Teaching Engineering Fundamentals Using Fundamental Dimensions: An Innovative Approach

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Abstract

In this paper, we will focus on an innovative way to teach some of the engineering fundamentals at the freshman level in an introductory engineering class. Unfortunately, today, many students graduate without a good grasp of these fundamental concepts—concepts that every engineer, regardless of his or her area of specialization should know. In this paper, we discuss how to introduce students right away to some of the fundamentals that they will see over and over in some form or other during their college years. We emphasize that from our observation of our surroundings, we have learned that we need only a few physical quantities (fundamental dimensions) to describe events and our surroundings. With the help of these fundamental dimensions we can define or derive other necessary physical quantities. In this paper, we explain that there are many engineering design variables that are related to these fundamental dimensions (quantities). We also emphasize that we need not only physical dimensions to describe our surroundings, but also some way to scale or divide these physical dimensions. For example, time is considered a physical dimension, but it can be divided into both small and large portions, such as seconds, minutes, hours, and so on. To become a successful engineer, a student must first fully understand these fundamentals. Then it is important for the student to know how these variables are measured, approximated, calculated, or used in engineering design and practice.

1. INTRODUCTION—FUNDAMENTAL DIMENSIONS AND UNITS

Over a period of thousands of years, we have observed and learned from our surroundings. We have used the knowledge gained from our observations of nature to design, develop, test, and fabricate tools, shelter, weapons, water transportation, and means to cultivate and produce food. Moreover, we have realized that we need only a few *physical quantities* to describe natural events and our surroundings. For example, the length dimension is needed to describe how tall, or how long, or how wide something is. We have also learned that some things are heavier than other things. So there is a need for another physical quantity to describe that observation. This realization led to the concept of mass and weight. Time was another physical dimension that we needed to explain our surroundings and to be able to answer questions such as: How old are you? How long does it take to go from here to there? The response to these questions in those early days may have been something like this: I am many many moons old, or it takes a couple of moons to go from our village to the other village on the other side of mountain. Moreover, to describe how cold or hot something was, humans needed yet another physical quantity, or physical dimension, that we now refer to as temperature. Today, based on what we know about our physical world, we need *seven fundamental or base dimensions* to express what we know of the natural world. They are *length, mass, time, temperature, electric current, amount of substance, and luminous intensity*.

The other important fact that we realized is that we not only needed physical dimensions to describe our surroundings, but also we recognized the need for some scale or divisions of these physical dimensions. This led to the concept of units. For example, time is considered a physical dimension, but it can be divided into both small and large portions, such as seconds, minutes, hours, days, years, decades, centuries, and so on. For example, one may explain to students that today, when someone asks you how old you are, you reply by saying, “I am 19 years old.” You don’t say that you are approximately 6,940 days old, even though this statement may very well be true! Or to describe the distance between two cities, we may say that they are 2000 kilometers apart; we don’t say the cities are 2,000,000,000 millimeters apart. The point of these examples is that we use appropriate divisions of physical dimensions to keep numbers manageable. We have learned to create an appropriate scale for these fundamental dimensions and divide them properly so that we can describe particular events, size of an object, thermal state of an object or its interaction with the surroundings correctly, and do so without much difficulty.

At the early stage of their education, students need to begin to develop a keen awareness about their surroundings and understand the role of these fundamental dimensions and units in engineering design and practice. They need to know how these physical variables affect engineering design decisions. The main purpose of introducing these fundamentals, early during first year, is to help students become aware of their importance and look for their relation to other engineering parameters in their future classes when they study a specific topic in detail. It is worth noting that the teaching method described in this paper was utilized by the author in a freshman (introduction to engineering) class at Minnesota State University three years ago. The author also teaches upper-classmen and has noticed a better grasp of the fundamentals by the juniors and seniors who were taught the fundamentals in the manner discussed in this paper. In order to keep the length of this paper at a reasonable level, we will discuss the role of only three of these fundamental dimensions in engineering. We will discuss the role of length and length related, time and time related, and mass and mass related variables in engineering. Table 1 shows these fundamental dimensions and the related variables that are commonly encountered in engineering practice.

Fundamental Dimension	Related Variables			
Length (L)	Radian (L/L), Strain (L/L)	Area (L^2)	Volume (L^3)	Area moment of inertia (L^4)
Time (t)	Speed (L/t)	Acceleration (L/t^2)	Volume Flowrate (L^3/t)	
Mass (m)	Mass Flowrate (m/t)	Momentum (mL/t)	Density (m/L^3), Specific Volume (L^3/m)	

Table 1: Examples of fundamental dimensions and related variables.

2. LENGTH AS A FUNDAMENTAL DIMENSION

Length and Length Related Variables in Engineering

In this section, we will discuss length (L) and length related variables in engineering application including radians (L/L), strain (L/L), area (L^2), volume (L^3), and second moment of area (L^4). As discussed earlier, through their observation of nature people recognized the need for a physical quantity or a physical dimension, so that they could describe their surroundings better. They also realized that having a common definition for a physical quantity, such as length, makes communication easier. Earlier humans may have used their finger length, arm span, stride length, a stick, or a rope to measure the size of an object.

