0.1 -- PURPOSE OF UNIT:

The purpose of this unit is to introduce some of the basic principles upon which the study of physics is based. First, the concept of measurement will be defined precisely by identifying several quantities as being measurements that are frequently made on radiotherapy patients. Then a number of basic physical quantities will be defined and used in order to derive additional physical quantities.

0.2 – INTRODUCTION

Before any patient can be treated by means of radiation therapy, a series of measurements is generally made on the patient. Certain physical quantities that may be relevant to the treatment of the patient are measured. These measurements are expressed in units of measurement that are specific to the quantity being measured. For example, when one patient first came to the radiation therapy clinic for evaluation, his weight was measured and found to be 63 kg. His body temperature was then measured and found to be 36.8°Celsius. His pulse was taken, and this measurement gave a value of 69 beats per minute. For the purposes of planning the radiation treatment of his right lung, a measurement was made of his anterior-posterior separation at the location of the central axis of the treatment field. This separation was found to be 20 cm. A field area was defined at the plane equidistant from his anterior and posterior surfaces. The dimensions of this field were given as 18.5 cm long by 18.5 cm wide. The patient was treated by radiation from a linear accelerator with an output of 0.827 cGy per monitor unit at midplane. These are a few of the measurements that were made in conjunction with this patient's radiation therapy. The complete list of such measurements is very much longer. The important point to be made is that quality radiation therapy is based upon careful application of some basic physical principles, and every application of physical principles is
dependent on the concept of measurement. Before the study of physics can be initiated, however, some basic physical concepts need to be defined and their measurements described.

In this chapter, we shall identify a set of these basic physical quantities necessary for the study of physics, as well as a number of quantities derived from these basic quantities. We will then discuss the concept of measurement of these physical quantities.

0.3 -- BASIC PHYSICAL QUANTITIES

The study of physics is different from the study of most other subjects in the training of medical personnel in that physics can be referred to as a constructive science. This term means that even though many widely divergent and diverse experiments may be performed on a system, and observations based on these experiments may be made, the results from these experiments can be compiled and concentrated into a small number of basic physical principles. From these basic principles all the experimental observations can be explained and further physical principles and phenomena can be inferred. Thus to start the study of physics of radiation therapy we begin by identifying a few basic principles. We then add further observations to these principles to construct the set of applications of physics to the practice of radiation therapy.

All physical phenomena which we observe in radiation therapy, in all of medicine, and in fact, in nature, can be expressed in terms of only six basic quantities. These six quantities are as follows:

1. length
2. time
3. mass
4. electrical charge
5. temperature
6. luminous intensity
Many physicists might actually object to a listing of as many as six basic quantities and would strive to reduce this number. A good argument, in fact, could be presented in favor of identifying both temperature and luminous intensity as derived quantities rather than fundamental quantities. Many physicists might also argue that length and time are one and the same, and one might even be able to construe an argument for equating length with mass and charge, but for the purposes of radiation therapy physics, it is really not important whether there are six, or four, or two basic physical quantities. It suffices to say that there are a small number (we will say six) of basic physical quantities, and that all other physical quantities can be defined in terms of the basic quantities.

0.4 -- ERRORS IN MEASUREMENT

Before we discuss specific physical quantities, some general concepts and definitions related to the measurement of physical quantities need to be presented. It is extremely important to realize that no measurement of a physical quantity can be a perfect measurement. All measurements, even those (or maybe, especially those) made by radiological physicists, are subject to error. When a measurement is made, and the result of the measurement presented, it is important to be able to assess “how good” the measurement has been made. Two important ways by which one describes how good a measurement has been made are by describing the precision and the accuracy of the measurement. These are two words that are commonly, but incorrectly, interchanged, thus, in the interest of good accuracy/precision in language, it is important to make the distinction between them.

