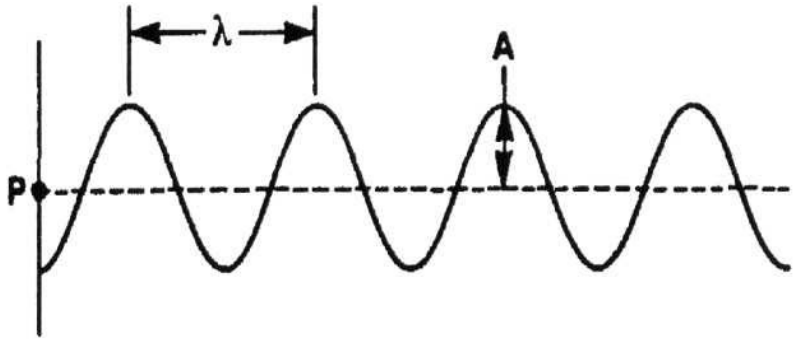
The wavelength is shown in the diagram. It is universally valid for progressive waves and standing waves. If the frequency is constant the wavelength is also constant.

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Progressive Waves



Standing Waves

Figure 90 Progressive and Standing Waves

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Interference Phenomena

General

When two or more waves are added, a new wave is generated. This phenomenon is called interference.

Constructive Interference

Constructive Interference is given when two waves of same frequency generate a wave which has a higher amplitude than one of the original waves.

Destructive Interference

Destructive Interference is given when two waves of the same frequency generate a wave which has a lower amplitude than one of the original waves.

The difference to a constructive interference is not caused by a difference of the frequency but by the phase shift of the waves.

Beat

In acoustics, a beat is an interference between two sounds of slightly different frequencies, perceived as periodic variations in volume whose rate is the difference between the two frequencies.

Standing Wave

A standing wave is a wave that remains in a constant position. The wave nodes remain in a constant position.

This phenomenon can occur because the medium is moving in the opposite direction to the wave, or it can arise in a stationary medium as a result of interference between two waves traveling in opposite directions.

This can happen when a wave is reflected.

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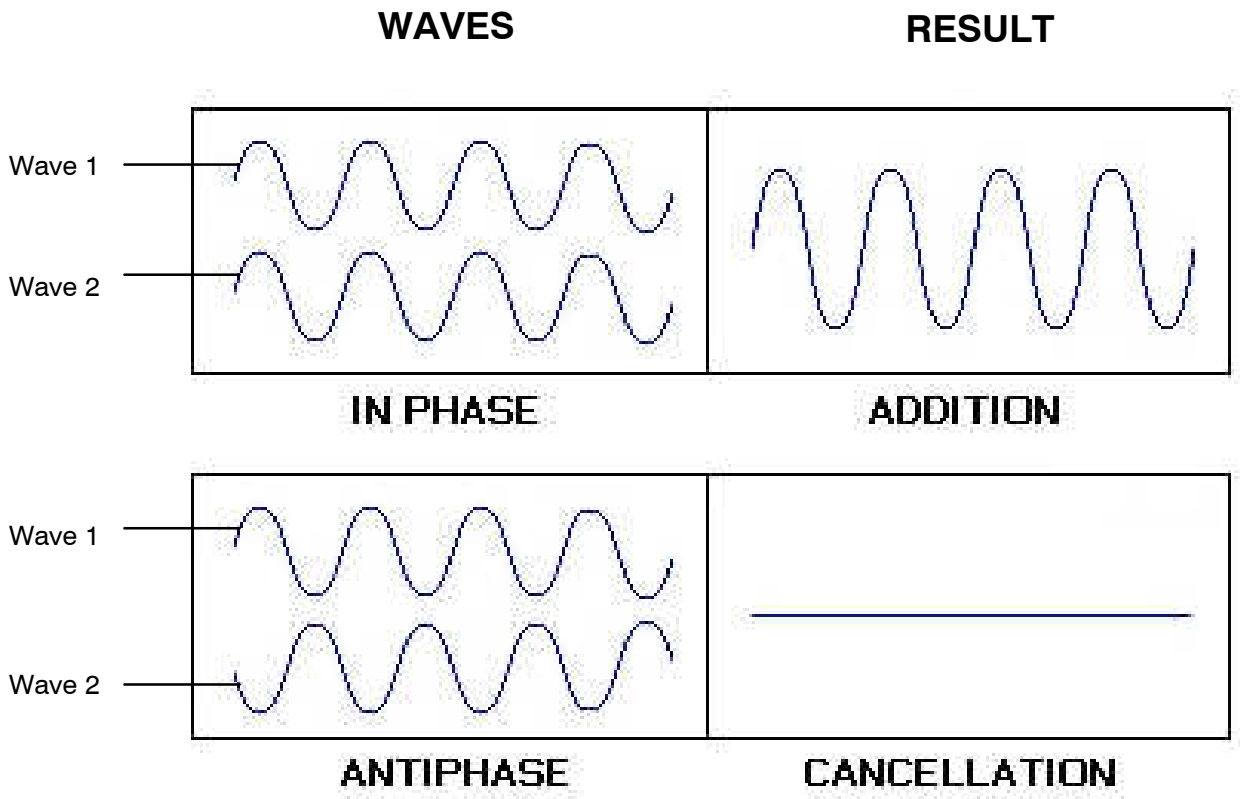


Figure 91 Interference

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Frequency

General

Consider a body that has been attached to a vertical spring, which has then been displaced from its neutral position and released. The spring will oscillate for some time, the physical situation is shown in the figure.

The frequency (f) of the oscillating body is defined as the number of complete oscillations in one second. Frequency is expressed in cycles/sec. or Hertz (Hz). The period (T) is defined as the time for one complete oscillation, expressed in seconds.

When the oscillating body complete 6 oscillations in one second it follows that the time for one oscillation is one–sixth of a second.

In this case:

$f = 6\text{Hz}$ and $T = \frac{1}{6}\text{s}$

From the example below we see that f and T are reciprocals of each other.

$T = \frac{1}{f}$ and $f = \frac{1}{T}$

We next seek a relationship between wave speed (v), frequency (f) and wavelength (λ). The wave moves forward a distance of one wavelength in a time of one period. The wave moves with speed (v).

Since the distance equals the speed times the time (T) we can write the equation as:

$$v = f \cdot \lambda$$

Example:

What is the wavelength of a wave moving with a speed of 5 m/s if the frequency of the oscillating body which is the source of the wave is 12 Hz?

$$\lambda = \frac{v}{f}$$

$$\frac{v}{f} = \frac{5\ \text{m/s}}{12\ \text{Hz}}$$

$\lambda = 0.417$ m

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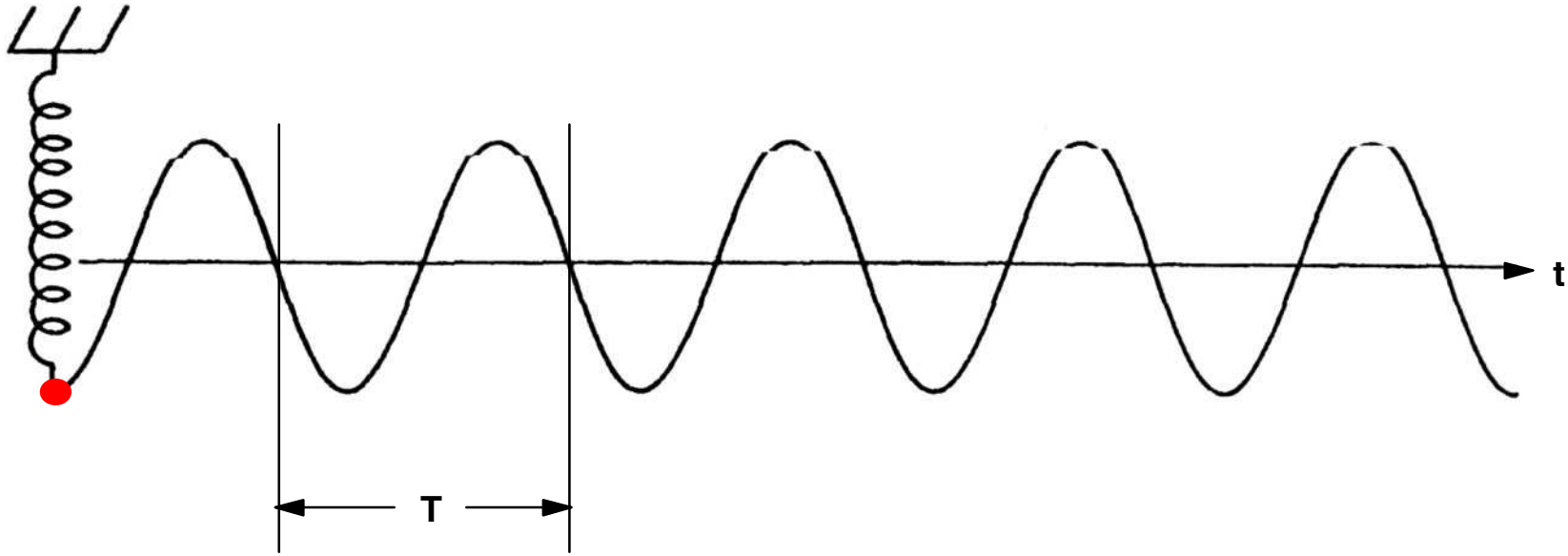


Figure 92 Frequency and Wavelength

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Sound

GENERATION OF SOUND

General

Sound waves are the same as pressure waves.

Sound pressure is defined as pressure oscillations which appear in a compressible medium caused by a sound source. The sound pressure differs from the the normal static pressure in the medium and is therefore an alternating pressure. Normally the wave is a sinus wave.

Sources of Sound

Sound can be produced by oscillating bodies like a bell, or by membranes like on a drum and elastic medium. Membranes can be moved by electro-mechanic forces. This is used in loudspeakers.

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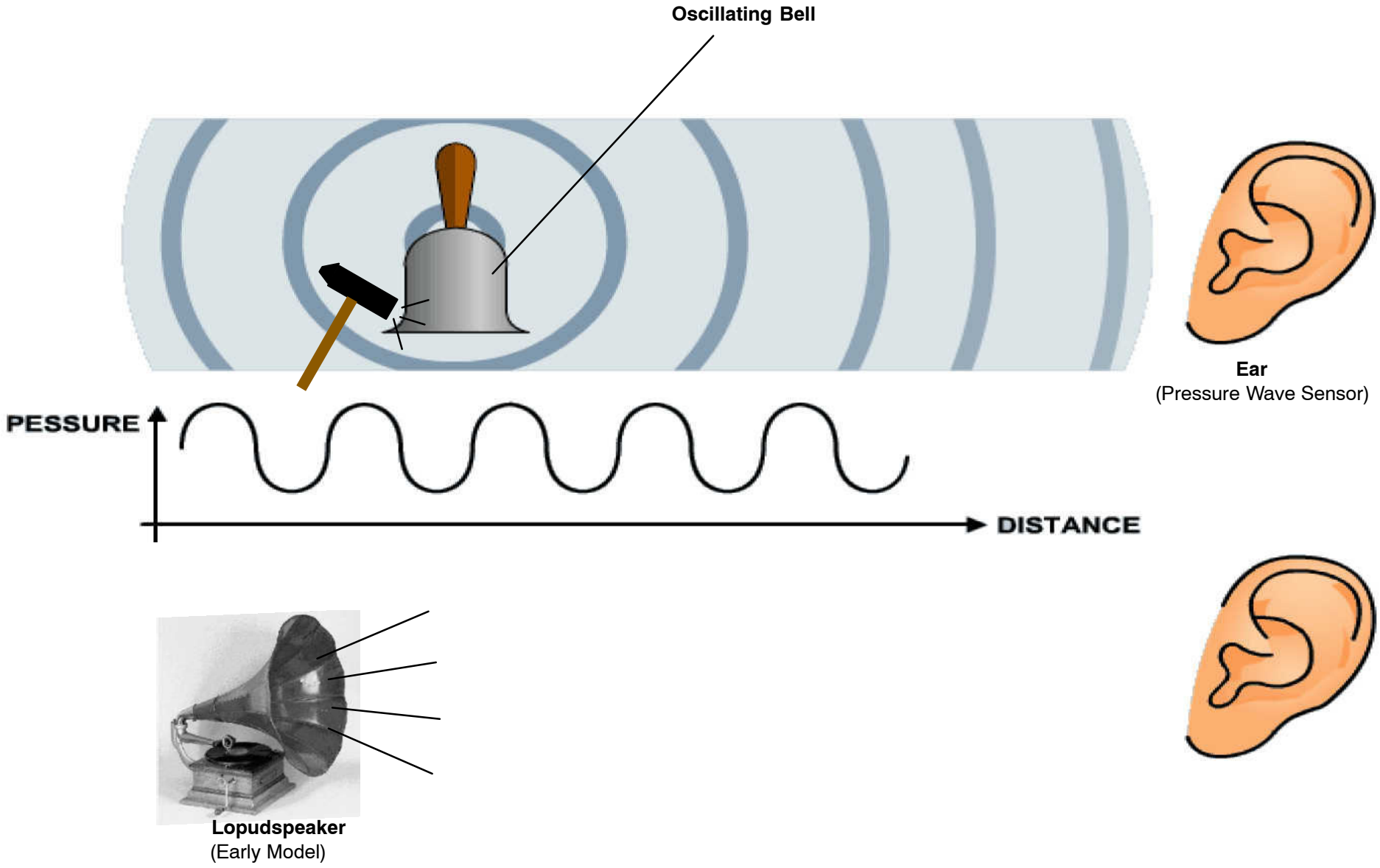


Figure 93 Sound Waves

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INTENSITY

Sound Intensity

Sound Intensity is also called Acoustic Intensity.

