7.2.1 MATTER AND ENERGY[M2]

The Earth is one small planet revolving around and average star, the Sun, which is located in the Milky Way galaxy. The Milky Way is a galaxy of average size that contains about 100 billion stars. There are tens of billions of galaxies, and the universe contains at least 10^{24} stars. All stars emit light, a form of radiant energy. The analysis of light emitted by stars enables scientists to determine their composition. Studies of the types of substances present at various stages in the life of a star indicate that all objects in the universe are composed of the same fundamental materials as the earth. Scientists classify material substances as *matter*. Thus, they broadly interpret the entire physical universe in terms of two major concepts: *matter* and *energy*.

Matter is, in fact, a form of energy, and the two are related by Einstein's famous equation $E=mc^2$. Matter and energy, nonetheless, have their own distinct characteristics.

7.2.1.1 Matter and its Measurement

Matter is a fundamental concept for which there is no precise definition. The best we can do is to describe its characteristics. Thus we begin with the general observation that *matter has mass and occupies space*.

Mass is the quantity of matter in a material body that gives it inertia. The *mass of a body is constant and is independent of location.* ***Inertia*** is that property possessed by a material body at rest that tends to keep it at rest. It is, in addition, that property possessed by a body in motion that tends to keep it in motion in the same direction and with the same velocity.

Determining the mass of an object by measuring its inertia is not practical. Scientists use weight as a measure of the mass of an object. ***Weight*** is actually a *force*. It is a measure of the gravitational attraction between the earth and the object being weighed. It depends upon the mass of the object, the mass of the earth, and the distance of the object from the centre of the earth. Whereas *mass is a fixed property of an object and remains constant, the weight of an object may vary.* For example, an object having a weight of 600 kg on earth would weigh 100 kg on the moon and be weightless in outer space. Its inertia, and hence its mass however, would be the same on the moon and on earth as it is in outer space. Since the weight of an object remains essentially constant everywhere on the earth's surface, however, the terms mass and weight are commonly used interchangeably. For the sake of accuracy, however, scientists prefer to use the term *mass*. We measure mass, and weight, in kilograms (kg).

This is an appropriate point at which to introduce the fundamental elements of measurement and mathematical notation used in the sciences.

7.2.1.1.1 Units of Measure

The International System of Units (abbreviated SI, from *Système International d'Unités*), the 'modern' form of the metric system[1], is used throughout the various fields of science in the measurement of physical quantities. Prior to the formal adoption of the SI system in 1960, different variants of the metric system were in use throughout the world. While they were all based on the same fundamental units, the MKS (metre-kilogram-second) and CGS (centimetre-gram-second) systems used units which were more convenient in particular fields of study. The SI system defines seven

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[1] The metric system was created during the French Revolution and formally adopted by First Consul Bonaparte (later Napoleon I) in France on 10 December 1799.

base units of measurement, each of which is, by convention, held to be dimensionally independent:

SI Base Units

Name	Symbol	Quantity
kilogram	kg	Mass
second	s	Time
metre	m	Length
ampere	A	Electrical Current
kelvin	K	Temperature
mole	mol	Amount of Substance
candela	cd	Luminous Intensity

All other units of measurement can be derived from these base units.

A prefix, as indicated in the following table, may be added to units to produce a multiple of the original unit.

SI Base Unit Prefixes

Power	Prefix	Symbol	Multiplier
10^{24}	yotta	Y	1 000 000 000 000 000 000 000 000
10^{21}	zetta	Z	1 000 000 000 000 000 000 000
10^{18}	exa	E	1 000 000 000 000 000 000
10^{15}	peta	P	1 000 000 000 000 000
10^{12}	tera	T	1 000 000 000 000
10^{9}	giga	G	1 000 000 000
10^{6}	mega	M	1 000 000
10^{3}	kilo	K	1 000
10^{2}	hecto	H	100
10^{1}	deca	da	10
10^{0}	*(none)*	*(none)*	1
10^{-1}	deci	d	0.1
10^{-2}	centi	c	0.01
10^{-3}	milli	m	0.001
10^{-6}	micro	µ	0.000 001
10^{-9}	nano	n	0.000 000 001
10^{-12}	pico	p	0.000 000 000 001
10^{-15}	femto	f	0.000 000 000 000 001
10^{-18}	atto	a	0.000 000 000 000 000 001
10^{-21}	zepto	z	0.000 000 000 000 000 000 001
10^{-24}	yocto	y	0.000 000 000 000 000 000 000 001