Precision is related to how finely a measurement can be made. For example, there are a number of ways one may measure the thickness of an object. If one used a pair of calipers and measured the separation with a wooden meter stick, one might come up with a series of measurements of 3.2 cm, 3.6 cm, 3.7 cm, and 3.5 cm. Using the caliper and the wooden meter stick for our measurements, we can say that the thickness of the object is most likely somewhere between 3.2 cm and 3.7 cm. Let us now repeat the caliper measurement, but this
time we will measure the separation with a metal ruler. We find that the measured values come out to be 3.4 cm, 3.5 cm, 3.4 cm, and 3.6 cm. With the metal ruler, we can now say that the object thickness is probably between 3.4 cm and 3.6 cm. Thus the uncertainty in measurement is reduced from 0.5 cm to 0.2 cm. Finally, we measure the object's thickness a third time, using a vernier caliper. This series of measurements comes out to be 3.46 cm, 3.47 cm, 3.42 cm, and 3.45 cm. In this third case, the object thickness is probably between 3.42 cm and 3.47 cm. With the vernier caliper, the uncertainty in the object's thickness has been reduced even more, down to 0.05 cm. We say that the vernier caliper is a much more precise method for measuring the object's thickness using than the caliper with either the meter stick or the metal ruler. Thus, precision is a measure of the uncertainty of a series of measurements.

Accuracy, on the other hand, describes how close the value of a physical quantity obtained by a measurement is to the true value of that quantity. In our example above, we said that the vernier caliper gave a very precise measurement of the object thickness. Suppose, however, that the caliper was built late on a Friday afternoon. Everyone knows that the workers in the caliper factory, looking forward to their weekend, tend to be sloppy on Fridays, and when building our vernier caliper, they attached the wrong scale to the vernier. Instead of the correct scale, they attached the scale for another model of the caliper, the one that is 10% larger. Thus, all our measurements are in error by about 10%. Even though our measurements are precise, they are not accurate, because the measured thicknesses differ from the true thicknesses by 10%. Thus we can conclude that a measurement that is precise may not necessarily be accurate because of errors inherent in the measurement system. This inaccuracy due to systematic errors is what is known as bias. Bias, then, can cause a precise measurement to be an inaccurate one.

Another complication that enters into the measurement process is the fact that the very act of measurement can perturb a system to such an extent that the quantity that is being measured has been changed. We can demonstrate a number of examples of clinical situations where this complication is true. For example, suppose you were asked to do a study to
determine whether or not patients remember to take a prescribed medication three times daily. Suppose your measurement process were to telephone the patient three times a day and ask, “Did you take your prescribed medication?” It is fairly obvious in this case that your measurement will also remind the patient to take the medication, and affect in that way the outcome of the experiment. In another study, you wish to examine the correlation of average pulse rate with the patient’s sex. The method you chose to measure the pulse rate of your subjects was to select an extremely attractive female nurse to do your measurements. From your measured data, you might arrive at the not-so-surprising conclusion that males tend to have a higher pulse rate than females. Such are the traps the unwary investigator might fall into if one fails to realize that the act of measurement may affect that quantity being measured.

It is clear that errors will enter into any measurement regardless of how carefully the measurement is done. In radiation therapy the most significant errors with which we must contend are those errors in the calculation and the measurements of the patients dose. One of the goals of a course in radiation therapy physics is to understand how these errors may arise and how significant these errors might be. Performing calculations on a pocket electronic calculator, one has a tendency to assume higher precision than is justified. For example, it is very easy to obtain a dose rate of 1.1826 cGy per monitor unit in a calculation involving the output of a linear accelerator. However, this apparent high degree of precision is really meaningless. A quoted value of 1.1826 implies that there is some way to tell the difference between 1.1826 and 1.1827 cGy per monitor unit. As we shall see later, this not possible using present methods of measurements. Thus it is important for one to be aware of degrees of accuracy and of precision, when both measurements and calculations are being done.

0.5 -- UNITS OF MEASUREMENT

Before we can make a measurement, there are two preliminary tasks that must be done. First, we must define the physical quantity we wish to measure, and second, specify its units of measurement. This is a non-trivial distinction. It is very easy to fall into a trap and define a
physical quantity in terms of its units of measurement. For example, we are not allowed to define length as “number of meters”. The meter is a unit of length and not a definition of length. The meter can only be specified after the quantity “length” has been defined, and not the other way around. This point seems quite obvious when related to such straightforward quantities as length, but there are many examples where the distinction between a physical quantity and its unit of measurement has not been made very clear. For example, the quantity known as radiation exposure was once defined in terms of number of roentgens, rather than by first defining the physical quantity “radiation exposure” and then specifying the unit of the roentgen for measuring exposure. When this incorrect procedure is done, we wind up defining a quantity in terms of itself. To prevent this from happening, we must be very careful first to define our physical quantities and then specify the units with which we plan to measure them.