Let's look at the role of length in design. Let's start in your classroom. Most of your students have been going to class for at least 12 years, but have they thought about classroom seating arrangements? For example, how far apart are the desks? Or how far above the floor is the presentation board? How far apart do students sit? What are the typical dimensions of seats and desks? How wide should a hallway be? Or when designing a supermarket, how wide should an isle be? What are important considerations when designing signs for a highway? How wide is a highway lane? In order to develop an engineering "sense" or a "feel" for the significance of size in design, you can ask students to look around home to think about the dimension length. Start with the size of a bed, what are its dimensions, how far above the floor is it? What is a typical standard height for steps in a stairway? What is the placement of a doorknob, showerhead, sink, light switch, and so on? At this point students should begin to see that length is a very important fundamental dimension, and thus, it is commonly used in engineering applications. Rectangular Coordinate systems are examples of another application where length plays an important role. Coordinate systems are used to locate things with respect to a known origin. In fact, you use a rectangular coordinate systems everyday, even though you don't think of it in that manner. When you leave your home and want to go to school or go to a grocery store or meet a friend for lunch, you use coordinate systems. The use of coordinate systems is almost second nature to you. You know which streets to take for what distance and in which directions to move to get to school. You may use north, east, west, or south directions to get where you are going. You can think of the axes of a rectangular coordinate system as aligning with, for example, east and north direction. Actually, people who are blind are expert users of rectangular coordinate systems. Because they can not rely on their visual perception, people with a vision disability know how many steps to take and in which direction to move to go from one location to another. Coordinate systems are also integrated into software that drives computer numerically controlled (CNC) machines. These machines, such as a milling machine or a lathe, cut materials into specific shapes.

Measurement of Length

Early humans may have used finger length, arm span, stride length (step length), a stick, rope, chains, and so on to measure the size of an object or displacement of an object. Today, depending on how accurate the measurement needs to be and the size of object being measured, we have developed measuring devices such as a ruler, a yard stick, and a steel tape. These devices are based on internationally defined and accepted units such as millimeter, centimeter, meter, or inch, foot, yard. For more accurate measurements of small objects we have developed measurement tools such as a micrometer or a Vernier caliper that allows us to measure dimensions within 1/1000 of an inch. In fact, machinists use micrometers and Vernier calipers every day.

In the last few decades, Electronic Distance Measuring Instruments (EDMI) have also been developed that allow us to measure distances from a few feet to many miles with reasonable accuracy. These electronic distance measuring devices are quite common for surveying purposes in civil engineering applications. After emphasizing the significance of the dimension length in the analysis of engineering problems, students should be taught some of the more common length units in use and reminded that they should try to develop a "feel" for the order of length quantity. For example, ask a student whether a yard or a meter is the larger quantity, or ask them to approximate the dimension of their calculators or laptop computers without actually measuring them, and so on.

Nominal Sizes Versus Actual Sizes

It is also very important for students to know the difference between nominal size and actual size. To introduce this difference, consider the following example. Those people who live in U.S. have seen or used a 2 x 4 piece of lumber. If you were to measure the dimensions of the cross section of a 2 x 4 lumber, you would find that the actual width is less than two inches (approximately 1.5 inches) and the height is less than 4 inches (approximately 3.5 inches). Then why is it referred to as a 2 by 4? Manufacturers of engineering parts use round numbers so that it is easier for people to remember the size and thus easier to refer to a specific part. The 2 x 4 is called the nominal size of the lumber. If you were to investigate other structural members, such as I-beams, you would also note that the referenced size quoted by the manufacturers is different from the actual size. You will find a similar situation when looking for pipes, tubes, screws, and many other engineering parts. Agreed upon standards are followed by manufacturers when providing information about the size of the parts that they make. Moreover, the manufacturers provide actual sizes of parts in addition to nominal sizes. This fact should be emphasized because, as students will learn in their future engineering classes, they need the actual size of parts for the engineering calculations.

Radians as Ratio of Two Lengths (L/L)

Radian is a simple length related concept that many students have trouble with. Radians represents the ratio of two lengths—an arc length and the radius of the arc. The relationship among the arc length *S*, radius of the arc *R*, and the angle in radians θ is given by $\theta = \frac{S}{R}$.

Sound understanding of the above relation is important in many engineering situations. For example, we use it to establish a relationship between angular motion and translational motion.

Strain as Ratio of Two Lengths (L/L)

Another length related variable is strain. When a material (e.g. a piece of material in the shape of rectangular bar) is subjected to a tensile load (pulling load), the material will deform (elongate). The deformation ΔL divided by the original length L is called normal strain according to: $strain = \frac{\Delta L}{L}$. Students should be reminded that they will learn in their mechanics of materials class how strain is related to stress [stress = (modulus of elasticity)(strain)]. Also note, for most engineering applications, strain values are relatively small.

Area (L^2)

Area is a derived or a secondary physical quantity. To determine area, you need two pieces of length information. Area also plays a significant role in many engineering problems. For example, the rate of heat transfer from a surface is directly proportional to the exposed surface area. That is why a motorcycle engine-head or a radiator has extended surfaces, or fins. For another example, ask students if they have ever thought about why they may want to use crushed ice rather than ice cubes to cool their drinks faster? It is because for the same amount of ice, the crushed ice has more exposed surface to the soda. You may have also noticed from your experience around the kitchen that given the same amount of meat, it takes longer for roast beef to cook than it takes stew. Again, it is because the stew has more surface area exposed to the water in which it is being cooked. So next time you are planning to make some mashed potatoes, make sure you first cut the potatoes into smaller pieces to cook and then mash them. The smaller the pieces, the sooner they will cook. Of course, the reverse is also true. That is, if you want to reduce the heat loss from something, one way of achieving this task would be to reduce the exposed surface area. For example, when we feel cold we naturally try to curl up to reduce our exposed surface area to the cold surroundings.

