Lecture W1

Physical Quantities and Units

1. Overview

Physics begins with observations of phenomena. Through rigorous and controlled experimentation and logical thought process, the physical phenomena are described quantitatively using mathematical tools. Any quantitative description of a property requires comparison with a reference For example, length needs a meter-stick. In this process we recognize a very obvious fact that properties of different kinds cannot be compared. You cannot compare the time of travel from point A to B with the distance between two points, although two quantities may be related. The time of travel is a physical quantity, *time* while the distance is a physical quantity, *length*. They are completely different types of physical quantities measured by different references and units.

Suppose you are measuring the size of your room to estimate the amount of wooden panels for your floor. You will probably use a tape measure and read out the lengths of the room in feet and inches. However, in Paris, people would do the exactly the same thing but they will write their measurements in meters and centimeters. So one can measure the same physical quantity but can express the size of the quantity in different ways (units). A physical quantity can have many different units depending on the location and culture. Scientists found that this was very inefficient and confusing and decided to set up a universal system of units, **International System of Unit (SI)**. *In this class we will use SI.*

2. Physical Quantities

Name physical quantities that you know: mass, time, speed, weight, energy, power, ... Scientists can even make up a completely new physical quantity that has not been known if necessary. However, there is a set of limited number of physical quantities of fundamental importance from which all other possible quantities can be derived. Those fundamental quantities are called **Base Physical Quantities**, and obviously the other derivatives are called **Derived Physical Quantities**. SI is built upon 7 base quantities and their associated units (see Table I).

TABLE I: SI Base Quantities and Units

Property	Symbol	Unit	Dimension
Length	L	meter (m)	L
Mass	m	kilogram (kg)	M
Time	t	second (s)	T
Temperature	T	kelvin (K)	θ
Electric Current	I	ampere (A)	I
Amount of Substance	N	mole (N)	1
Luminous Intensity	F	candela (cd)	J

TABLE II: SI Examples of Derived Quantities and Their Units

Property	Symbol	Unit	Dimension
Force	F	newton (N)	kg·m·s^{-2} = kg·m·/s^2
Speed	v	meter per second (m/s)	m·s^{-1} = m/s
Pressure	P	pascal (Pa)	(force per unit area) kg·m^{-1}·s^{-2}
Energy	E	joule (J)	kg·m^2·s^{-2}
Power	W	watt (W)	(energy per unit time) kg·m^2·s^{-3}

A physical quantity can be expressed with a *unique combination* of 7 base quantities. One can also make a physical quantity with a combination of derived quantities. But it will be eventually reduced to a combination of base quantities. For example, *Kinetic Energy* (E) is a type of energy represented in joule (J) and is a derived quantity through $\frac{1}{2}mv^2$ *i.e.* (1/2)(**mass**)x(speed)x(speed). Since speed is a derived quantity itself: (speed) = (**length**)/(**time**), one can express energy using base quantities: (1/2)(**mass**)x(**length**)^2/(**time**)^2. Note that the base quantities are in bold. Some of the important derived physical quantities are listed in Table II.

3. Conversion of Units

Below is the table for commonly used unit conversion. It is also useful to know metric prefixes (Table IV). Let us do a couple of examples of unit conversion.

TABLE III: Unit Conversion of Base Quantities

Quantity	From	To	Operation
Length	inch (in)	m	(inch) $\times$ 0.0254
	foot (ft)	m	(foot) $\times$ 0.3048
	mile (mi)	m	(mile) $\times$ 1609.34
Mass	pound (lb)	kg	(pound) $\times$ 0.4536
	metric ton (t)	kg	(ton) $\times$ 1000
	ounce	kg	(ounce) $\times$ 0.02835
Volume	liter (l)	m^3	(*liter*) $\times$ 0.001
	gallon (ga)	m^3	(gallon) $\times$ 0.00379
Temperature	fahrenheit (F)	K	$\{(\text{fahrenheit}) - 32\} \times \frac{5}{9} + 273.15$
	celcius (C)	K	(celcius) + 273.15

Examples

1. Length 0.02 in can be converted into SI unit in meters using Table I: (0.02in) $\times$ 0.0254 = 0.000508 m. Too many zeros below decimal points here. Since 0.000508 = 0.508 $\times$ 10^{-3} = 508 $\times$ 10^{-6}, it is also 0.503 mm (millimeter) or 508 μm (micrometer).
2. Honda Fit weighs about 2,500 lb. It is equivalent to 2500lb $\times$ 0.4536 = 1134.0kg.