0.6 -- THE BASIC AND DERIVED QUANTITIES

Earlier in this unit we identified six basic physical quantities. We now wish to define these quantities and the units normally used to measure these quantities. Rather than attempt to present a precise rigorous definition for these basic quantities, we shall appeal to our intuition and our experience and give a more or less practical definition. The basic physical quantities are so familiar to us that this lack of rigor in the definition will not cause us harm. Once appropriate basic quantities have been identified, we shall then derive many additional quantities from the basic ones. When this is done, we shall be somewhat more rigorous since a number of these derived quantities are not so familiar and obvious.

0.6.1 -- LENGTH, AREA, VOLUME

The first of the basic physical quantities that we have listed is length. As we have indicated, we shall appeal to our intuition and our experience for a definition as we have indicated, and identify length as the straight-line distance between two points. For example, the source-to-skin distance is an example of a length. It is the distance from the radiation source to the patient's
Another length is the patient's height, the straight-line distance from the top of the patient's head to the ground while the patient is standing flat-footed. The unit of length that is most commonly used in radiation therapy physics is the meter. The meter is defined as equal to a specific length, originally the distance between two points on a metal bar that was kept in a vault near Paris, France. Now the meter is defined in terms of the wavelength of a specific atomic process, which turns out to be a much more precise method of defining the meter.

Very often, however, we will need to discuss lengths that are very much larger or very much smaller than a meter. In order to avoid carrying large powers of 10 in our notation, we will use various prefixes which identify multiples or fractions of a meter. The ones most commonly used are given in the following table:

**TABLE 0.1---COMMONLY USED METRIC PREFIXES**

<table>
<thead>
<tr>
<th>Prefix</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>kilo-</td>
<td>$10^3$</td>
</tr>
<tr>
<td>mega-</td>
<td>$10^6$</td>
</tr>
<tr>
<td>milli-</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>micro-</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>nano-</td>
<td>$10^{-9}$</td>
</tr>
</tbody>
</table>

These same prefixes can be used with any unit of measurement.

In addition to the basic quantity identified as length, two other quantities that have been derived from length are commonly used. The first of these is area, obtained by multiplying one length by another length. The second is volume, which consists of three lengths multiplied by each other. Again, rather than attempting to give a rigorous definition to area and volume, we shall be more practical and probably less confusing by appealing to experience and recall the practical definitions of area and volume. The unit for area is the square meter, abbreviated m².
Actually, it probably should be called the “meter squared,” but common usage dictates use of the former term. The unit for volume is the cubic meter (or “meter cubed”), abbreviated as m$^3$.

Even though we have referred to length as if it were a single quantity, two quantities are generally required to specify a length. First, one must specify the magnitude, the actual distance between two points. The second quantity that frequently needs to be specified is the direction between the two points. For example, the SSD has been defined as the distance between the radiation source and the patient's skin surface. This quantity is actually only the magnitude of the SSD. For a complete identification of the SSD, we must also specify the direction. In this case, the direction is that along a straight line from the source to the patient. An entity like length, which requires two quantities for its specification, is called a vector, while if only one quantity needs to be specified, the entity is called a scalar. Length, when both a magnitude and a direction are necessary for its specification, is a vector quantity. If only the magnitude is required, then it is a scalar.

A second basic quantity required to describe physical phenomena is time. Again, we shall use an intuitive definition for time, that is, the duration of an event. An example of time is the time that a teletherapy machine is left with its source in the “on” position, that is, the treatment time. The unit of time is the second, once defined in terms of a fraction of the period of the earth's rotation about its axis, but now defined, as with length, in terms of an atomic event. As also with length, periods of time that are much larger or much smaller than the second are described with one of the appropriate prefixes listed in Table 1.1. Thus we can talk about events of long duration lasting kiloseconds as well as events of short duration lasting microseconds.