Area plays an important role in aerodynamics studies as well. The air resistance to motion of a vehicle is something that all students are familiar with. As they may also know, the drag force acting on a car is determined experimentally by placing the car in a wind tunnel. Engineers have learned, when designing new cars, that total exposed surface area and the frontal area of a car are important factors in reducing air resistance to motion of a car. The lift force acting on the wings of a plane is also proportional to the area (planform) of the wing. The planform area is the area that you would see if you were to look from the top at the wing from direction normal to the wing.

Cross sectional area also plays an important role in distributing a force over an area. Foundations of buildings, hydraulic systems, and cutting tools are examples where the role of area is important. For example, ask students if they have ever thought about why the edge of a sharp knife cuts well? What do we mean by a "sharp" knife? A good sharp knife is one that has as small as possible cross sectional area along its cutting edge. For the same push on the knife by decreasing the cross-sectional area you can increase the cutting pressure (pressure = force/area). We can also reduce the pressure by increasing the area. When we go skiing, we use the area to our advantage and distribute our weight over bigger surface so we won't sink into the snow. Considering explanation offered above, students should then understand why high heeled shoes are designed poorly as compared to walking shoes. You can use the above examples to demonstrate the important role of area in design. During a student's engineering education, he/she will learn many new concepts and laws that are either directly or inversely proportional to the area. After emphasizing the significance of area in the analysis of engineering problems, students should be taught some of the more common area units in use and reminded that they should try to develop a "feel" for the order of area quantity. For example, ask a student whether a square of yard or a square of meter is the larger quantity, or ask students to approximate their body surface area, and so on.

Area Calculation and Measurement

After the important role of area—a length related variable—in engineering, through examples, is demonstrated, then how it is calculated or measured should be discussed. The areas of common shapes, such as a triangle, a circle, and a rectangle, can be obtained using simple formulae. It is a common practice to refer to these simple areas as primitive areas. However, there are many practical engineering problems that require calculation of planar areas of irregular shapes. If the irregularities of the boundaries are such that they will not allow for the irregular shape to be represented by a sum of primitive shapes, then we need to resort to an approximation method. For these situations, we may approximate planar areas using any of the following procedures. You can approximate the planar areas of an irregular shape using the Trapezoidal Rule [1] with reasonably good accuracy. You can then explain the rule in detail. There are other ways to approximate the surface areas of irregular shapes. One such approach is to divide a given area into small squares of known size and then count the number of squares. You then need to add to the areas of the small squares the leftover areas which you may approximate by areas of small triangles. Sometimes it may be advantageous to first fit large primitive area(s) around the unknown shape and then approximate and subtract the unwanted smaller areas. You may also emphasize that for symmetrical areas you may make use of symmetry of the problem. Approximate only ½ or ¼ or ⅛ of the total area, and then multiply your answer by the appropriate factor at the end.

Another approximation procedure which requires the use of an accurate analytical balance from a chemistry lab is explained next. Assuming the profile of the area to be determined can be drawn on an 8½ x 11 sheet of paper, first weigh a blank 8½ x 11 sheet of paper. Using the analytical balance, weigh the sheet and record its weight. Next, draw the boundaries of the unknown area on the blank 8½ x 11 sheet of paper, and then cut around the boundary of that area. Determine the weight of the piece of paper that has the area drawn on it. Now by comparing the weights of the blank 8½ sheet of paper to the weight of the paper with the profile you can determine the area of the given profile. In using this approximation method, we assumed that the paper has uniform thickness and density.

Volume (L^3)

Volume is another important physical variable that does not get enough respect! We live in a three-dimensional world, so it is only natural that volume would be an important player in how things are shaped or how things work. To introduce students to volume, you may begin by considering the role of volume in our daily lives. Today you may have treated yourself to a can of soda which on average contains 12 fluid ounces or 355 milliliters of your favorite beverage. You may have driven a car whose engine size is rated in liters. Depending on the size of your car, it is also safe to say that in order to fill the gas tank you need to put in about 15 to 20 gallons (57 to 77 liters) of gasoline. We also express the gas consumption rate of a car in terms of so many miles per gallon of gasoline. Doctors tell us that we need to drink at least 8 glass of water (approximately 2.5 to 3 liters a day). We breathe in oxygen at a rate of approximately 16 ft^3/hr (0.453 m^3/hr). Also, we each consume on average about 20 to 40 gallons of water per day for personal grooming and cooking. Volume also plays an important role in food packaging and pharmaceutical applications. For example, a large milk container is designed to hold a liter or a gallon of milk. When administering drugs, the doctor may inject you with so many milliliters of some medicine. Many other materials are also packaged such that the package contains so many liters or gallons of something. For example, you can purchase a gallon of paint. Clearly we use volume to express quantities of various fluids that we consume. Volume also plays a significant role in many other engineering concepts. For example, density of a material represents how light or heavy a material is per unit volume. Buoyancy is another engineering principle where volume plays an important role. Buoyancy is the force that a fluid exerts on a submerged object. The net upward buoyancy force arises from the fact that the fluid exerts a higher pressure at the bottom surfaces of the object than it does on the top surfaces of the object. Thus, the net effect of fluid pressure distribution acting over the submerged surface of an object is the buoyancy force. The magnitude of the buoyancy force is equal to the weight of the volume of the fluid displaced. It is given by $F_B = \rho V g$. In this relationship, F_B is the buoyancy force (N), ρ represents the density of the fluid (kg/m^3), and g is acceleration due to gravity (9.81 m/s^2). If you were to fully submerge an object with a volume V, you would see that an equal volume of fluid has to be displaced to make room for the volume of the object. In fact, you can use this principle to measure the unknown volume of an object.