7.2.1.1.2 Scientific Notation

When making scientific calculations, we are often required to use very large or very small numbers. For convenience, such numbers are generally presented in an exponential form known as *scientific notation*. In scientific notation a number is written as a two-part product—the first part is the *digit term*, and the second the *exponential term*. For example, the speed of light, 300,000,000 m/sec, is expressed in scientific notation as 3×10^8 m/sec.

Scientific notation also includes an element of *accuracy*. The value for the speed of light given above indicates that the speed of light is not exactly 3×10^8 m/sec—there is some uncertainty in the figure 3. Should we wish to be more precise, we might write 3.0×10^8 m/sec. This representation indicates that there is no uncertainty in the figure 3, but that the zero that follows the decimal point is uncertain. However, we can be sure that the speed of light is not 2.9×10^8 m/sec or 3.1×10^8 m/sec—it is somewhere in between these two values. There is some degree of uncertainty in all scientific measurements. One way of indicating uncertainty is to include in a number only one digit that is not certain. The total number of digits in such a number is referred to as the number of significant digits or *significant figures*.

7.2.1.2 Exploring the Nature of Matter

How might we discover more about the characteristics of matter? We might try to bend it, stretch it, squeeze it, scratch it, heat it or cool it. These and many other tests might help us to understand how matter behaves.

Let us look fist at what happens when we heat matter (Experiment 2.0).

7.2.1.2.1 States of Matter

Note what happens when we heat some chunks of ice in a test tube. Adding heat to ice causes a change in the ice. The ice melts, and turns into water. We know that if we take the heat away again (by placing the water in a freezer), the water will turn back into ice. So ice can evidently exist in at least two states: the solid state we know as ice, or the liquid state we know as water. When ice melts to form water or water freezes to form ice, the change is called a **change of state**.

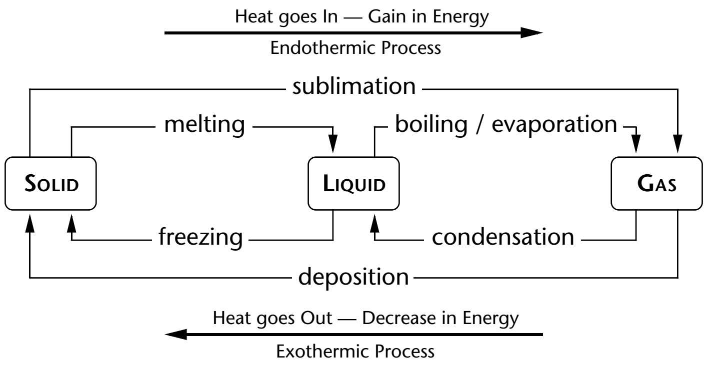
If we continue to heat the water in the test tube, we note that it begins to bubble, or boil. If we hold a cold watch glass above the mouth of the test tube we soon see droplets of water appearing on the surface of the watch glass. In the 'clear' space between the water in the test tube and the drops of water on the watch glass, there is water existing in a third state. It is not a solid and it is not a liquid. It is a gas or vapour, and this gaseous form of water is steam.

We have found a common form of matter that can exist in three states. Heat is involved in changing from one state to another. The solid state **melts** when it is heated, forming a liquid. The liquid **boils**, or **evaporates**, when heated to form a gas. Cooling the gas—taking the heat away from it—causes it to **condense** back to a liquid, which if cooled further ultimately **freezes** to become a solid.

Changes in which a system absorbs heat energy are known as **endothermic changes**. Thus, melting and boiling are endothermic state changes. Changes in which a system liberates heat energy are known as **exothermic changes**. Thus, freezing and condensation are exothermic state changes.

Observe some other forms of matter [sulphur, naphthalene & iodine] when they are heated and note how they behave (Experiments 2.1 – 2.3).