Symbol and Unit

The symbol for quantitiy is *I* (I like India).

The unit is Watts per square meter, written as $\frac{W}{m^2}$.

Formula

For progressive waves in a plane, it is defined as the sound power P_{ac} per unit area A.

By this, the formula is as follows: $I = \frac{P_{ac}}{A}$.

Sound Intensity Level

When referring to measurements of power or intensity, a ratio can be expressed in decibels by evaluating ten times the base−10 logarithm of the ratio of the measured quantity to the reference level.

The decibel (dB) is a logarithmic unit of measurement that expresses the magnitude of a physical quantity relative to a specified or implied reference level.

Since it expresses a ratio of two quantities with the same unit, it is a dimensionless unit.

Formula

The formula is as follows: $L = 10 \cdot \log_{10} \left(\frac{I_1}{I_0}\right)$ db

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Examples

Situation and sound source	sound power P_{ac} in Watts	sound power level L_W dB re 10^{-12} W
Rocket engine	1,000,000 W	180 dB
Turbojet engine	10,000 W	160 dB
Siren	1,000 W	150 dB
Loudspeaker rock concert	100 W	140 dB
Machine gun	10 W	130 dB
Jackhammer	1 W	120 dB
Trumpet	0.3 W	115 dB
Chain saw	0.1 W	110 dB
Helicopter	0.01 W	100 dB
Loud speech	0.001 W	90 dB
Usual talking	10^{-5} W	70 dB
Refrigerator	10^{-7} W	50 dB

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PITCH AND QUALITY

Pitch

Pitch is related to frequency.

Frequency is the scientific measure of pitch.

While frequency is objective, pitch is completely subjective.

Sound waves themselves do not have pitch, but their oscillations can be measured to obtain a frequency.

Only thinking beings can sense sounds as various kinds of pitch.

Music instruments do not generate sinus waves, but their sound can be divided into pitches by most people. Most people also sense the relationship between the various pitches of an instrument.

Quality

Sound ”quality” or ”timbre” describes those characteristics of sound which allow the ear to distinguish sounds which have the same pitch and loudness. Quality is then a general term for the distinguishable characteristics of a tone.

For example, a “C“ can be played with a guitar or with a piano. The pith is the same, the quality is different.

However, some sound engineers manage to make an electric guitar sound like a piano.

Example:

A music band has various instruments. each of them has one typical sound quality and can generate various pitches.

When the quality of the musicians is good, too, then the quality of the music will also be good.

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Figure 94 Music Band

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Speed of Sound

General

The speed of sound is the speed of the small pressure waves which occur when you ring the bell.

The speed of sound is denoted by '**a**'.

In the formula of the speed of sound, the number **20** is an approximation of the total of all the relevant constant values.

'**T**' for temperature represents the only variable value. The temperature must be expressed in **Kelvin** and denoted in meter per seconds! That leads to the following formula:

$$a = 20 \cdot \sqrt{T} \left[\frac{m}{s}\right]$$

Medium

This page and the following pages are about the velocity of sound in the atmosphere.

When the medium is not air but water or a solid mass, the velocity is different!

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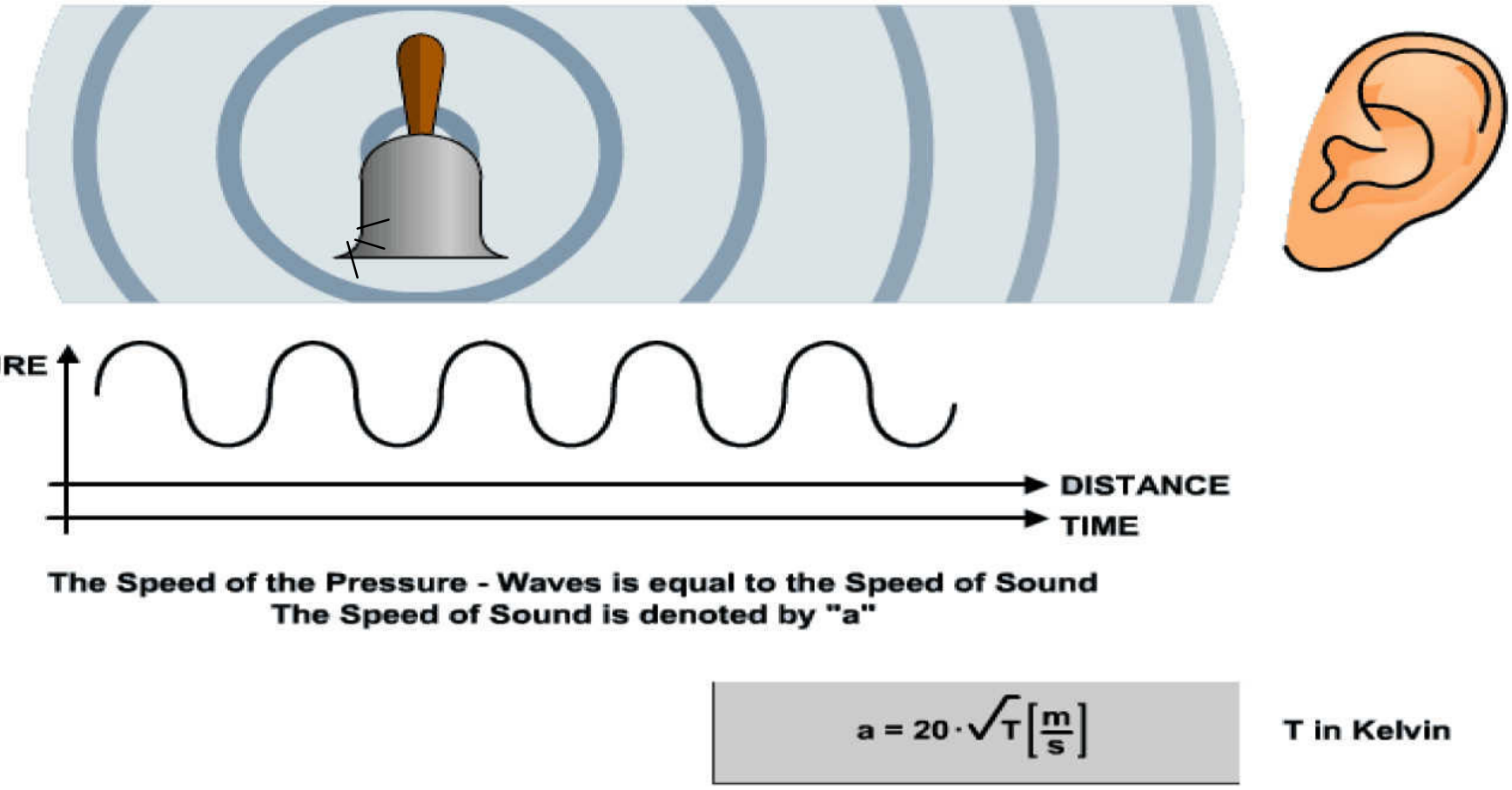


Figure 95 Sound Waves

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Example

Now you know that the speed of sound depends on the temperature only.

For example if the temperature on a summer day is 15 degrees Celsius, which is 288 Kelvin then we calculate the speed of sound to be 339.4 meters per second which correspnds to 1220 km/h if you multiply it by 3.6.

If the temperature decreases in winter to minus 50 degrees Celsius, which is 223 Kelvin then the speed of sound is 298.6 meters per second or 1075 km/h.

The speed of sound is less at high altitudes because the temperature decreases.

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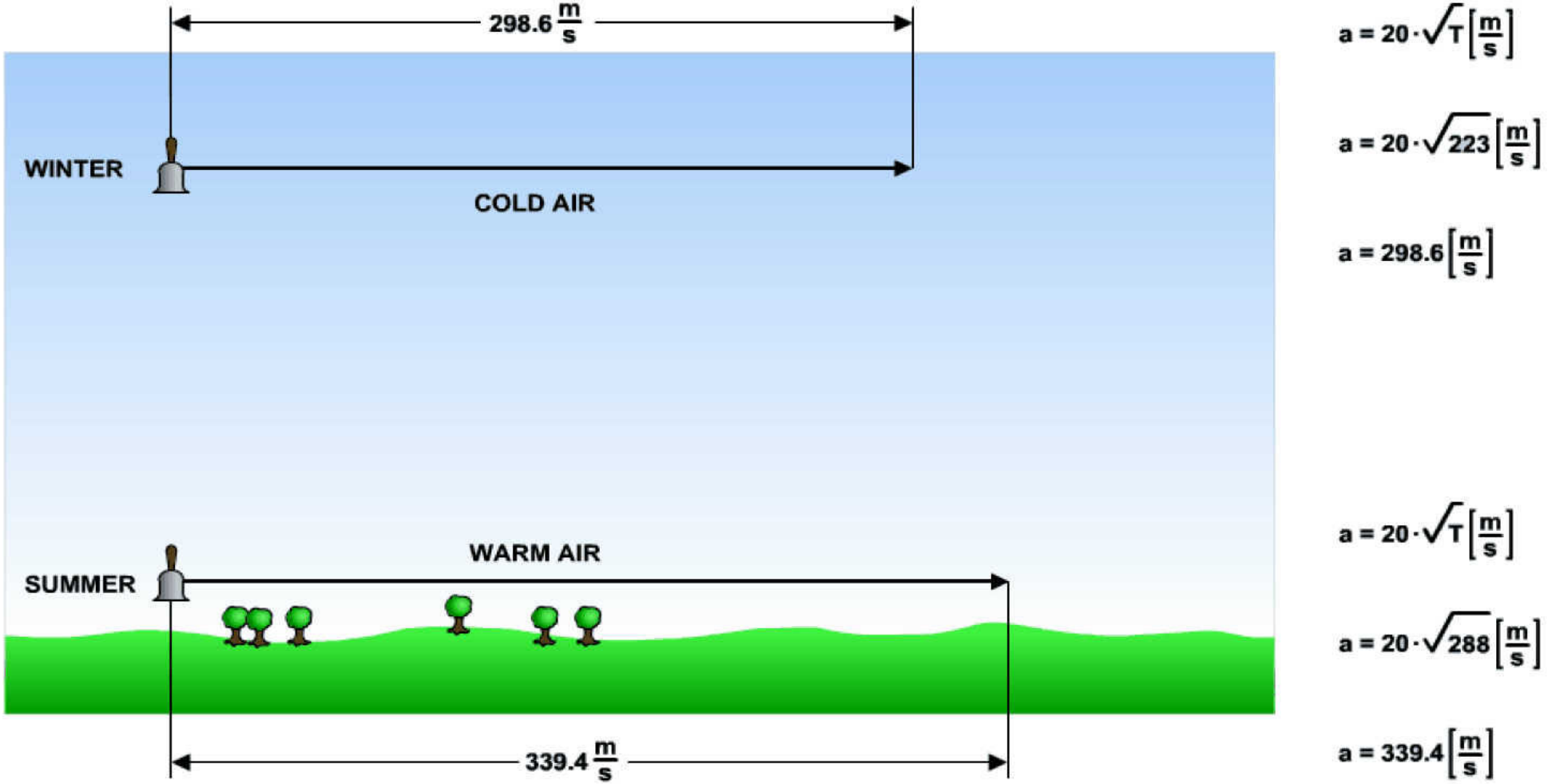


Figure 96 Speed of Sound

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Moving Source of Sound

Now let us see what happens if the source of the sound moves, for example if we have an aircraft flying.