NASA astronauts also make use of buoyancy and train underwater to prepare for on-orbit repair of satellites. This type of training takes place in the Underwater Neutral Buoyancy Simulator. The changes in the apparent weight of the astronaut allow him or her to prepare to work under near zero gravity (weightlessness) conditions.

After emphasizing the significance of volume in the analysis of engineering problems, students should also be taught some of the more common volume units in use and reminded that they should try to develop a “feel” for the order of volume quantity. For example, ask a student whether a pint or a liter is the larger quantity, or ask students to approximate the volume of their classroom without actually measuring its dimensions, and so on.

Volume Calculations and Measurement

Similar to area calculations, the volume of simple shapes, such as a cylinder, a cone, or a sphere, may be obtained using simple volume formulae. For complex shapes, we can use the buoyancy effect to measure the exterior volume of an object. We will consider two procedures. First, we obtain a large container that can accommodate the object. We will then fill the container completely to its rim with water and place the container inside a dry empty tub. We next submerge the object with the unknown volume into the container until its top surface is just below the surface of the water. This application will displace some volume of water which is equal to the volume of the object. The water that overflowed and was collected in another container can then be poured into a graduated cylinder to measure the volume of the object.

The second procedure makes direct use of the buoyancy force. We first suspend the object in air from a spring scale to obtain its weight. We then place the object as it is suspended from the spring into a container filled with water. Next, we record the apparent weight of the object. The difference between the actual weight of the object and the apparent weight of the object in water is the buoyancy force. Knowing the magnitude of the buoyancy force and using the relationship between buoyancy force and volume we can then determine the volume of the object. These simple examples can be readily demonstrated in class to engage students and enhance learning.

Second Moment of Areas (L^4)

Another important engineering variable is a property of an area known as the second moment of area. Second moment of area provides information on how hard it is to bend something. Ask students next time they walk by a construction site take a closer look at the cross-sectional area of the support beams, and notice how the beams are laid out. Ask them to pay close attention to the orientation of the cross-sectional area of an I-beam with respect to the directions of expected loads. Steel I-beams, which are commonly used as structural members to support various loads, offer good resistance to bending, and yet they use much less material than beams with rectangular cross-sections. We find I-beams supporting guard rails, and I-beams are used as bridge cross members also as roof and flooring members. To provide a better understanding of this important property of an area and the role of second moment of inertia in offering a measure of resistance to bending, try the following experiments in class. Obtain a thin wooden rod and a yardstick. Try to bend the rod and the yardstick about different directions. If you were to report your findings, you would note that circular cross-section of the rod offers the same resistance to bending regardless of the direction of loading. This is because the circular cross-section has the same distribution of area about an axis going through the center of the area. Note that we are concerned with bending a member and not twisting it! However, when bending the yardstick in different directions, you will note that the yardstick will offer different resistance depending on the direction of bending. This is because, the second moment of area about the centroidal axis is higher for one orientation as compared to the other. At this point you may remind students that they will take a Statics class where they will learn more in depth about the formal definition and formulation of second moment of area and its role in design of structures.

Again, it is important to emphasize, to students, the fact that all physical variables discussed in this section are based on the fundamental dimension length. Area has a dimension of $(\text{length})^2$, volume has a dimension of $(\text{length})^3$, and second moment of area has a dimension of $(\text{length})^4$. In the next section, we will look at time dimension and time and length related variables in engineering.

3. TIME AS A FUNDAMENTAL DIMENSION

Time and Time and Length Related Variables in Engineering

Students should have a good grasp of yet another fundamental dimension in engineering, namely time, and its role in engineering analysis and why the time variable is needed to describe events, processes, and other occurrences in our physical surroundings. They should recognize the role of time in calculating frequency, speed, acceleration, and flow of traffic, as well as flow of materials and substances. In this section of the paper, we will discuss the role of time as a fundamental dimension and other time related engineering parameters such as period (t), frequency (# of cycles/t), linear speed (L/t), acceleration (L/t^2), volumetric flow rate (L^3/t), and flow of traffic (# of cars/t).