0.6.2 -- VELOCITY AND ACCELERATION
Once length and time have been defined, several derived quantities based on length and time can be introduced. Two of these derived quantities commonly used in physics are velocity and acceleration. Velocity is defined as the change of position with time. It is calculated according to the formula

\[ v = \frac{d}{t}, \]  

(0.1)

and its units are units of length divided by units of time. We generally express velocities in terms of m/sec (meters per second), with an appropriate prefix if necessary. For example, if we find that a bicyclist can travel 3 km (3000 m) in 325 sec, we say that the velocity is 3000 m/325 sec, or 9.23 m/sec. Velocity, just as length, implies both a magnitude and a direction, so it, too, is a vector quantity. Thus to describe the bicyclist's velocity properly, we might refer to a velocity of 9.23 m/sec in an easterly direction. If we identify only the magnitude part of a velocity and not the direction, the quantity which we are describing is the speed. We can say that our bicyclist is traveling with a speed of 9.23 m/sec. If distance vs time is plotted on a graph, then we can identify the velocity as the slope of the distance vs time line.

The second derived quantity, acceleration, is defined as the change of velocity with time, expressed by the formula

\[ a = \frac{v}{t}. \]  

(0.2)

The units for acceleration are units of velocity divided by time, or m/sec\(^2\), which we read as “meters per second squared”. Acceleration, just as velocity and distance, is a vector quantity, but there is no simple word for the magnitude part of the acceleration. If we plot velocity vs time on a set of coordinates, the acceleration will be the slope of the velocity vs time line.

Several useful relationships can be derived between distance, velocity, and acceleration. These will be presented here without derivation; the reader is advised to consult an elementary physics text for their derivation. If an object is moving with a uniform velocity \( v \), then the distance \( d \) it travels after a period of time \( t \) is given by
If the object moves at constant acceleration $a$ for a period of time $t$, then the distance traveled is given by

$$d = \frac{1}{2}at^2.$$  

(0.4)

Finally, if it moves at a constant acceleration, its final velocity as a function of the distance traveled is

$$v_f = \sqrt{2ad}.$$  

(0.5)

0.6.3  --  FORCE, MASS, AND MOTION

One of the most important concepts in the entire field of physics is the concept of force. We can define a force as that which causes an object to accelerate, or more naively, as a push or a pull. That is not really as precise definition as we might want, but without introducing several other concepts, we would find it hard to present a rigorous definition. As was the case with some of the other physical concepts that have been presented, it would be far more practical to appeal to an intuitive concept of force rather than to attempt to define it precisely. Another definition of force that is frequently used is the change of momentum per unit time. We will not use this definition here because it involves introducing the concept of momentum, a concept that is important for physics, but not one that is absolutely necessary for radiation therapy physics. Probably by looking at a force using the naive concepts of a push or a pull, we can adequately, if not absolutely rigorously, describe whatever phenomena we wish at this point.

We commonly encounter two basic types of forces. The first type of force is the type with which we are most familiar, a direct force. For example, when we lift a patient, we exert a direct force on the patient. This direct force pushes the patient in an upward direction. The other type of force is the indirect force, sometimes referred to as action at a distance.
A good example of an indirect force is the force of gravity. When we lift a patient the direct force acting upward on the patient must overcome the indirect force of gravity pulling downward on the patient. If the upward force exceeds the downward force, the patient rises. If the upward force equals the downward force, the patient remains stationary. If the upward force is removed, the patient falls to the floor. A situation when the upward force equals the downward force occurs when the patient lies on the treatment couch. There is an upward force exerted by the couch that is exactly equal to the downward force of gravity. The two forces balance out, thus the patient does not move.

The relationships between force and motion were first identified by Sir Isaac Newton in the 17th century and are called Newton's Laws of Motion. They are as follows:

1. A body at rest remains at rest, or a body in motion remains in motion unless acted upon by a force.
2. A body's acceleration is directly proportional to the force acting on it.
3. Every action has an equal reaction in the opposite direction.