Aircraft below Speed of Sound

First we see an aircraft flying at a speed which is below the speed of sound.

You can see that the pressure wave moves ahead of the aircraft and also behind it.

Aircraft at Speed of Sound

Next we see an aircraft flying at the same speed as the speed of sound.

The pressure wave cannot escape at the front of the aircraft and we get a big pressure wave forming. This pressure wave is known as a shock wave.

Aircraft above Speed of Sound

Finally we see an aircraft flying at a speed which is above the speed of sound. In this case the pressure waves increase behind the aircraft and shock waves form outside the periphery of the pressure waves.

Summary

Now you know that different aircraft speeds affect the sound waves.

The pilot must know the relationship between the speed of the aircraft and the speed of sound.

On most aircraft the pilot must make sure that the speed of the aircraft is less than the speed of sound.

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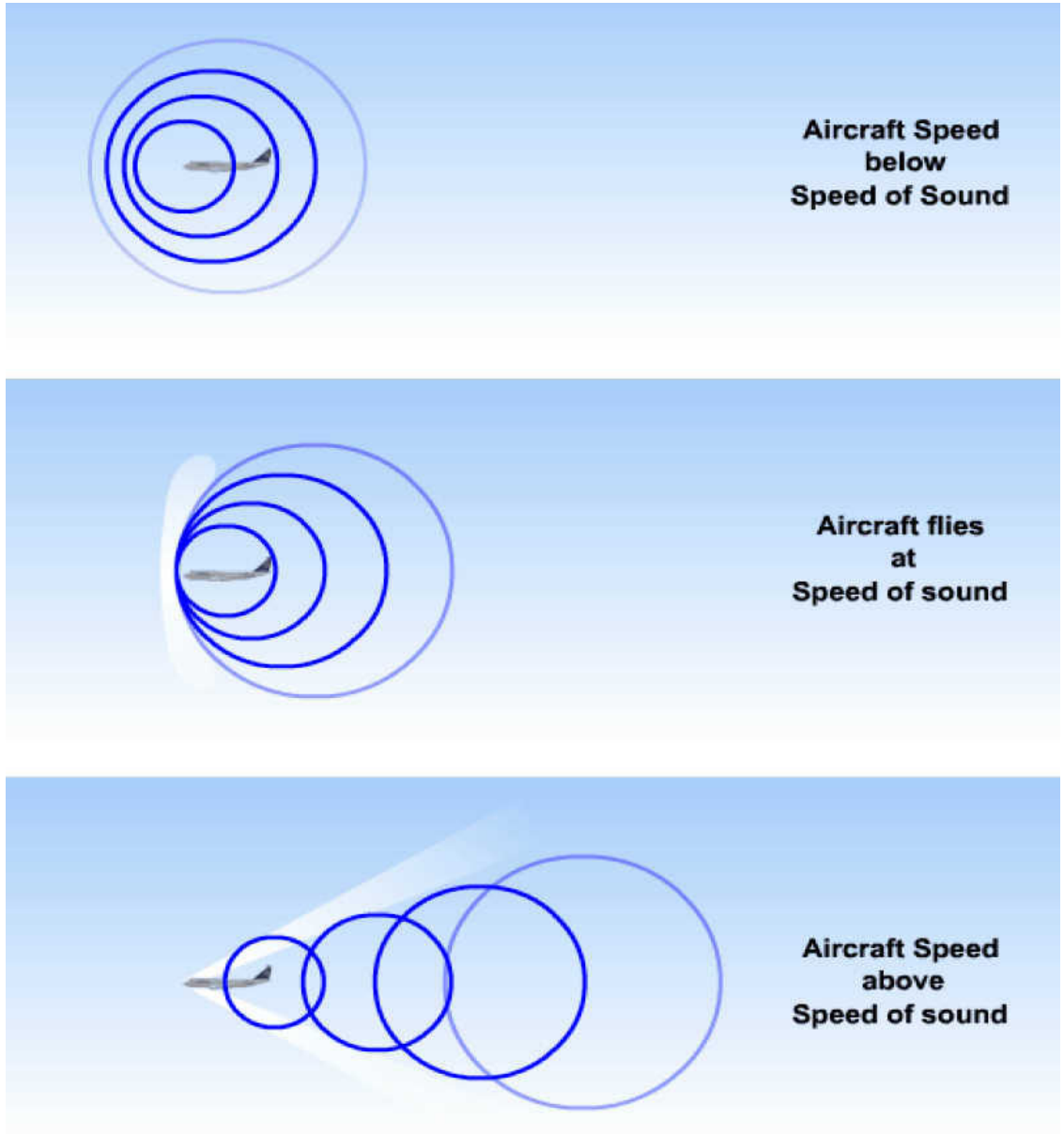


Figure 97 Aircraft Speed

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Temperature

Now let us see what happens when an aircraft flies at a constant speed but in different temperatures. In this example the aircraft is flying at a low altitude with a speed of 300 meters per second.

You can see that the aircraft speed is below the speed of sound at this altitude. We assume the speed of sound is 330 meters per second.

Now the same aircraft is flying at an altitude of 10 kilometers. The aircraft continues to fly with a speed of 300 meters per second.

At this higher altitude the temperature is lower and the speed of sound decreases to 300 meters per second.

Now the aircraft is flying at the speed of sound and you can see that shock waves are produced.

Mach Number

A special indication known as the Mach number, '**M**' is used to keep the pilot informed of the relationship between the speed of the aircraft and the speed of sound.

The Mach number is the the ratio of the speed of the aircraft divided by the speed of sound.

In our example the aircraft flying at an altitude of 10 kilometers has a Mach number of one **(M = 1)**. A Mach number of one indicates that the aircraft is flying at the speed of sound.

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$$\text{Mach Number [M]} = \frac{\text{SPEED OF AIRCRAFT}}{\text{SPEED OF SOUND}}$$

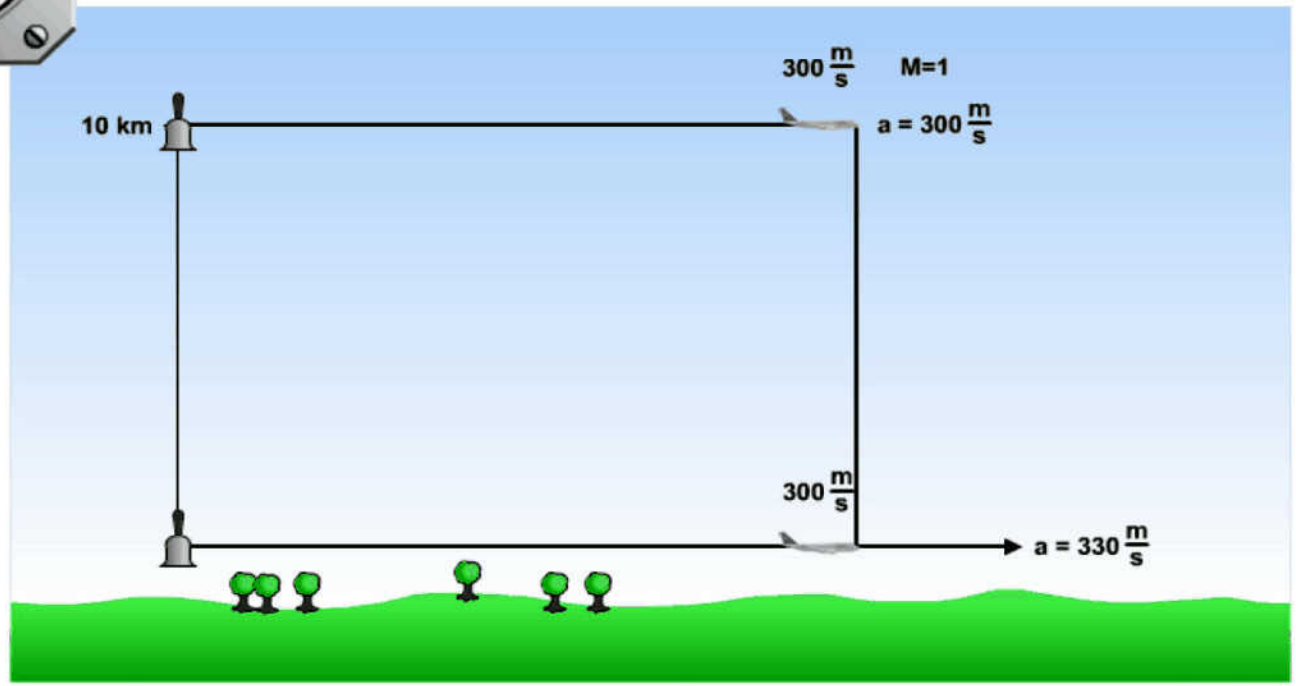


Figure 98 Mach Number

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Doppler Effect

General

The doppler effect can be observed when a pitch of a sound is created and a different pitch is received. The reason is a movement of the sound generator or a movement of the receiver. Sometimes, both move.

To make it easier, we talk about a sound which is a constant sinus form frequency. So we talk about frequencies, not about pitches.

For calculations concerning sound frequency, three factors must be regarded:

- velocity of the sound generator
- velocity of the receiver
- velocity of the medium.

The medium for the sound is air. In most cases, the air is regarded a not moving.

Calculations

The following formula gives a possibility to calculate the frequency which is received.

a is the speed of the sound waves in air

v_s is the velocity of the sound transmitting generator

v_r is the velocity of the receiver

f_o is the originally transmitted frequency

f_r is the frequency which is received

The formula is as follows: $f_e = \frac{a + v_r}{a + v_s} \times f_o$

Radar

The Doppler effect is used in some types of radar, to measure the velocity of detected objects.

The main difference to the doppler effect on sounds is that a beam is sent, reflected on an obstacle and turns back. When the transmitter and the object do not have a constant distance (they depart or approach), the received frequency is not the same as the transmitted frequency.

A radar beam is fired at a moving target e.g. a motor car, as police use radar to detect speeding motorists as it approaches or recedes from the radar source.

In either situation, calculations from the Doppler effect accurately determine the car's velocity.

Doppler Radar System

In older aircraft, a Doppler Radar System was installed.

This system was used to send radar beams to the earth's surface and to detect the frequency shift of the echo.

By this, the ground speed was calculated.