Note from our experiments that we are not able to observe the liquid state of iodine under normal atmospheric conditions: it changes directly from a solid to a gas. This state change is known as **sublimation**. Similarly, when iodine vapour cools, it forms a solid without first forming a liquid. This state change is known as **deposition**. Carbon dioxide (dry ice) also behaves in this way, although it sublimes at a much lower temperature (-78.5 °C) than iodine.



Having observed that matter can exist in three different states, carry out some more tests and note any differences in the behaviour of matter in these three states.

7.2.1.2.2 Compressibility

Using syringes filled respectively with air (acetylene) and water (methylated spirit, shellite), note the relative compressibility of these substances (Experiments 2.4 & 2.5).

Note the general lack of compressibility in solids: metals, rocks, crystals in general.

7.2.1.2.3 Space-Filling Behaviour

Observe the space filling behaviour of nitrogen dioxide, water (and other liquids) and any available solids (Experiment 2.6).

7.2.1.2.4 Rate of Diffusion

Observe the diffusion (mixing) of one gas (propane) with another (air).

Observe the diffusion of nitrogen dioxide generated by the action of nitric acid on copper (Experiment 2.6).

Observe the diffusion of copper nitrate solution into water (Experiment 2.7).

Observe the diffusion of potassium dichromate solution through gelatin (Experiment 2.8).

Note the general lack of diffusion in solids—distinct layers of rock, millions of years old, and solid objects in general that do not mix with each other when left in contact or even clamped tightly together.

7.2.1.2.5 Summary

Through our experiments, we have been able to observe that matter can exist in three states. Furthermore, in these different states matter exhibits the different properties summarised in the following table.

Phase	Volume	Shape	Compressibility	Diffusion
Solid	definite volume	definite shape	incompressible	negligible diffusion
Liquid	definite volume	shape of container	incompressible	diffuses slowly
Gas	no definite volume	no definite shape	very compressible	diffuses rapidly

There is actually a fourth state of matter—plasma—but this does not occur commonly on earth because it's too cold for most matter to reach that state. Lightning is an example of a natural plasma, and neon and fluorescent tubes use [artificial] plasmas to conduct electricity. Plasmas are, nonetheless, the most common state of matter in the universe—stars are made of plasma. Plasmas consist of freely moving charged particles (electrons and ions) and are formed at high temperatures when electrons are stripped from atoms.

7.2.1.3 The Particle Nature of Matter

The observations we have made, and many others like them, have lead to the proposition that all matter is made of small particles.

There are four basic principles embraced by the particle model of matter:

1. Matter is made of tiny particles;
2. There is empty space between the particles;
3. The particles are in constant motion;
4. There are forces that act between the particles.

Let us look at how we can explain the properties of matter that we have observed so far, in terms of the particle model.

7.2.1.3.1 The Particle Model and State Properties

We first noted that matter exists in three different states. How might we explain these different states using our particle model?

Since we can squeeze a gas into a smaller space, we might suggest that, in the gaseous state, particles are spread out. Compressing a gas would then involve pushing the particles closer together. The closer the particles become, the less space there is to squeeze them into and so the gas becomes more difficult to compress. We noticed however, that neither the liquid nor solid states were compressible. We might then propose that in these two states the particles are very close together, with little or no space in between to allow for compression.

If we think of the particles of a solid as being joined to one another so that they cannot move past one another, this would explain why solids have shapes. The particles in a liquid, on the other hand, even though they are close together, would have to be able to move more freely, so that they can move past each other and take up different positions. This would account for a liquid taking the shape of its container and for its ability to be poured.

When a solid melts then, its particles are broken away from each other, so that they are able to move more freely, as they do in the liquid state. When a liquid boils, particles leave the liquid and move away from it as they form a gas.

7.2.1.3.2 Particle Motion and Temperature

Next, we noticed that gases diffuse very readily. We also noticed that while liquids diffuse more slowly than gases, they diffused more quickly the warmer they were. We did not see any diffusion in solids.

We can explain the diffusion of gases if we assume that the gas particles are in rapid and violent motion, constantly colliding with one another and so being spread further apart—from regions of high to low concentration.