The relationship between force and acceleration is thus spelled out in Newton's Second Law, that force and acceleration are directly proportional to each other. The proportionality constant relating acceleration to force is the mass. Thus, we can write

\[ F = ma. \]  \hspace{1cm} (0.6)

We can also say that a force, acting on a mass, will cause it to accelerate. The unit for mass is the kilogram (kg), thus the unit for force will be the unit for mass times the unit for acceleration, or kg m/sec\(^2\). Since force is such a commonly used quantity, it has been given a special unit, the newton (nt). One nt is equal to 1 kg m/sec\(^2\).

Even though the terms are sometimes used interchangeably, we should be very careful to make the distinction between mass and weight. An object's mass is the ratio between the force that acts on the object and the resulting acceleration. The weight is a measure of a specific force, the force of gravity. Mass is an inherent property of an object, independent of where a measurement is made on it. Weight depends on the force of gravity on the object.
outer space, where the force of gravity is negligible, your weight will be negligible, but your mass will always be the same. The distinction between weight and mass is commonly confused, but it must be made.

0.6.4  -- SOME FUNDAMENTAL FORCES

Another of the basic quantities used in physics is electric charge, a property of matter that gives rise to one of the fundamental forces in nature. The unit of charge is the coulomb, described in terms of the magnitude of an electric force. The coulomb is considerably larger than most charges we encounter on an atomic or nuclear level; the charge on an electron is $1.6 \times 10^{-19}$ coul. The flow of charge through space is called current. The unit of current is the coul/sec, which has been given the name ampere (amp).

Previously we identified the gravitational force as a force at a distance. Two other forces at a distance that we commonly encounter in radiation therapy physics are the electrical force which is the force between two charges, and the magnetic force, a force that occurs between two moving charges. Charges may have two different forces acting upon them, an electrical force, which always acts on them, and a magnetic force, which will act on them only if they are moving. The equations describing the three forces are as follows:

1. gravity

\[ F_G = k_G \frac{m_1 m_2}{r^2}, \quad (0.7a) \]

\[ k_G = 6.67 \times 10^{-11}. \]

2. electrical

\[ F_e = k_e \frac{Q_1 Q_2}{r^2}, \quad (0.7b) \]

\[ k_e = 8.99 \times 10^9. \]

3. magnetic
\[ F_m = k_m \frac{Q_1 v_1 Q_2 v_2}{r^2}, \]  

(0.7c) 

\[ k_m = 1.00 \times 10^{-7}. \]

The various constants are chosen so that if the masses are given in kg, the distances in m, the charges in coul, and the velocities in m/sec, then the forces will be expressed in nt. Note in particular that all three forces have the same mathematical form. In the numerator we see a property of one body, either its mass, or its charge, or its charge multiplied by its velocity. This property is multiplied by the same property of the other body and divided by the square of the distance between the two bodies. Because of this distance relationship we say that all three forces follow an “inverse square law,” a property that we shall encounter several more times in our studies of radiation therapy physics. However, you saw it first in our discussion for fundamental forces in nature.

0.6.5 **WORK AND ENERGY**

Another concept commonly used in physics is the concept of work. Whenever a force is applied to move an object, and the object actually moves, then work is being done on the object. The amount of work done, in fact, is given by the force multiplied by the distance. We can write this as

\[ W = Fd. \]

(0.8)

The unit of work is the unit of force multiplied by the unit of distance. Since the unit of force is the newton and the unit of distance is the meter, the unit of work becomes the newton meter. Since work is such a commonly used quantity, it has been given a special unit, the joule (J). One joule is defined as 1 nt m. Another frequently used unit of work that we shall encounter later in this course is the erg. One erg is 1.0 x 10^{-7} joule.

It is important to realize that work is only done when a force actually moves an object. Without motion there is no work. Thus, a 90 lb radiation therapist may struggle for hours trying to move a 400 lb patient, but until that patient is actually moved, there is no work, at least not
from a physicist's point of view. (The therapist may have a different opinion of this.) For work to occur there must have been motion.

Now that work has been defined, we can introduce the concept of energy. Energy is defined as the ability to do work. Energy in a body is used up as the body does work. Early in the day, after several cups of coffee, radiation oncology personnel have a large amount of energy. As the day wears on, and patients are seen and moved, equipment is carried, and forces are exerted to move masses, work is done, and the amount of energy decreases. The energy is being converted into work. The units of energy are, in fact, the same as the units of work.