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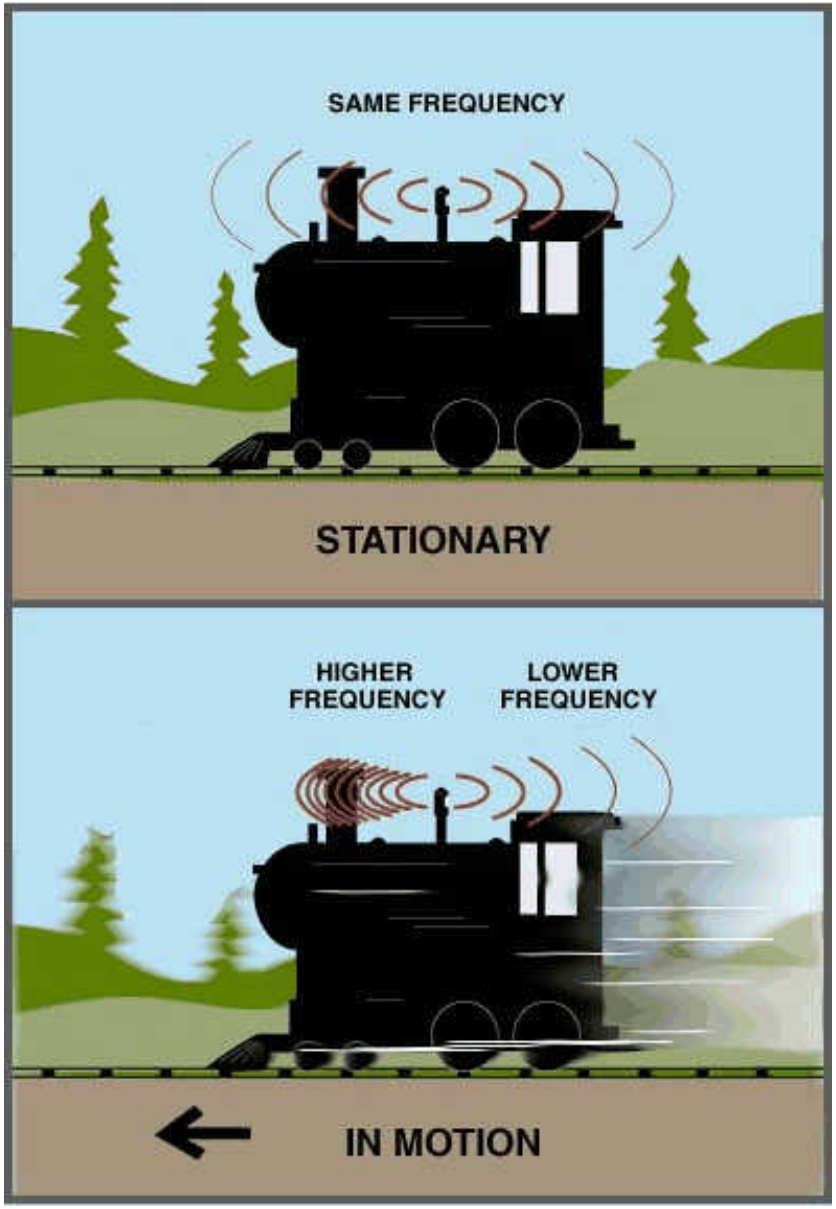


Figure 99 Doppler Effect

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M2.4 OPTICS AND LIGHT

Nature of Light

General

Light was always a mystery to early physicists, they could use light but nobody could really work out what it was, even the great English physicist Sir Isaac Newton did not know what it was. It had been observed that light travelled at a definite speed and could be influenced by the gravity of planets but it was not until the 1800s that it was realized that light would react to interference from magnetism and was therefore some kind of electromagnetic wave.

Light is the term generally used to describe the electromagnetic radiation which is visible to the human eye but really includes frequencies which we cannot see.

Electromagnetic waves consist of a magnetic field and an electric field travelling together but displaced at 90 degrees to each other each describing a sinusoidal pattern. A diagram of an electromagnetic wave is shown in the figure below.

Sources of Light

Light is given off by materials at very high temperatures such as a tungsten filament in a light bulb and in some gasses by bombarding gas molecules with electrons such as in a gas discharge lamp. Anything which gives off light such as the sun or a light bulb is said to be 'self-luminous' whereas most objects that we can see simply reflect the light which falls on them.

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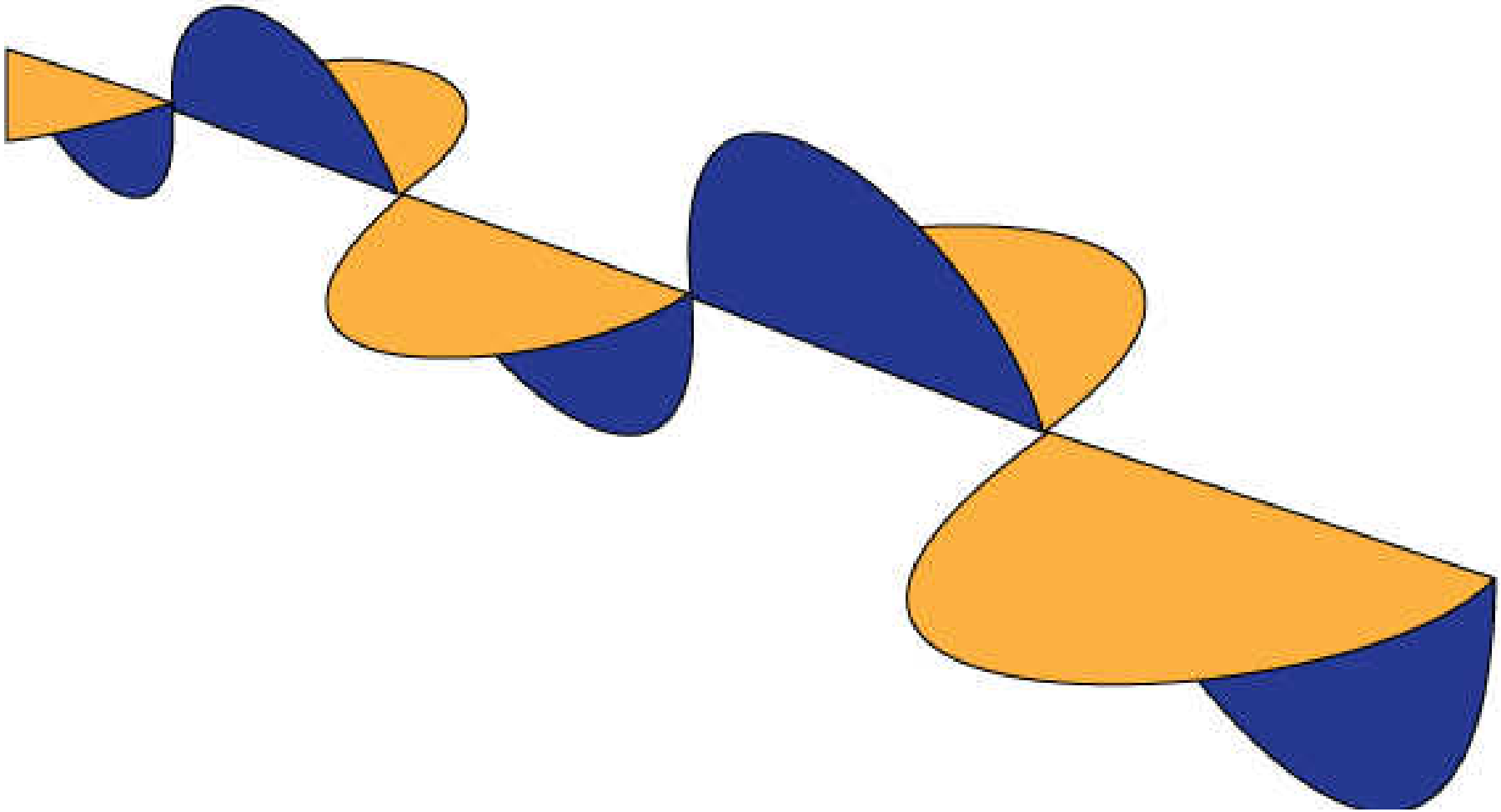


Figure 100 Electromagnetic Wave

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Speed of Light

General

The electromagnetic waves which make up light, travel at a definite speed which changes depending on the medium through which it is travelling. The speed of light in free space (a vacuum) is 299 792 458 m/s or 299 792.5 km/s which corresponds to 186 000 miles per second. This is always constant and is one of the fundamental constants used in physics. The speed of light changes according to the substance so in water for example the light travels much slower.

As with any type of wave the frequency is equal to the number of complete oscillations per second so the greater the wavelength, the smaller the frequency. Additionally the speed of the wave is equal to the wavelength multiplied by the frequency.

$c = \lambda \times f$

Where c= speed of light,
λ= wavelength and
f= frequency.

Example

If a radar wave has a frequency of $3 \times 10^{10} Hz$, what is the wave length?

This frequency is 30 GHz. According to the formula the wave length is 1cm.

Journeys of Light

An other example is our planet system. From the surface of the sun, light needs a different amount of time to each planets.

Rays of light from the sun need 6.2 minutes to reach the planet Venus.

Rays of light from the sun need 8.3 minutes to reach the Earth.

Light needs 1.3 seconds from the earth to the moon.

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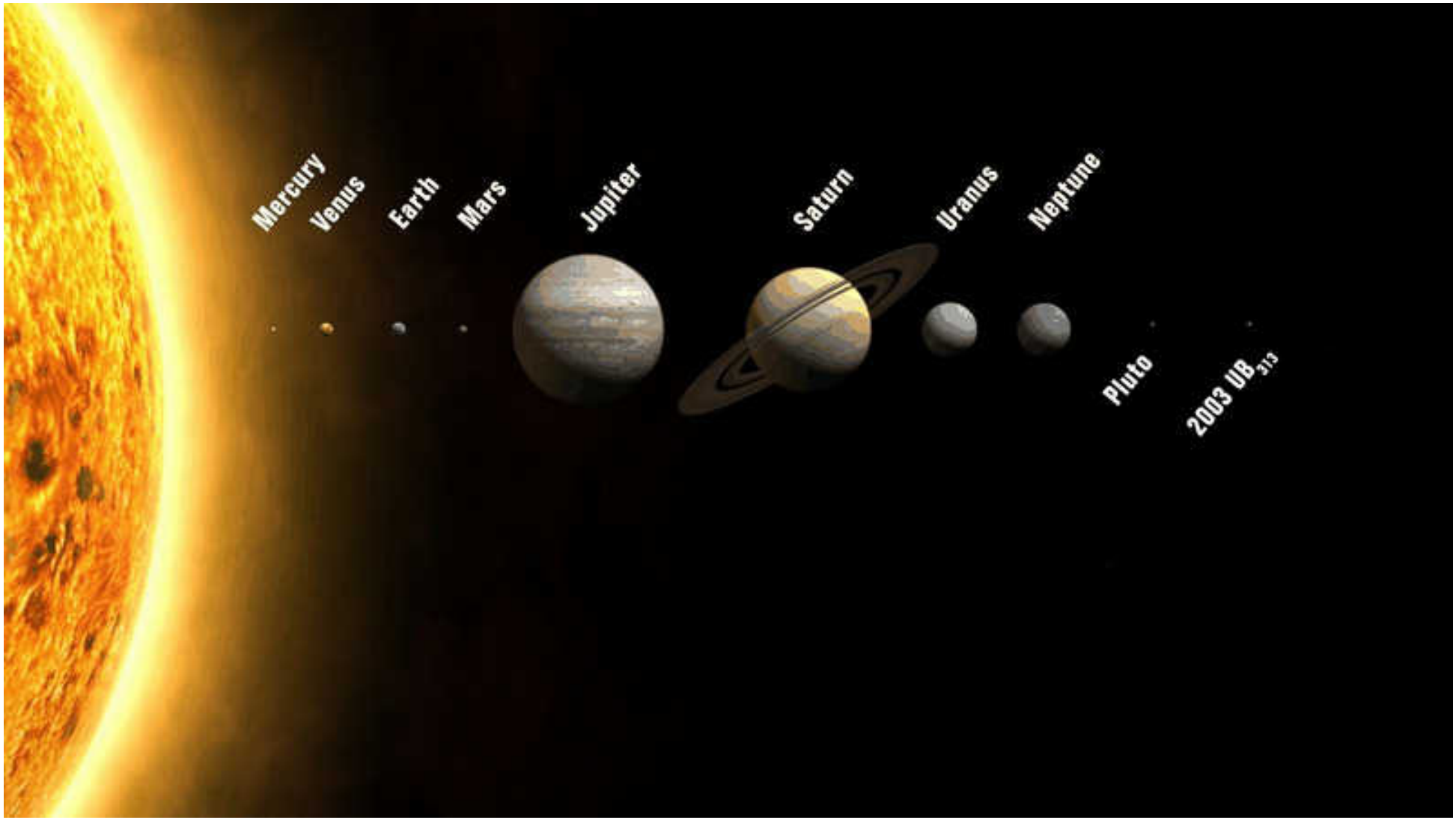


Figure 101 Planets

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Color

General

The differences in color of light that we perceive with our eyes are actually differences in the frequency or wavelength of the electromagnetic waves falling on the retina. The higher the frequency of light, the bluer the light will appear to us until the frequency is so high that it becomes ultra violet and is outside the visual range of our sight. Likewise, the lower the frequency of the light, the redder it will appear until the frequency is so low that it becomes infra red and again cannot be detected by our eyes.