The particles within a liquid, being much closer together, will not be able to move about as freely. They will collide with neighbouring particles far more frequently than do the particles of a gas, but they will move about, albeit more slowly. We can picture the particles of a liquid as sliding past each other and often colliding with other particles.

Because solids hardly diffuse at all, we must think of their particles as keeping their positions. This does not, however, mean that they have to be completely still. Although it is not apparent from our current observations, we picture the particles of a solid as keeping their place, but constantly vibrating.

Temperature is the most common measure of heat. As we heat matter, its temperature rises. Temperature, therefore, provides us with a measure of how much the particles in matter are moving, or how much **energy** the particles possess.

In a hot gas then, the constituent particles are rushing around very rapidly. As the gas is cooled and condenses into a liquid, so the particles tend to move more and more slowly. Finally, when the substance is cooled so as to solidify, the particles become fixed in their positions and just vibrate to and fro. On further cooling still, the speed of this vibration too will decrease.

What happens if the particles stop moving altogether? In this case, a substance is said to be at the **absolute zero** of temperature. Nothing can be colder than this. Absolute zero occurs at 0 kelvin (see 7.2.1.1.1 Units of Measure above), which is equivalent to -273 °C.

7.2.1.3.3 Particle Size

Finally, we have observed that the particles that make up matter must be extremely small. We will see that the size of the individual particles that make up matter, known as atoms, varies widely but that it is between 0.3 and 3.0 ångströms (Å). An ångström[2] is one tenth of a nanometre or 1×10^{-10} metres (see 7.2.1.1.1 Units of Measure above) and is a unit commonly used to measure the size of atoms.

7.2.1.3.4 Summary

Our particle model has now provided a little more insight into what we have observed about matter:

- We see a solid as made up of particles almost touching one another, keeping the same positions but constantly vibrating;
- We see a liquid as made up of particles very close together, but moving past one another. The particles frequently collide with each other;
- We see a gas as made up of particles spaced well apart, moving violently in all directions and often colliding with each other.

7.2.1.4 Density

The space-filling characteristic of matter is called its **volume**. The **density** of a substance is subsequently defined as the mass of a substance in a given volume of that substance. As a consequence, we can only define density for substances in their liquid or solid states, since, as we have noted, gases do not tend to occupy fixed volumes.

Observe the relationship between different volumes of some liquids or solids and their respective masses (or weights).

Note that the mass of a given volume of a liquid or solid is proportional to the volume:

$$m \propto V$$

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[2] Named after the Swedish physicist Anders Jonas Ångström (1814–1874), one of the founders of spectroscopy.

Density is the proportionality constant that relates the mass of a substance to its volume. Thus:

$$m = dV$$

or

$$d = m/V$$

We say that density is the mass per unit volume of a substance. When mass is expressed in grams and volume in cubic centimetres (cm^3), the unit of density is g/cm^3.

The density of a substance depends on the masses of the particles making it up and the closeness with which they are packed.

Density is measured by finding the **mass of unit volume** of the substance:

$$\textbf{density} = \frac{\textbf{mass}}{\textbf{volume}}$$

7.2.1.4.1 Flotation

A substance **floats** in water if its **density** is **less** than that of **water**. It **sinks** if its **density** is **greater** than that of **water**.

7.2.1.5 Energy and its Measurement^{M3}

Energy is the ability or capacity to do **work**. An object has energy if it has the ability to do something. Energy can thus take many forms: heat, light, sound, electricity, chemical reactions.

Observe the energy produced by range of sources: a clockwork spring (Meccano motor), heat (steam driven paddle wheel), light (photoelectric cell), electricity (room light & appliances), batteries (a form of chemical energy—light up a light bulb, ignite steel wool), chemicals (sulphuric acid & water; potassium permanganate & glycerin; sulphur & powdered zinc).

Illustrate the many forms of energy that are involved in electric power generation and usage.

In hydroelectric power generation, the potential energy of water stored in dams hundreds of metres above, and piped down into the power station is used to turn the turbines of the power generators.

Energy is measured in a number of ways, using a variety of measurement units, depending on the type of energy being measured.