We live in a dynamic world. Everything in the universe is in a constant state of motion. Think about it! Everything in the universe is continuously moving. The earth and everything associated with it moves around the sun. All of our solar planets, and everything that comprise them, are moving around the sun. We know that everything outside our solar system is moving too. From our everyday observation we also know that some things move faster than others. For example, people can move faster than ants, or a jet plane moves faster than a car. *Time* is an important parameter in describing motion. How long does it take to cover a certain distance? A long time ago, humans learned that by defining a variable called *time* they could use it to describe the occurrences of events in their surroundings. Ask students to think about the questions that are frequently being asked in everyday life: How old are you? How long does it take to go from here to there? How late are you open? How long is the Christmas break? We have also associated time with natural occurrences in our lives. For example, to express the relative position of the earth with respect to the sun, we use day, night, 3:00 p.m., or May 30th. The parameter time has been conveniently divided into smaller and larger intervals, such as seconds, minutes, hours, days, months, years, centuries, and millennia. As the technology advanced so did the need for a shorter and shorter time divisions, such as microseconds and nanoseconds. We have also learned from our observation of the world around us that we can combine the variable time with the variable length to describe how fast something is moving.

Before discussing the role of time in engineering analysis, you may want to focus on the role of time in our lives—our limited time budget. Today we can safely assume that the average life expectancy of a person living in the western world is around 75 years. You may use this number and perform some simple arithmetic operations to illustrate some interesting points to students. Converting the 75 years to hours we have 657,450 hours. On an average basis, we spend about 1/3 of our lives sleeping; this leaves us with 438,300 waking hours. Considering that traditional college freshmen students are eighteen years old, they have 333,108 waking hours still available to them if they live to the age of 75 years. Think about this for a while. Then ask students if you were given only $333, 108 for the rest of your life, would you throw away a dollar here and a dollar there as you were strolling through life? Perhaps not, especially knowing that you will not get any more money. Life is short! We should make good use of our time, and at the same time enjoy our life.

Next you can look at the role of time in engineering problems and solutions. Most engineering problems may be divided into two broad areas of *steady* and *unsteady* analysis. The problem is said to be *steady* when the value of a physical quantity under investigation does not change over time. If the value of a physical quantity changes with time, then the problem is said to be *unsteady* or *transient*. There are many engineering problems that are steady or unsteady. You may use examples such as the response of a car's suspension system as you drive through a pothole, the response of a building to an earthquake, or cooling and heating of a building to shed light on unsteady problems in engineering.

Measurement of Time

Early humans relied on the relative position of the earth with respect to the sun, moon, stars or other plants to keep track of time. The lunar calendar was used by many early civilizations. The celestial calendars were useful in keeping track of long periods of time, but humans needed to devise a means to keep track of shorter time intervals, such as what today we call an hour. This need led to the development of clocks. Sun clocks, also known as shadow clocks or sun dials, were used to divide a given day into smaller periods. The moving shadow of the dial marked the time intervals. As with other human made instruments, the sun dial evolved over time into elaborate instruments that accounted for the shortness of the day during the winter as compared to summer to provide for a better year-round accuracy. Sand glasses (glass containers filled with sand) and water clocks were among the first time measuring devices that did not make use of the relative position of the earth with respect to the sun or other celestial bodies. The water clocks were basically made of a graduated container with a small hole near the bottom. The container held water, and the container was tilted so that the water would drip out of the hole slowly. The next revolution in time keeping came during the 14th century when weight-driven mechanical clocks were used in Europe. Later, during the 16th century the spring-loaded clocks were used. The spring mechanism design eventually led to smaller clocks and watches. The period of free or natural oscillation of a pendulum was the next advancement in the design of clocks. The quartz clocks eventually replaced the mechanical clocks around the middle of the twentieth century. A quartz clock or watch makes use of the piezo electric property of quartz crystal. It is important for students to be familiar with the history of time, length, mass, or temperature measuring device developments. It emphasizes the fact that measuring devices evolve and as future engineers, they could be involved in development of devices that we may use in the future.

The Need for Time Zones

Everyone knows that the earth rotates about an axis that runs from the south pole to the north pole, and it takes the earth 24 hours to complete one revolution about this axis. Moreover, from studying globes and maps, students may have noticed that the earth is divided into 360 degree circular arcs that are equally spaced from east to west; these arcs are called longitudes. The zero longitude was arbitrarily assigned to the arc that passes through Greenwich, England. Because it takes the earth 24 hours to complete one revolution about its axis, every 15 degrees longitude correspond to 1 hour (360 degrees/24 hours = 15 degrees per one hour). For example, someone exactly 15 degrees west of Chicago will see the sun in the same exact position one hour later as observed by another person in Chicago. The earth is also divided into latitudes which measure the angle formed by the line connecting the center of the earth to the specific location on the surface of the earth and the equatorial plane. The latitude varies from 0 (equatorial plane) degrees to 90 degrees north (North Pole) and from 0 degrees to 90 degrees south (South Pole). The need for time zones was not realized until the latter part of the 19th century when the railroad companies were expanding. The railroad companies realized a need for standardizing their schedules. After all, 8:00 a.m. in New York City did not correspond to 8:00 a.m. in Denver, Colorado. Thus a need for a uniform means to keep track of time and its relationship to other locations on earth was born. It was the railroad scheduling and commerce that eventually brought nations together to define time zones.

Daylight Saving Time

Daylight savings time was originally put into place to save fuel (energy) during hard times such as World War I and World War II. The idea is simple; by forwarding the clock in the spring and keeping it as such during the summer and the early fall, we extend the daylight hours, and consequently we save energy. For example, on a certain day in the spring, without daylight savings time, it would get dark at 8:00 p.m., but with the clocks forwarded by one hour, it would then get dark at 9:00 p.m. So we turn our lights on an hour later. According to a U.S. Department of Transportation study, the Daylight Savings Time saves energy because we tend to spend more time outside of our homes engaging in outdoor activities. Moreover, because more people drive during the daylight hours, Daylight Savings could also reduce the number of automobile accidents, consequently saving many lives.