TABLE IV: Metric Prefix

Prefix Name	Prefix Symbol	Base 10	Decimal	English Word
peta	P	1,000,000,000,000,000	10^{15}	quadrillion
tera	T	1,000,000,000,000	10^{12}	trillion
giga	G	1,000,000,000	10^{9}	billion
mega	T	1,000,000	10^{6}	million
kilo	k	1,000	10^{3}	thousand
deca	da	10	10^{1}	ten
		1	one	
centi	c	0.01	10^{-2}	hundredth
milli	m	0.001	10^{-3}	thousandth
micro	μ	0.000,001	10^{-6}	millionth
nano	n	0.000,000,001	10^{-9}	billionth
pico	p	0.000,000,000,001	10^{-12}	trillionth
femto	f	0.000,000,000,000,001	10^{-15}	quadrillionth

Let us look into a derived quantity. Julia is driving her Honda Fit on I-75 at 70 mph (miles per hour). Any moving object carries a physical quantity called *kinetic energy*; you will soon learn about this. The kinetic energy is given by $\frac{1}{2}mv^2$. So if you use the conventional units, it will give $0.5 \times 2500 \times 70 \times 70$ lb(mph)^2. This quantity of energy needs to be expressed in SI units in this class. So convert the mass into kg and the speed mph into m/s (meter per second).
Step 1 Convert mass. It is already done in the above example $m = 1134$ kg.
Step 2 Convert speed. $v = 70$ mile/hr $= 70$ (1609.34 m)/(3600 s) $= 70 \cdot 1609.34/3600 =$ 31.29 m/s.
Step 3 Carry out the calculation using the quantities in SI. (kinetic energy) $= \frac{1}{2}mv^2 = 0.5 \cdot 1134 \cdot (31.29)^2 = 555,129.3$ kg$\cdot$m^{2}s^{-2}. This is equivalent to 555,129.3 J (joule) (see Table I).

Q1 The length scale in astronomy is much larger than what we are used to. So scientist uses a different length unit called *light-year* (ly) which is the distance that light travels for one year (speed of light is 3×10^8 m/s). One of the nearest star from the solar system is about 4.2 ly away. Express 4.2 ly in km.
Answer: about $4 \times 10^{+13}$ km.

Sirius is the brightest star in the night sky. It is 8.6 ly away from Earth. When you look at Sirius on a clear night, light from the star was emitted 8.6 years ago and traveled at the speed of light for 8.6 years to reach your eyes.

4. Weight and mass, they are not the same quantities in physics!

Measure your weight on a scale. Suppose that the scale reads 120 lb. Let's investigate this little further. Table I says pound is a conventional unit for a base quantity, **mass**. So your scale measures your mass 120 lb = 54.43 kg. However, if you bring your scale to the moon and measure your weight, it will give you 19.9 lb = 9.03 kg about 1/6 of the quantity on

Earth. Has your mass changed? Mass is the total amount of material or atoms–everything is composed of atoms–in an object. Ignoring the possible weight loss during the space travel, the amount of substance in your body should not change. What happened?

When you step on a scale, you apply a force on the top of the scale. The force that you are applying is due to gravitational pull (proportional to mass) of you by the earth. This force will press down the top of your scale and the scale measures internally the force you applied on the surface. The gravitational pull is weaker on the moon than on Earth. That is why the scale reads 1/6 of the reading on Earth. The scale is calibrated (designed to be used on Earth) to show you the mass equivalent to the force detected on Earth. *Weight* is the *force* due to gravitational pull. So it should be expressed in unit of newton (N) not in kg!

Note: When a quantity A is proportional to a quantity B, it means mathematically $A = c \cdot B$ where c is a constant (fixed) number. Knowing the value of c, the knowledge of one quantity immediately produce the value of the other quantity. Conversely, if you know both A and B, then you can calculate $c = \frac{A}{B}$.

It took a long time through Galileo and Newton to figure out the force of gravitational pull is proportional to mass; $F = gm$. The proportional constant g is called *gravitational acceleration* on Earth (g = 9.8 m/s^2). The gravitational acceleration on the moon is 1.6 m/s^2 which is about 1/6 of the Earth value. You can directly measure g in many ways, which we will do in our laboratory session.

5. The Length Scale of the Universe

Length is one of the fundamental base quantities. We are very familiar with length: height, distance of travel, size of a cell phone, ... You will be surprised to know what range of length physicists are dealing with. Visit http://scaleofuniverse.com/ and survey the full range of length in physics: from the shortest side, "Planck length" approximately 10^{-35} m to the longest, the size of universe about 10^{27} m. The size of the largest virus is about 10^{-6} m, the size of atom is about 10^{-10} m, and the radius of Earth is about 6×10^6 m. You may think the numbers are outrageously small or large. But physicists have a quite good idea how to understand phenomena occurring in these outrageous length scales: quantum physics describes phenomena in very small length scale such as subatomic world and astrophysics for, as you imagine, astronomical phenomena such as expansion of universe.