Unit

The light waves have very small wavelengths and they are measured in nanometers (nm).

Typical values for light wavelengths of different colors would be:

Red	700 nm
Yellow	580 nm
Violet	400 nm

Frequency

Frequency, speed of the wave and wavelength depend on each other.

The relationship between speed (v), frequency (f) and wavelength (λ) is as follows: the wave travels along the distance of one wavelength in the time taken to complete one oscillation. This is the velocity v.

For the speed of light, c is used instead of v.

Distance = speed x time:

$\lambda = c \cdot T = \frac{c}{f}$, since $T = \frac{1}{f}$

To find the frequency f:

$f = \frac{c}{\lambda}$

Yellow has the frequency of 518 THz.

Visible and Invisible Wavelengths

Wavelengths greater than 700 nm and less than 400 nm are invisible to the human eye but this does not mean that they are not there.

Many types of electromagnetic wave are invisible to the eye but can be detected by instruments such as X-rays. We cannot see the radiation but it is detected by the X-ray film and can be developed as an image.

Old Unit

An old unit to measure the wavelength of light is Angstroms.

1 Angstrom = $1 \times 10^{-10} m$.

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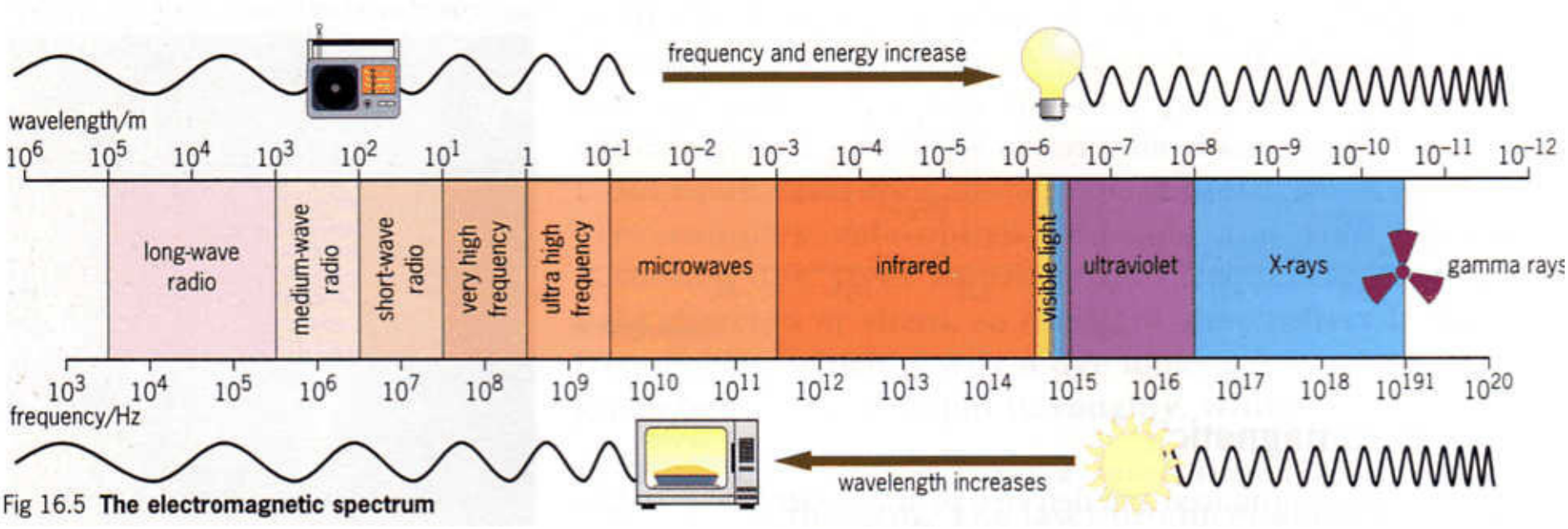


Fig 16.5 **The electromagnetic spectrum**

Figure 102 Electromagnetic Spectrum

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Reflection

General

When light falls on a surface then some of the light bounces off and is said to have been reflected. As we look at reflection we shall refer to the light falling onto the surface as the 'incident ray' and the light coming off as the 'reflected ray'.

In the figure below it can be seen that the light falling onto a mirror surface is reflected away at an angle. It has been found by experiment that the angle of incidence (i) is equal to the angle of reflection (r). This is also mentioned in Snell's law of reflection:

$$(i) = (r)$$

The diagram below (left) shows this.

Reflection at Plane Surfaces

Everyone has seen a mirror and observed their own reflection in it but where is the reflection and why is it there? If we move towards the mirror we observe that the reflection appears to get closer to us and as we move away so the image moves back. From this it appears that the image is behind the mirror but we know this is impossible as we cannot see through the mirror so the image must be an illusion. This illusory image is known as a ***virtual image*** as the image is not really there. A virtual image cannot be projected onto a screen but a ***real image*** can. The mirror image that we see is also a lateral inversion as can be seen by trying to read a number plate in the rear view mirror of a car.

If two mirrors are used then the image in the second mirror will be inverted again and will be the right way round such as in a periscope.

The image observed in a plane mirror is:

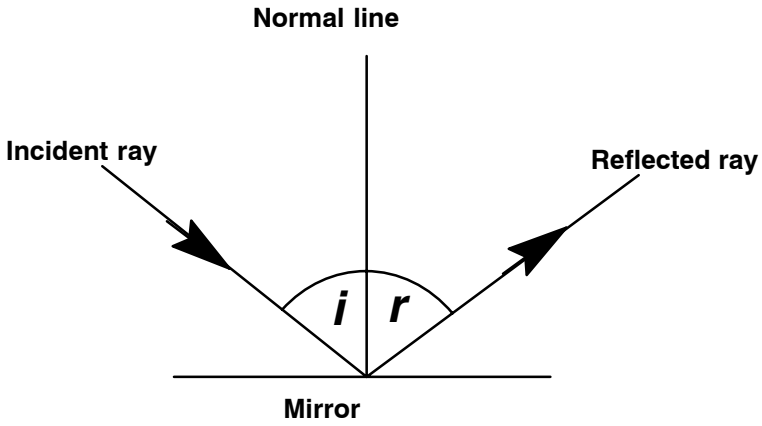
- laterally inverted but the right way up,
- the same size as the object,
- virtual,
- as far behind the mirror as the object is in front.

In the diagram below (right) we see a reflection in a plane mirror and it can be seen that although the object is in front of the mirror, the image is behind the mirror and must then be a virtual image as we could not capture this image on a screen, we can only see it as an illusion.

Also from this diagram we can see that the image is the same size as the object and is the same distance behind the mirror as the object is in front of it.

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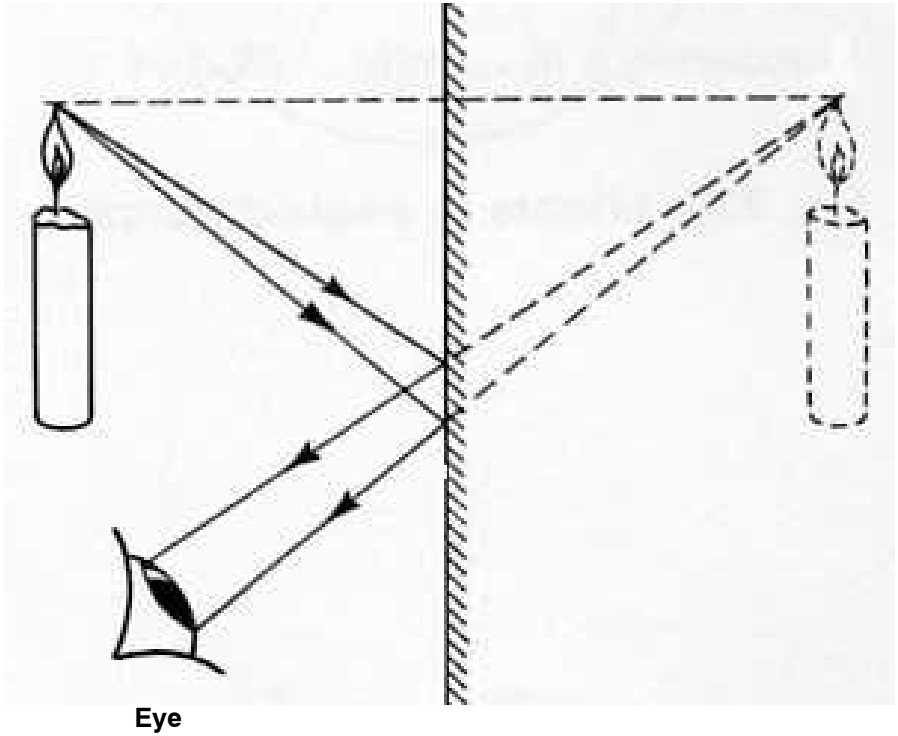


Figure 103 Reflection in a Plane Mirror

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Reflection by Spherical Mirrors

The general rules discussed above for reflection can be applied to reflections in mirrors of any shape. The incident ray will fall on the mirror surface and be reflected at the same angle but on a curved or irregularly shaped mirror the incident ray will fall at many different angles within a small area and cause a distortion of the image. Most of us have observed for example that our image viewed in a spoon appears upside down while our image on the back or a spoon appears very small. This is due to incident rays falling on a constantly changing surface.

Concave Mirrors

A concave mirror can be thought of as the inside surface of a spoon.

If the curve is constant, ie. the mirror makes up part of a sphere, then a line drawn at 90 degrees to the center of the surface of the mirror is known as the principal axis. All incident rays parallel to the principal axis will be reflected by the mirror and will be focussed on a point on the axis known as the focal point normally denoted as F. The focal point of the mirror will be on the principal axis and at a distance from the mirror surface of half the radius of the mirror's curvature.

If an object is reflected in a concave mirror it can be observed that sometimes the image is the right way up and sometimes inverted. If the object is between the focal point and the mirror then the image will be the right way up. If the object is further away than the focal point of the image is inverted and the image is real.

The degree of magnification is dependent upon the actual distance away.

Convex Mirrors

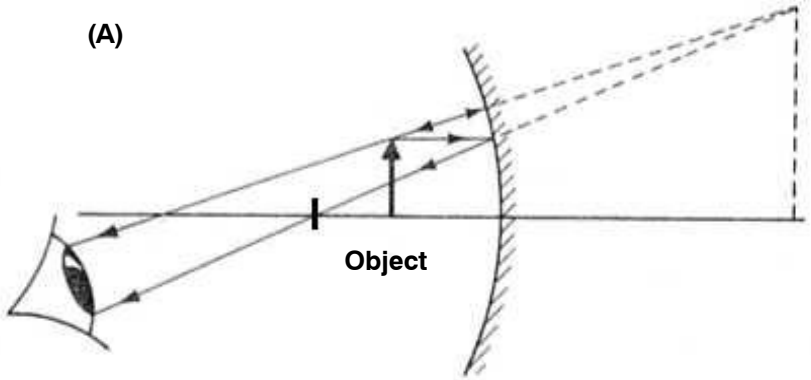
A convex mirror can be considered as the back of the spoon.

If our image is viewed in a convex mirror then it appears the right way up but diminished in size. The focal point is again half of the radius of the mirror's curvature but this time it is behind the mirror. The image is virtual.