Period & Frequency

Many students have trouble understanding the difference between period and frequency. For periodic events, *period* is the time that it takes for the event to repeat itself. For example, every 365.25 days the earth lines up in exactly the same position with respect to the sun. The orbit of the earth around the sun is said to be periodic because this event has been repeating itself. The inverse of period is called *frequency*. For example, the frequency at which the earth goes around the sun is once a year. Oscillatory systems such as shakers, mixers, and vibrators are good examples of engineering systems with periodic motion. The piston inside a car's engine cylinder is another good example of periodic motion. You may use the following examples to further explain frequency and period. A spring-mass system represents a very simple model for a vibratory system, such as a shaker or a vibrator. The frequency of natural oscillation of mass in a manner that manifests itself by the up and down motion is given by $f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$.

In this relationship, f_n is the natural frequency of the system in cycles per second, or Hertz, k represents the stiffness of the spring or an elastic member (N/m), and m is the mass of the system (kg). The period of oscillation T for the given system, the time that it takes for the mass to complete one revolution is given by $T = \frac{1}{f_n}$. The pendulum is another good example of a periodic system. The period of oscillation for a pendulum is given by $T = 2\pi\sqrt{\frac{L}{g}}$. In this equation, L is the length of the pendulum (m) and g is the acceleration due to gravity (m/s^2). Not too long ago, oil companies used measured changes in the period of an oscillating pendulum to detect variations in acceleration due to gravity that could have indicated an underground oil reservoir. Understanding of periods and frequencies is also important in design of electrical and electronic components. It is also important to explain to students that in general, excited mechanical systems have much lower frequencies than electrical/electronic systems.

Once the fundamental dimension time is discussed, you may then consider *derived physical quantities* that are based on the fundamental dimensions of length and time.

Linear Speed (L/t)

You may begin by emphasizing the fact that knowledge of linear speed and acceleration is important to engineers when designing conveyer belts that are used to load suitcases into airplanes and product assembly lines, treadmills, elevators, automatic walkways, escalators, water or gas flow inside pipes, space probes, roller coasters, transportation systems (such as cars, boats, airplanes, and rockets), snow removal equipment, backup computer tape drives, and so on. Civil engineers are also concerned with velocities, particularly wind velocities, when designing structures. They need to account for the wind speed and its direction in their calculations when sizing structural members.

All students are familiar with a car speedometer. It shows the instantaneous speed of a car. Before you explain in more detail what you mean by the term instantaneous speed, define a physical variable which is more easily understood, the average speed, which is defined as: $\text{average speed} = \frac{\text{distance travelled}}{\text{time}}$. Note that the fundamental (base) dimensions of length and time are used in the definition of the average speed. The average speed is a *derived physical quantity.*

To understand the difference between average and instantaneous speed, you may ask students to consider the following mental exercise. Imagine that you are going from New York City to Boston, a distance of 220 miles (354 km). Let us say that it took you 4.5 hours to go from the outskirts of New York City to the edge of Boston. Then the average speed is 49 mph (79 km/hr). You may have made a rest stop somewhere to get a cup of coffee. Additionally, the posted highway speed limit may have varied from 55 mph (88 km/hr) to 65 mph (105 km/hr), depending on a stretch of highway. Based on the posted speed limits and other road conditions, and how you felt, you may have driven the car faster during some stretch of the highway, and you may have gone slower during other stretches of highway. These conditions led to an average speed of 49 mph (79 km/hr). Now ask students the following question. If someone needed to locate you, would he or she be able to locate the car knowing just the average speed of the car? The knowledge of the average speed of the car would not be sufficient for someone to locate the car. To know where the car is at all times you need more information, such as the instantaneous speed of the car and the direction in which is traveling. This means you must know the instantaneous velocity of the car. Note that when we say velocity of a car, we not only refer to the speed of the car but also the direction in which it moves. Ask students to imagine that they recorded the speed of your car as indicated by the speedometer every second. The actual speed of the car at any given instant while you were driving the car is called the *instantaneous speed*.

Linear Acceleration (L/t^2)

Acceleration provides a measure of how velocity changes with time. Something that moves with a constant velocity has a zero acceleration. *Because velocity is a vector quantity and has both magnitude and direction, any change in either the direction or the magnitude of acceleration can create acceleration*. For example, a car moving at a constant speed following a circular path has an acceleration component due to change in the direction of the velocity vector. If you begin with a simple example of an object moving along a straight line. The average acceleration is defined as

$$\text{average acceleration} = \frac{\text{change in velcity}}{\text{time}} .$$

Remind students that the acceleration uses only the dimensions of length and time. Acceleration represents the rate at which the velocity of a moving object changes with time. The difference between instantaneous acceleration and average acceleration could be explained in a way similar to the difference between instantaneous velocity and average velocity.