Two kinds of energy can be converted into work. One kind is the energy of motion. A fast moving object has more energy than a slow moving object. It can do more work than a slow moving object. Also a more massive object can do more work than a less massive object. Thus this energy of motion, called kinetic energy, is related to both the mass and the velocity of the object and is given by the relation

\[ KE = \frac{1}{2}mv^2. \]  \hspace{1cm} (0.9)

The second kind of energy is the energy of position, called potential energy. An object that is sitting on top of a table has more potential energy than an object on the floor. When the object on the tabletop is pushed off the table and falls, it will have more kinetic energy than the object on the floor. Thus, before it is moved, its position makes it capable of doing more work than the object on the floor. It therefore has more potential energy than the object on the floor.

Notice that as the object falls, the potential energy it possessed as a result of its position gets converted into kinetic energy. The total energy in the object remains the same. We say that the energy is conserved. This is an example of the Law of Conservation of Energy, a law that holds true no matter what transformation the energy undergoes. For example, in a linear accelerator, electrical energy is transformed to microwave electromagnetic energy, which is
transformed to kinetic energy of the accelerated electrons. The electrons strike a target and their energy is converted to x-ray electromagnetic energy. The x-rays interact with the patient and their energy is transformed into the breaking of chemical bonds and heat. In all cases, if we are careful to identify all the energy that is being produced in an interaction, we see that all the energy that enters an interaction will come out of the interaction, but usually in a number of different forms. The Law of Conservation of Energy is usually stated that energy can be neither created nor destroyed, but only transformed from one form to another. This conservation law is one of the fundamental laws of physics.

Another conservation law that has the same level of importance is the Law of Conservation of Matter. It reads the same as that for energy, but with matter substituted for energy. In any type of interaction matter can be transformed from one form to another, but never created nor destroyed. In some respects, the study of interactions in physics becomes a complex accounting exercise. We must keep careful track of what enters an interaction and careful track of what leaves the interaction. The application of these conservation laws can often tell us what results from such an interaction. We will see many examples of this latter in this course.

0.6.6  -- MASS-ENERGY RELATIONSHIPS

For many years physicists believed that the Law of Conservation of Matter and the Law of Conservation of Energy were distinct and separate laws. Early in the twentieth century, however, Einstein demonstrated that matter and energy were actually two forms of the same thing. Thus, matter could be transformed into energy and vice versa. The relationship between matter and energy is given by

\[ E = mc^2, \]

(0.10)

where \( E \) is the energy, \( m \) is the mass, and \( c \) is the speed of light in vacuum. This quantity is equal to 3.00 x 10^8 m/sec, a very large number. Thus a small amount of mass, completely converted into energy, produces a large amount of energy. We will be using this relationship
when we look at radioactive decay, because matter-energy conversions play a large part in these processes.

0.6.7  -- ELECTRICAL ENERGY

Before we finally leave this introduction to matter and energy, we must look at the most important form of energy used in radiation therapy, electrical energy. Electrical energy is involved whenever electrical charges are moved. When a charge \( Q \) is moved through an electrical potential \( V \), work is being done. The amount of work is the charge times the electrical potential, or \( Q \) times \( V \). In problems encountered in radiation oncology physics a much smaller unit of energy is frequently used. This unit is the electron volt, defined as the energy acquired by an electron passing through a potential difference of 1 volt. One electron volt (eV) is equal to \( 1.6 \times 10^{-19} \) J. We will describe the energy of radiation in terms of electron volts, or more commonly kiloelectron volts (keV) or megaelectron volts (MeV). We can thus convert such energies into the more commonly used units of joules or ergs. For example, mycosis fungoides is sometimes treated by irradiating the patient's entire skin surface with a beam of electrons of energy around 3 MeV. Expressed in joules, this energy becomes \( 4.8 \times 10^{13} \) J. It is important for one to become familiar with both sets of units for measuring energies, because some quantities in radiation therapy physics, like x-ray or electron energies are expressed in multiples of electron volts, while other quantities like radiation dose are expressed in quantities related to multiples of joules.