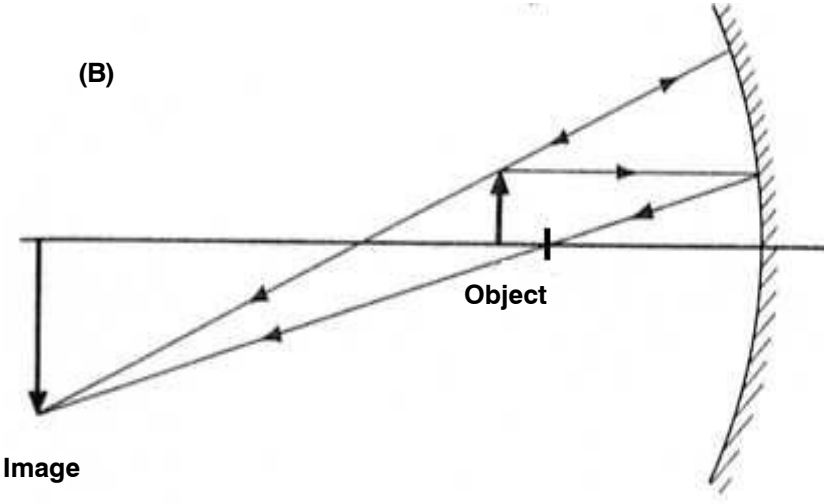
In each of these cases, convex and concave, the image is beyond the mirror surface and is a virtual image.

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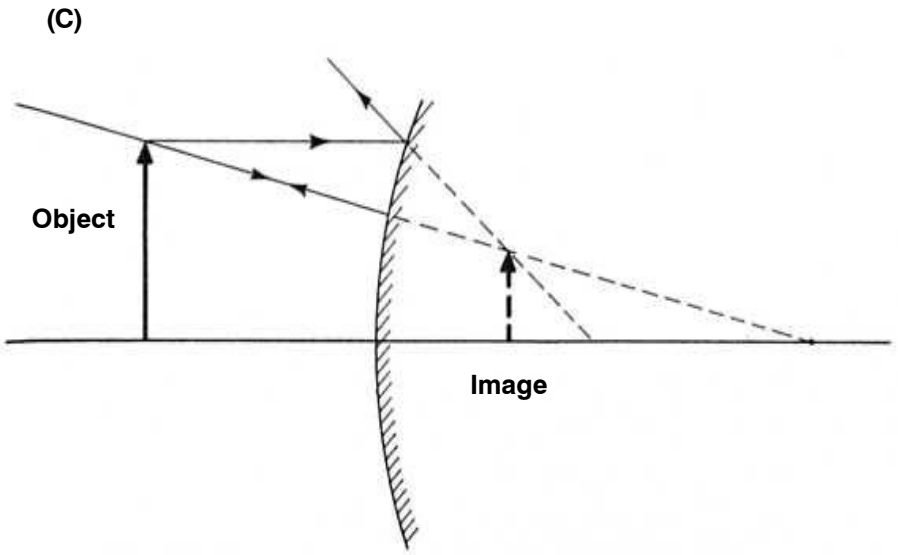
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(A) Object placed between principal focus and concave mirror causing virtual image.



(B) Object placed beyond principal focus causing real image.



(C) Object placed in front of convex mirror causing virtual image.

Figure 104 Reflection in Curved Mirrors

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Refraction

General

We have all observed that a stick placed half in, half out of a pond appears to be bent at the water's surface or that a tarmac road appears to shimmer on a hot sunny day. These phenomena are caused by refraction. As the light passes from one medium to another, such as air to water or hot air to cold air, the light changes direction and causes the image to be distorted. This change of direction is caused by the fact that light travels at different speeds through different materials.

Block of Glass

In the figure below it can be seen that if the light passes from air into a piece of glass at any angle other than 90 ° then the light will bend. Because it cannot travel as fast in glass as in air causing the wavelength to change ($c_{glass} = 186\,000\ \frac{km}{s}$; $c_{air} = 299\,793\ \frac{km}{s}$). If light is observed crossing from air into a block of glass and a line is drawn at 90 ° to the surface of the glass (a *normal* line) at the point the light enters, the light is seen to bend towards the normal. Likewise the light as it passes from glass into air is seen to bend away from the normal.

If the piece of glass has parallel sides then the ray emerges in the same direction as it entered but is displaced along the block.

A ray entering along the normal (at 90 ° to the surface) it is refracted parallel to itself.

Prism

It should be noted that the refraction is different for light of different frequencies. This can be proven in a prism where white light (which is made up of light of many frequencies and thus many colors) can be split and the colors of the rainbow observed. (See Newton's experiment below). This effect can also be observed to a lesser extent in cheap optical devices where a multicolored fringe can be seen and also in the atmosphere when rain is falling whilst the sun is shining and a rainbow appears.

Laws of Refraction

The laws describing refraction were established by a Dutch scientist named Snell who was a student of law at the University of Leiden in the Netherlands but who also had an interest in mathematics.

Snell's law states that the ratio of the sine of the angle of incidence and the sine of the angle of refraction is a constant.

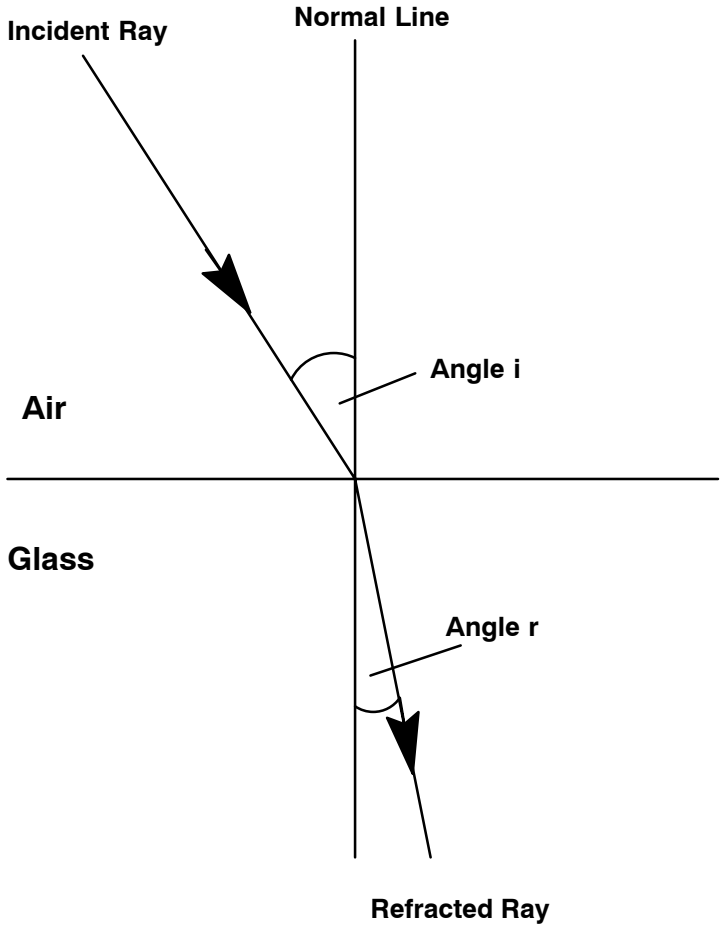
$$\frac{(\sin i)}{(\sin r)} = k$$

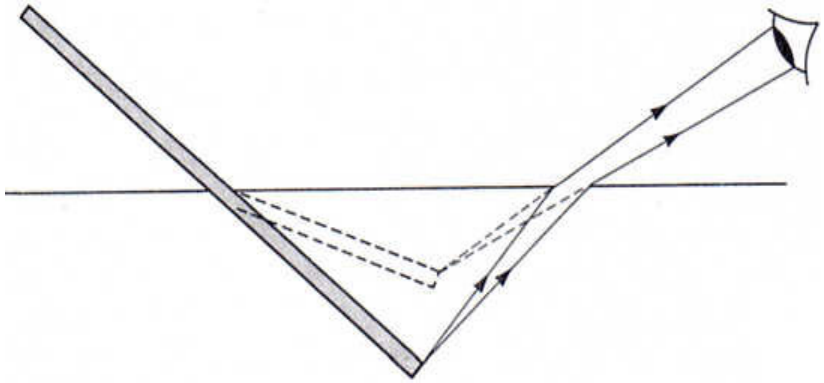
Refractive Index

The constant *k* is referred to as the refractive index of the second medium with respect to the first.

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The reason a stick appears bent when half in, half out of the water

Figure 105 Refraction at a Plane Surface

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Newton's Dispersion Experiment

General

Sir Isaac Newton experimented with light and found that if he allowed sunlight to enter through a very small hole in a window shutter it projected a white spot on the wall of the room. Then he placed a triangular glass prism in front of the light and found that an area of multicolored light was formed. Newton did not fully understand light but today we know that the reason for this phenomena is that white light is made up of light of all colors and because different colored light is refracted at different angles, the various colors were refracted in different directions. Newton called this colored band the spectrum.

The process of the splitting of light into different colors is known as dispersion.

Colors of the Spectrum

The colors of the spectrum are widely accepted to be red, orange, yellow, green, blue, indigo and violet but in reality there are no color boundaries as one color fades seamlessly into the next and the spectrum does not stop at red and violet but continues into the frequencies which are invisible to the human eye, infrared and ultraviolet.

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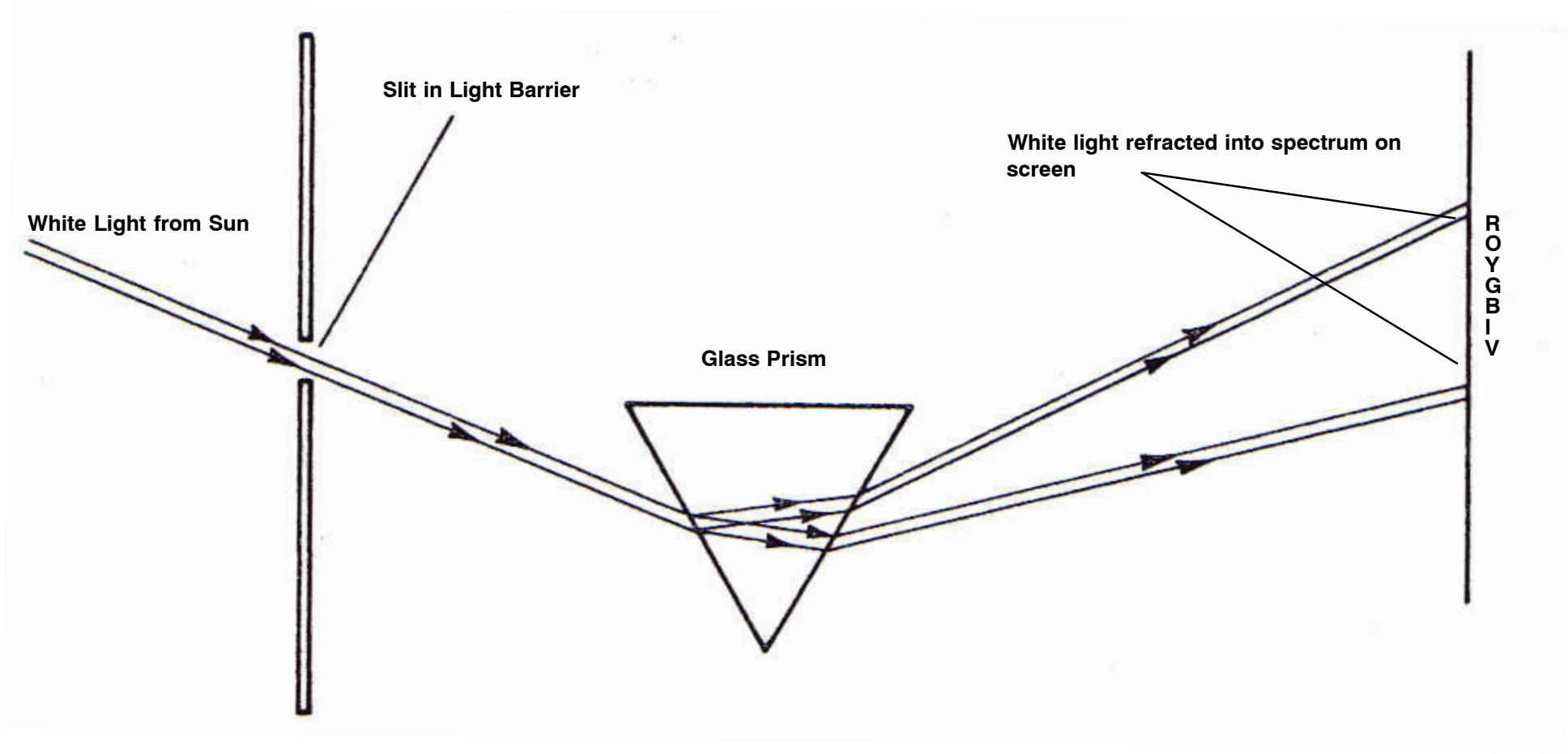


Figure 106 Dispersion of White Light through a Prism

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Lenses

General

A lens is an optical device normally used to enhance an image and focus it upon a certain point. Lenses form images in much the same way as curved mirrors but by refraction rather than reflection.