Flow of Traffic

Those of you who live in a big city know what we mean by traffic. A branch of civil engineering deals with the design and layout of highways, roads and streets and the location and timing of traffic control devices that move vehicles efficiently. Let us begin by defining what we mean by traffic flow. In civil engineering, traffic flow is formally defined by the following relationship $q = \frac{3600n}{T}$, where *q* represents the traffic flow in terms of number of vehicles per hour, *n* is the number of vehicles passing a known location during a time duration *T* in seconds. Another useful variable of traffic information is density—how many cars occupy a stretch of a highway. Density is defined by $k = \frac{1000n}{d}$, and in this relationship, *k* is density and represents the number of vehicles per kilometer, and *n* is the number of vehicles on a stretch of highway *d* measured in meters.

Knowing the average speed of cars also provides valuable information for the design of road layouts and the location and timing of traffic control devices. The average speed of cars is determined from $\bar{u} = \frac{1}{n}\sum_{i=1}^{n} u_i$, where u_i is the speed of individual cars, and *n* represents the total number of cars. There is a relationship among the traffic parameters, namely the flow of traffic, density, and the average speed according to $q = k\bar{u}$, where *q*, *k*, and *u* were defined earlier. Finally, you may want to explain to students that traffic engineers use various measurement devices and techniques to obtain real time data on the flow of traffic. They use the collected information to make improvements to move vehicles more efficiently. You may have seen examples of traffic measurement devices such as pneumatic road tubes and counters. Other common traffic measurement devices include magnetic induction loops and speed radar.

Volume Flow Rate (L^3/t)

Engineers design flow measuring devices to determine the amount of a material or a substance flowing through a pipeline in a processing plant. Volume flow rate measurements are necessary in many industrial processes to keep track of the amount of material being transported from one point to the next point in a plant. Additionally, knowing the flow rate of a material, engineers can determine the consumption rate of a material so that they can provide the necessary supply for a steady state operation. Flow measuring devices are also employed to determine the amount of water or natural gas being used by us in our homes during a specific period of time. City engineers need to know the daily or monthly volumetric water consumption rates in order to provide an adequate supply of water to our homes and commercial plants. Companies providing the natural gas need to know how much fuel—how many cubic meters of natural gas—are burned every month, by each home so that they can correctly charge the customers. In sizing the heating or cooling units for buildings, the volumetric flow of warm or cool air must be determined to adequately compensate for the heat loss or heat gains for a given building. Ventilation rates dealing with the introduction of fresh air into a building are also expressed in cubic feet (or meter) per minute or per hour.

After you introduce the concept of volumetric flow rate, through examples, you should formally define it. The volume flow rate is simply defined by the volume of a given substance that flows through something per unit time, i.e., $\text{volume flow rate} = \frac{\text{volume}}{\text{time}} = \frac{L^3}{T}$. Note that in the definition given, the fundamental dimensions of length (length cubed) and time are used. After defining the volume flow rate, you should introduce some of the more common units for volume flow rate including, m^3/s, m^3/hr, liters/s, ml/s ft^3/s, ft^3/min, or gallons/minute (gpm). For flowing fluids through pipes, conduits, or nozzles, there exists a relationship between the volumetric flow rate, the average velocity of the flowing fluid, and the cross-sectional area of the flow according to:

$$\text{volume flow rate} = (\text{average velocity})(\text{cross - sectional area of the flow}) = (\frac{L}{T})(L^2) = \frac{L^3}{T}$$

This is another concept that all engineering students should know. They should also recognize the role of length and time in this concept.

4. MASS AS A FUNDAMENTAL DIMENSION

Mass and Mass Related Variables

As we discussed earlier, from their day to day observations humans noticed that some things were heavier than others and thus recognized the need for a physical quantity to describe that observation. Early humans did not fully understand the concept of gravity; consequently, the correct distinction between mass and weight was made later. Students should have a good understanding of what is meant by mass and know about the important roles of mass in engineering applications and analysis. They should realize that mass provides a measure of resistance to translational motion. Students should also know that if you want to rotate something, the distribution of mass about the center of rotation also plays an important role. The further the mass from a center of rotation, the more resistance mass offers to rotational motion. They should know how we define momentum for a moving object. They should also know that something with a relatively small mass could have a relatively large momentum. They should know that in engineering to show how light or heavy materials are, we use properties such as density, specific volume, and specific gravity. They should also have a good understanding of what is meant by mass flow rate and how it is related to volume flow rate.

Mass also plays an important role in storing thermal energy. The more massive something is, the more thermal energy you can store within it. Some materials are better than others at storing thermal energy. For example, water is better at storing thermal energy than air is. In fact, the idea of storing thermal energy within a massive medium is fully utilized in the design of passive solar houses. You will find massive brick or concrete floors in the sun rooms. Some people even place big black barrels of water in the sun rooms to absorb the available daily solar radiation and store the thermal energy in the water to be used overnight.

Measurement of Mass

In practice, mass of an object is measured indirectly using how much something weighs. The weight of an object on earth is the force that is exerted on the mass due to the gravitational pull of earth. Students are familiar with spring scales that measure the weight of goods at a supermarket, or bathroom scales at home. Force due to gravity acting on the unknown mass will make the spring stretch, or compress. From the knowledge of deflection of the spring, one can determine the weight and consequently the mass of the object that created that deflection. Students should understand the difference between weight and mass, and be careful how they use them in engineering analysis.

Once the fundamental dimension mass is explained, then you may consider introducing derived physical variables that are based on fundamental dimension mass, length, and time.