7.2.1.5.1 Units of Energy

Energy and work are generally measured in joules (J), the SI unit of energy ($kg{\cdot}m^2/s^2$) named after the English physicist James Prescott Joule (1818–1889), who studied the nature of heat and discovered its relationship to mechanical work.

Another convenient measure is the calorie, a French word derived from the Latin *calor*, meaning heat, and equal to the heat required to raise the temperature of 1 g of water by 1 °C.

$$1 \text{ cal} = 4.184 \text{ J}$$

A dietary Calorie = 1000 calories = 1 kcal

7.2.1.6 Kinds of Energy

7.2.1.6.1 Potential Energy

Potential energy is the capacity for doing work that a body possesses because of its position or condition. Potential energy is stored energy. For example, a weight lifted to a certain height above the ground has potential energy because of its position in the earth's gravitational field. The energy stored in a battery is also potential energy.

Potential energy may be:

Chemical energy: due to the position of electrons relative to atomic nuclei in bound atoms;

Gravitational energy: due the position of an object in a gravitational field;

Electrostatic energy: due the relative positions of charged particles;

Strain energy: due to the compression or stretching of an elastic material.

A compressed or stretched object possesses potential energy because it tends to return to its original shape when released. This type of energy is sometimes referred to as **energy of strain**. A material that springs back to its original shape or size, or close to it, after the release of a straining effort is called an **elastic material**. It is said to possess **elasticity**. The most common example of an elastic material used specifically in this way is spring steel, as used in a clock spring (not so common these days!) or the springs in the suspension of a car. There is generally, however, a point beyond which even elastic materials will fracture, or simply not return to their original shape or size. This point is known as the material's **elastic limit**.

Many materials are not elastic. When they are strained or distorted by twisting or stretching they do not return to their former shape after release. Such materials are said to be **plastic**. Putty, plasticine and lead are examples of plastic materials. What we commonly call plastics today is a class of materials that hold their new form when pressed into various shapes in moulds.

7.2.1.6.2 Kinetic Energy

Kinetic energy is the energy of a moving object. Even apparently stationary objects can, however, possess kinetic energy. The temperature of a body, for example, is a measure of the [vibrational] kinetic energy of its constituent atoms or molecules.

Kinetic energy may be:

Thermal energy: submicroscopic particles in motion;

Mechanical energy: macroscopic objects in motion;

Electrical energy: movement of electrons through a conductor;

Sound energy: compression/expansion of spaces between molecules.

7.2.1.7 Conservation of Energy[M9]

The Law of Conservation of Energy[3] states that:

Energy cannot be created or destroyed, but can change its form.

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[3] This Law is not attributable to any one individual. It was developed over a period of several hundred years, possibly starting with formulations made by the German mathematician Gottfried Leibniz (1676–1689), with contributions from many natural philosophers (from the fields of chemistry, mathematics, medicine, physics and engineering) who noted relationships between the various forms of work and energy. Einstein's work on special relativity was probably responsible for the unification of many of these ideas, but the basic concept existed well before Einstein's time.

This law applies equally to the conservation of matter, since matter can be thought of as a form of energy. Conversion of one type of matter into another is always accompanied by the conversion of one form of energy into another. Usually heat is released or absorbed, but sometimes the conversion involves light or electrical energy instead of, or in addition to heat. Many transformations of energy, of course, do not involve chemical changes. Electrical energy can be changed into either mechanical, light, heat or potential energy without chemical changes.

Energy is continually being changed from one form to another, and many different conversions are possible, for example:

A pendulum	potential energy is continually changing to kinetic energy and back again
A thermocouple	heat energy changes to electrical energy
A dry cell	chemical energy changes to electrical energy
A photoelectric cell	light energy changes to electrical energy
A generator	mechanical energy is changed into electrical energy
Friction	kinetic energy of motion changes to heat, itself a form of kinetic energy
The Sun	radiant energy changes to chemical potential energy in the process of photosynthesis—this, however, is just one example of how energy from the sun is converted into other forms of energy

Regardless of the change, however, all of the energy involved always appears in some form after the change is completed.