Lenses are manufactured in a variety of shapes according to their intended use and by applying our knowledge of refraction we can analyze the function and uses of some of these lenses.

CONVEX LENSES (CONVERGING LENSES OR BICONVEX LENSES)

A simple convex lens has two spherical convex surfaces each of the same curvature. This is the kind of lens we have all used as a magnifying glass and is used in many other optical devices such as spectacles, projectors etc.

As discussed above, a ray of light as it enters the lens will be refracted towards the normal. This time however the sides of the glass are not parallel so the light leaving the lens is travelling in a different direction to the light entering.

As this focussing is caused by the rays of light being directed towards each other, a convex lens is also called a *converging* lens.

If an object is viewed through a convex lens it is possible to obtain an image which is either erect or inverted depending on the distance from the lens to the object (the object distance).

Principal Focus

In the case of a convex lens all the rays will be focussed on one point known as the ***principal focus***.

Focal Length

For an optical system in air, it is the distance between the optical centre and the focus.

The symbol for Quantity is *f*.

The meter (m) is the unit of the focal length.

Distance < f

If the object is closer to the lens than the principal focus (distance < f, see Object 1) then the image will be virtual image, right up, and will appear larger than the object (magnified).

The magnification is due to the virtual image that appears to the eye.

Distance > f

If the object is beyond the principal focus (distance > f, see object 2) then the image will be real, upside down and will be magnified, when the distance is more then 2f the image is reduced.

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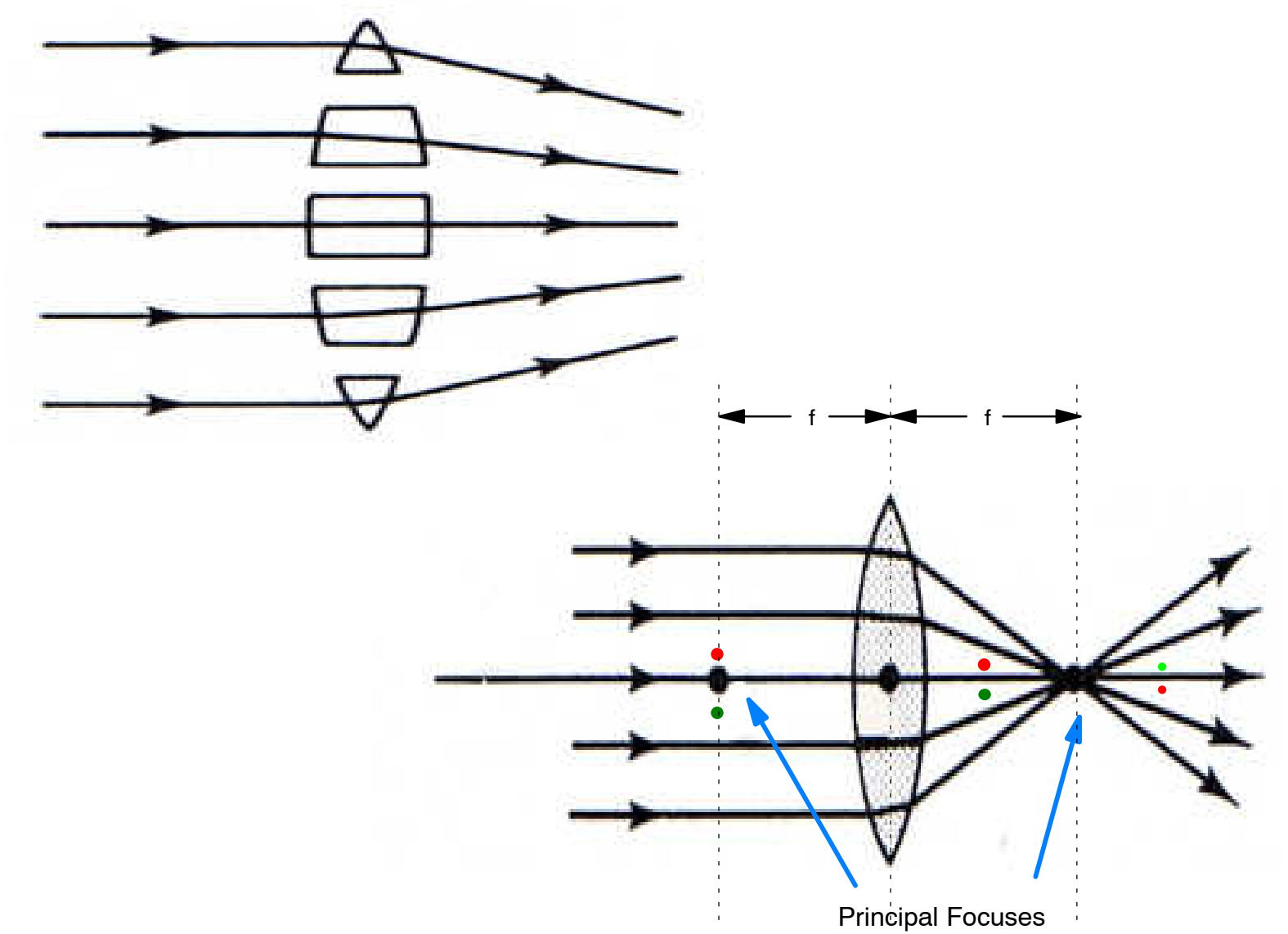


Figure 107 Refraction Through Convex Lenses

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CONCAVE LENSES OR DIVERGING LENSES

A concave lens is thicker at the ends than in the middle and has two spherical sides. This kind of lens is also used in optical devices such as spectacles, camera lenses etc. As in the case of the convex lens, it causes refraction of the light rays falling on it but this time because of it's different shape the effect is different. The lens has a principal focus but this time the light does not focus on this point but appears to originate from it.

The image formed by a concave lens is always virtual, right way up and reduced in size.

As the rays of light fall on the lens they are refracted away from each other and for this reason a concave lens is also called a *diverging* lens.

The function of each type of lens can be better visualized if the lens is considered as a series of small individual prisms and the light is considered as individual rays.

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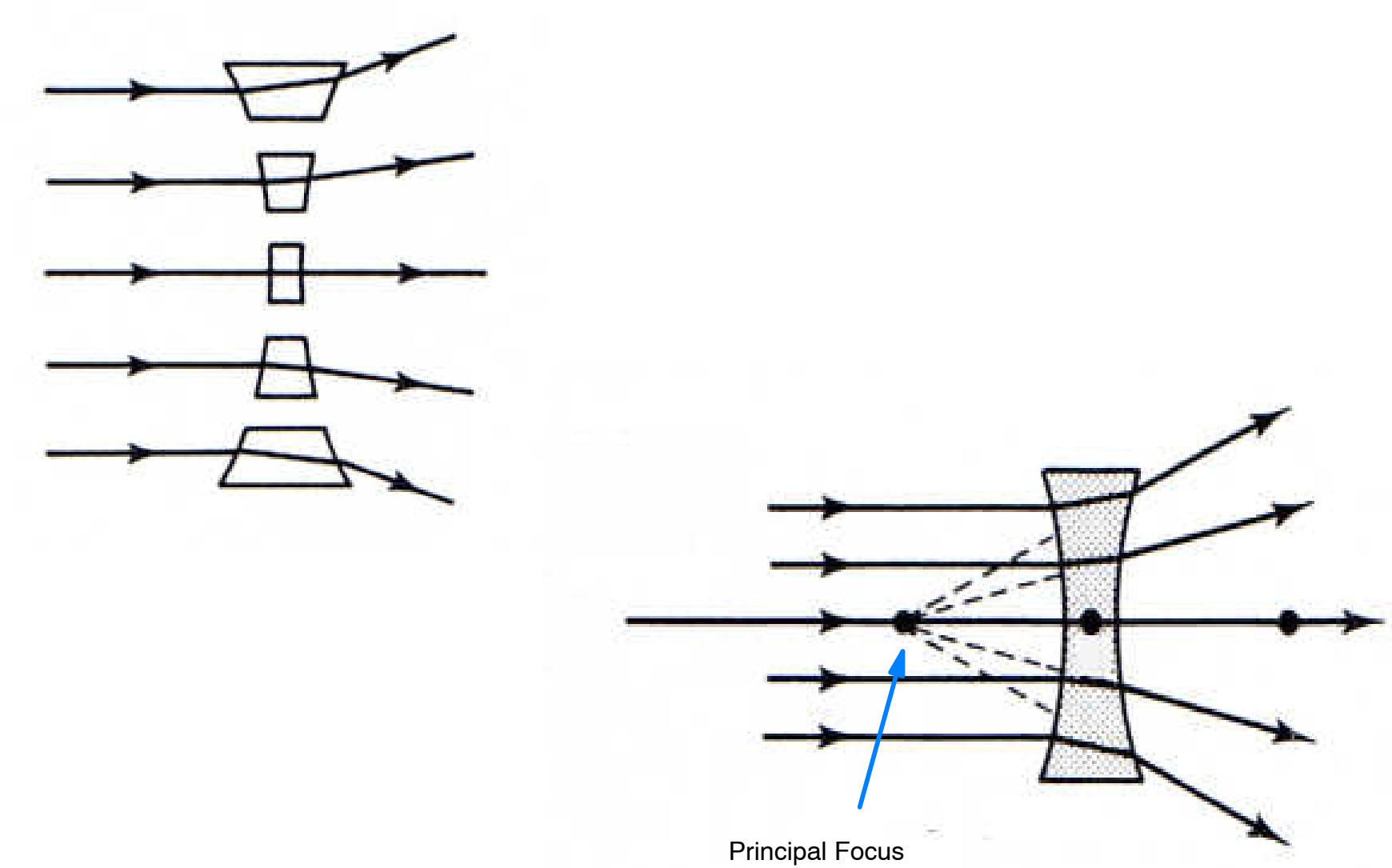


Figure 108 Refraction through Concave Lenses

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Fibre Optics

General

Fibre optics are used in all sorts of applications for the transmission of data. The information is converted to a light signal which is transmitted along a hair-thin strand of glass or plastic and then at the other end the signal is reconverted into information.

Advantages

Fibre optics have certain advantages over metal wires.

They are lighter and smaller, a fibre optic cable of 0.005 in diameter with a protective jacket of 0.25 in diameter can replace a wire bundle 3 in in diameter. This is an obvious advantage on an aircraft where space and weight are critical.

They can carry far more information than metal wires. A single pair of fibre optic cables can carry as much information as 64,000 telephone calls simultaneously.

They are safer, there is no electricity being conducted so there is less risk of damage to the cables causing a fire.

Disadvantages

The main disadvantage of fibre optic cables is that they are difficult to terminate.

The fibres are also difficult to repair because they are so small, thinner than a human hair.