Density (m/L³), Specific Volume (L³/m), Specific Gravity

In engineering practice, to represent how light or how heavy materials are we often define properties that are based on a unit volume. You may ask students given one cubic feet of wood and one cubic feet of steel, which one has more mass? The steel of course! The density of any substance is defined as the ratio of the mass by the volume that it occupies, according to: $\text{Density} = \frac{\text{Mass}}{\text{Volume}} = \frac{m}{L^3}$. Density provides a measure of how compact the material is for a given volume. Materials such as mercury or gold with relatively high values of density have more mass per one ft^3 volume or one m^3 volume than those with lower density values such as water. The specific volume which is the inverse of the density and is defined by:

$$\text{Specific Volume} = \frac{\text{Volume}}{\text{Mass}} = \frac{L^3}{m}.$$

The specific volume is commonly used in the study of thermodynamics. Another common way to represent the heaviness or lightness of some material is by comparing its density to the density of water. This comparison is called Specific Gravity of a material and is formally defined by: $\text{Specific Gravity} = \frac{\text{Density of a material}}{\text{Density of Water@4}^{o}\text{C}}$.

Mass Flow Rate (m/t)

Earlier, we discussed the significance of volume flow rate. The mass flow rate is another closely related parameter that plays an important role in many engineering applications. Mass flow rate tells engineers how much material is being used or moved over a period of time so that they can replenish the supply material. The mass flow rate is simply defined by the amount of mass that flows through something per unit of time, i.e., $\text{Mass flow rate} = \frac{\text{Mass}}{\text{Time}} = \frac{m}{t}$. Ask students how would they measure the mass flow rate of water coming out of a faucet or a drinking fountain? Place a cup under a drinking fountain and measure the time that it takes to fill the cup. Also, measure the total mass of the cup and the water and then subtract the mass of the cup from the total to obtain the mass of the water. Divide the mass of the water by the time interval it took to fill the cup.

We can relate the volume flow rate of something to its mass flow rate provided that we know the density of the flowing material. The relationship between the mass flowrate and the volume flow rate is given by:

$$\text{mass flow rate} = \frac{\text{mass}}{\text{time}} = \frac{\overbrace{(\text{density})(\text{volume})}^{mass}}{\text{time}} = (\text{density})(\frac{\text{volume}}{\text{time}})$$

$$\text{mass flow rate} = (\text{density})(\text{volume flow rate})$$

You may also explain to students that the mass flow rate calculation is also important in excavation or tunnel digging projects in determining how much soil can be removed in one day or one week, taking into consideration the parameter of the digging and transport machines.

Mass Moment of Inertia (mL²)

When it comes to rotation of objects, the distribution of mass about the center of rotation plays a significant role. The further away the mass is located from the center of rotation, the harder it would be to rotate the mass about the given center of rotation. A measure of how hard it is to rotate something with respect to center of rotation is called mass moment of inertia. Students may be reminded that they will take a class in physics and some of them may even take a dynamics class where they will learn in more depth about the formal definition and formulation of mass moment of inertia.

Momentum (mL/t)

Mass also plays an important role in problems dealing with moving objects. Momentum is a physical variable that is defined as the product of mass and velocity, according to $\vec{L} = m\vec{V}$. In this equation, *L* represents momentum vector, *m* is mass, and *V* is the velocity vector. Because the velocity of the moving object has a direction, we associate a direction with momentum as well. The momentum's direction is the same as the direction of velocity vector or the moving object. So a 1000 kg car moving north at a rate of 20 m/s has a momentum with a magnitude of 20,000 kg.m/s in the north direction. Because the magnitude of linear momentum is simply mass times velocity, something with relatively small mass could have a large momentum value, depending on its velocity. For example, a bullet shot out of a gun with a relatively small mass can do lots of harm and penetrate a surface because of its high velocity. The magnitude of the momentum associated with the bullet could be relatively large.

5. CONCLUDING REMARKS

In this paper, we discussed how to introduce freshmen students right away to some of the fundamentals—using fundamental dimensions—that they will see over and over in some form or other during their college years. Successful engineers have a good grasp of these fundamentals, which they can use to understand and solve many different problems. We also emphasized that from our observation of our surroundings, we have learned that we need only a few physical quantities to describe events and our surroundings. Today, based on what we know about our physical world, we need *seven fundamental or base dimensions* to express what we know of the natural world. They are *length, mass, time, temperature, electric current, amount of substance, and luminous intensity*. We explained that there are many engineering design variables that are related to these fundamental dimensions. We also emphasized that we need not only physical dimensions to describe our surroundings, but also some way to scale or divide these physical dimensions. To become a successful engineer a student must first fully understand these fundamentals and related variables. Then it is important for the student to know how these variables are measured, approximated, calculated, or used in engineering design and practice. Moreover, it is important to note that in order to keep the length of this paper at a reasonable level, we only discussed the role of length, time, and mass in engineering. You can use similar approach to introduce students to other fundamental dimensions and their roles in engineering. Finally, it is worth noting that the teaching method described in this paper was utilized by the author in a freshman (introduction to engineering) class at Minnesota State University three years ago. The author also teaches upper-classmen and has noticed a better grasp of the fundamentals by the juniors and seniors who were taught the fundamentals in the manner discussed in this paper.

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