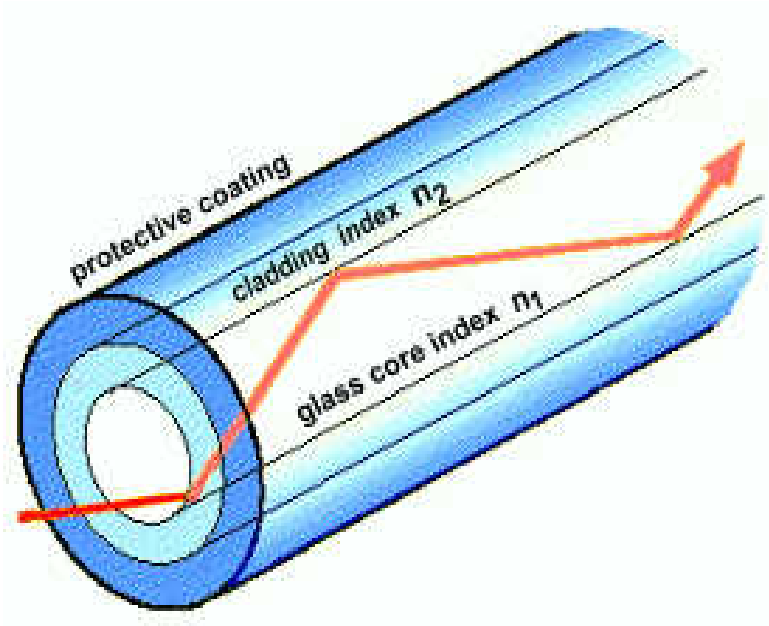
Construction and Operation

A fibre optic strand has a core with a high refractive index and a sheath with a low refractive index so that all of the light is reflected back into the fibre and as little as possible is lost. This is known as 'total internal reflection'. In this way the signal can be transmitted over large distances with little loss of signal. The greatest loss of signal occurs at connectors and couplings.

In the left picture on the next page we can see a cut away view of a fibre optic cable showing the internal reflection of the light along the fibre. On the right a bundle of fibres is shown giving some idea of their size.

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Cross section of a fibre optic cable.



Bundle of fibres

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Figure 109 Fibre Optic Cables

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SI Units

INTRODUCTION

Unit Systems

The system of measurement is based mainly on the International System of Units, usually abbreviated SI (french: System International).

However, aircraft maintenance data expressed in imperial units (English system) and US units are still used and will remain in use for many years.

Therefore the aircraft mechanic need to know both the SI and imperial systems together with some US variations of the imperial system, and the knowledge of conversion.

General

Seven base units are used in the SI system.

The seven base (or primary) SI units are:

The Symbol for Quantity may be different depending on the language. For example, the Symbol for Voltage is V, whereas in German the symbol for “Spannung“ is U.

There are also minor differences between British English and American English. For example, for length the Americans write “meter“ , whereas the British write “metre“.

BASE UNITS

Name of Quantity	Symbol for Quantity	SI Base Unit	Symbol for Unit
Length	*l, d* and others	meter	m
Time	*t*	second	s
Mass	*m*	kilogram	kg
Electric Current	*I* or *i*	ampere	A
Thermodynamic Temperature	*T*	kelvin	K
Amount of Substance	*n*	mole	mol
Luminious Intensity	I_v	candela	cd

Supplementary Units

Two supplementary units relate to quantities of angle. One is for plane angles (the region cut out in a plane by two straight lines diverging from a point), and the other for solid angles (the region cut out in space by an orbitrary cone):

Name of unit	Quantity	Symbol
radian	plane angle	rad
steradian	solid angle	sr

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DERIVED UNITS

Introduction

Derived units are always made up from two or more other units which may be base units, supplementary units or other derived units. Some derived units such as the joule, the watt and the newton are named after eminent scientists.

Others have complex names which are derived from the units comprising them, such as meter per second (a combination of two base units) and radians per second (a combination of a supplementary unit and a base unit).

Derived Units

Name of Quantity	Derived Unit	Symbol for Unit
Frequency	hertz	Hz
Force	newton	N
Pressure	pascal	Pa
Work	joule	J
Power	watt	W
Electric Charge	coulomb	C
Voltage (Electromotive Force)	volt	V
Electrical Capacitance	farad	F
Electrical Resistance	ohm	Ω
Electrical Conductance	siemens	S
Electrical Inductance	henry	H

Derived Units with Complex Names

Name of Quantity	Derived Unit	Symbol for Unit
Heat Capacity	joule per kelvin	J/K
Apparent Power	volt ampere	VA
Velocity, Speed	meter per second	m/s
Torque	newton meter	N m
Density	kilogram per cubic meter	kg/m^3

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SI SYMBOLS AND PREFIXES

General

The plural of a symbol is identical to its singular form, as with 1 m and 153 m.

Symbols for derived units with complex names are combinations of the constituent unit symbols.

Products

The product of two or more unit symbols may be indicated by a half-high dot, or where there is no risk of confusion with another unit symbol, the dot may be omitted and a space is used.

Thus N · m or N m is the symbol for newton meter.

Divisions

The division of one unit by another in a complex unit is indicated by a negative index, an oblique stroke(/), or a horizontal line.

For example, a kilogram per cubic meter (the unit for desnity) is expressed as

- kg m^{-3},
- kg/m^3,or
- $\frac{kg}{m^3}$

Multiples and Submultiples

Factors of 10 are always used as multiples and submultiples of SI units.

The meter for example, is useful for measuring objects such as the size of a hangar, but many zeros would be required to express the maximum range of a jet airliner in meters.

Similarly it would be cumbersome to express small measurements, such as a conact breaker gap, as a decimal fraction of a meter.

Prefix

Multiples and submultiples of SI units are formed by attaching a prefix to the name of the unit. The symbol and the multiplication factor of the prefix listed in the table.

Generally, it is preferable to use the prefixes that advance or decline by factors of 10^3. Thus the use of hecto, deca, deci and, to a lesser extent, centi, are not encouraged. The most commonly used prefixes are

- kilo
- mega
- milli and
- micro.

Prefix symbols should be written or printed without spacing between the prefix symbol and the unit symbol, as in mm and kW.

Compound prefixes, such as milli–micro should not be used.

In general only one prefix should be used in forming the symbol for a unit.

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Metric Prefixes

Prefix	Symbol	Multiplication factor
tera	T	10^{12}
giga	G	10^{9}
mega	M	10^{6}
kilo	k	10^{3}
hecto	h	10^{2}
deca	da	10
deci	d	10^{-1}
centi	c	10^{-2}
milli	m	10^{-3}
micro	μ	10^{-6}
nano	n	10^{-9}
pico	p	10^{-12}
femto	f	10^{-15}
atto	a	10^{-18}

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ICAO SPECIFIED UNITS FOR A/C COMMUNICATIONS

General

The International Civil Aviation Organization (ICAO) in its role of promoting international standards and recommended practices has published two alternative tables of units of measurement for use in air to ground communication.

These are:

- the ICAO Table and
- the Blue Table.

They differ only in the units specified for altitudes and vertical speed.

Most English–speaking countries have adopted the Blue Table, but some of these countries vary from it for some units.

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Measurement of	UNITS IN ICAO TABLE	UNITS IN BLUE TABLE
Distance used in navigation position reporting etc. — generally excess of 2 to 3 nautical miles	NAUTICAL MILES and TENTHS	NAUTICAL MILES and TENTHS
Relatively short distances such as runway lengths	METERS	METERS
Altitudes, elevations and heights	METERS	feet
Horizontal speed including wind speed	KNOTS	KNOTS
Vertical speed	METERS PER SECOND	feet per minute
Wind direction for landing and taking off	DEGREES MAGNETIC	DEGREES MAGNETIC
Wind direction except for landing and taking off	DEGREES TRUE	DEGREES TRUE
Visibility including runway visual range	KILOMETERS or METERS	KILOMETERS or METERS
Altimeter setting	MILLIBARS	MILLIBARS
Temperature	DEGREES CELSIUS (CENTIGRADE)	DEGREES CELSIUS (CENTIGRADE)
Weight (see Note 2 below)	METRIC TONS (TONNES) or KILOGRAMMES	METRIC TONS (TONNES) or KILOGRAMMES
Time	HOURS and MINUTES, THE DAY OF 24 HOURS BEGINNING AT MIDNIGHT	HOURS and MINUTES, THE DAY OF 24 HOURS BEGINNING AT MIDNIGHT

Note 1: Wherever units are common to both tables they appear in the Blue Table printed in capitals.

Note 2: ICAO uses the term 'weight' to denote 'mass'.

Figure 110 ICAO Tables

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CONVERSION OF UNITS

General

As already mentioned, the majority of the countries in Europe and most of the countries in the world are using the SI units to define the basic units and their derived units.

The remaining countries e.g. Great Britain and the USA are using an older system called the imperial system. The imperial system uses units which are historically grown and developed over centuries (e.g. feet, inches, yards, pounds and gallons). It is still used in aviation until today.

Length

1 in (inch)	=	25.4 mm
1 m	=	39.37 in or 3.281 ft
1 ft (foot)	=	12 in or 0.3048 m
1 yd (yard)	=	3 ft or 36 in or 0.9144 m
1 km	=	0.621 miles
1 mile	=	1760yd = 5280 ft or 1.61 km
1 n.m.	=	1.151 miles or 1.852 km

Area

1 m^2	=	10.000 cm^2
1 m^2	=	10.76 ft^2
1 acre	=	4840yd^2 = 4046.87m^2
1 yd^2	=	9 ft^2
1 ft^2	=	144 in^2 or 0.0929 m^2
1 in^2	=	6.452 cm^2

Volume

1 m^3	=	1 000 000 cm^3 = 1000 litre
1 ft^3	=	1728 in^3 = 0.0283 m^3
1 litre	=	1000 cm^3 = 1.0576 qt (US)
1 qt (US quart)	=	0.8327 qt (UK) = 0.9464 litre
1 gal (US gallon)	=	8 pints (US)
1 gal (UK)	=	4.546 litres
1 gal (US)	=	3.785 litres

Mass

1 metric ton	=	1000 kg
1 kg	=	1000 g
1 lb	=	0.4536 kg = 453.6 g
1 lb	=	16 oz
1 oz	=	28.3495 g

Velocity

1 km/h	=	3.6 m/s
1 m/s	=	3.281 ft/s
1 mph	=	1.47 ft/s
1 mph	=	1.61 km/h
1 knot	=	1.688 ft/s
1 knot	=	1.151 mph
1 knot	=	1.852 km/h

Force & Weight

1 N	=	0.2248 lbf
1 N	=	3.5969 ozf

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Torque

1 daNm	=	10 Nm
1 Nm	=	8.851 lbf in
1 lbf ft	=	12 lbf in

Power

1 HP (metric)	=	735.4988 W
1 HP (UK)	=	745.6999 W
1 HP (metric)	=	0.9863 HP (UK)
1 HP (metric)	=	542.4760 lbf ft/s
1 HP (UK)	=	550 lbf ft/s
1 W	=	0.738 ft lb/s
1 Btu/h	=	0.293 W

Pressure

1 Pa	=	0.000145 lb/in^2
1 bar	=	100 000 Pa = 1000 hPa
1 bar	=	14.5038 PSI
1 bar	=	750.0638 mmHg
1 bar	=	29.53 inHg
1 atm	=	29.92 inHg
1 PSI	=	689 kPa

Energy

1J	=	0.738 ft lb
1 cal	=	4.186 J
1 Btu	=	252 cal

Time

1 year	=	365 days
1 day	=	24 h = 1440 min

Temperature (conversion formula may required)

Δ1 °C	=	Δ1 K (Kelvin)
1 °C	=	33.8 °F (Fahrenheit)
1 °F	=	– 17.22 °C
1 °C	=	493.47 °R (Rankine)
1 °R	=	– 272.59 °C or – 458.67 °F or 0.5556 K
0 K	=	– 273.15 °C or – 459.67 °F or 0 °R

$$^{\circ}F = \left(^{\circ}C \times \frac{9}{5}\right) + 32$$

$$^{\circ}C = (^{\circ}F - 32) \times \frac{5}{9}$$

Other Useful Data

1 litre water	=	1 kg
1 pint water	=	1 lb

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