Q2 What are the physical entities in the femtometer (fm) range? What is the typical size of galaxies? *You can get the answers from the web, http://scaleofuniverse.com/.*

Q3 How many years would it take light to traverse a typical galaxy (light-year)? How long would it take to pass through an atom in seconds?

6. How cold it can get?

On a day of winter storm, the temperature in Antarctica can reach -100 F. This is much colder than your freezer. Then what is the lowest temperature one can get? Deep in space far far away from the sun, is that the coldest spot in the universe? Is -1,000,000 F possible? If you convert Fahrenheit into kelvin using the formula in Table III, -100 F is equivalent to 199.82 K. One reason that physicists use kelvin scale rather than Celcius or Fahrenheit is directly related to the question posed above. The lowest temperature allowed in physics–therefore, one can reach– is zero kelvin, 0 K. One can not reach negative kelvin temperature, very convenient! And we call this *absolute zero*. Then what is the temperature of deep space? Surprisingly it is not absolute zero. Physicists know the average temperature of deep space with very high accuracy, about 2.73 K *now*. It used to be hotter than now and will get colder in the future.

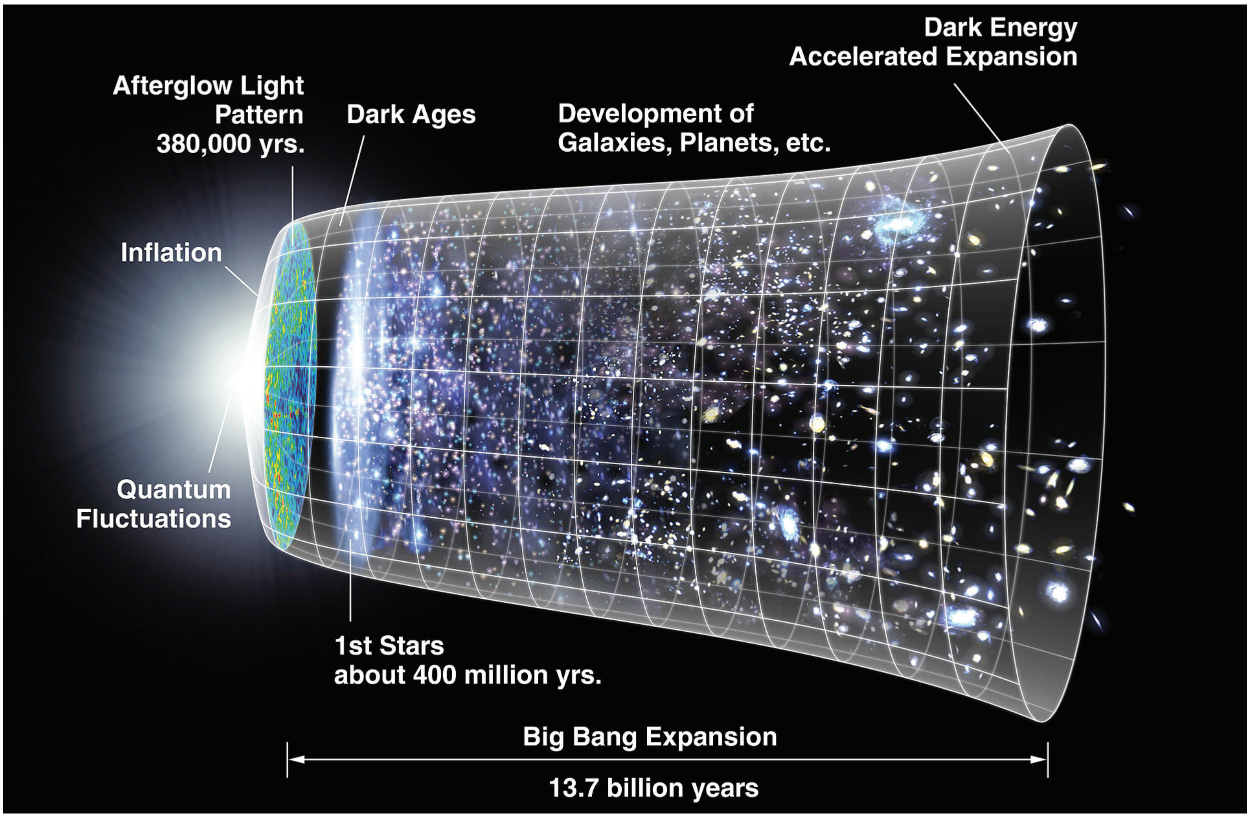

FIG. 1: Diagram of evolution of the universe from the Big Bang. From wikipedia, modified from the original NASA/WMAP.

The current understanding of the universe is that it started from a point in which all matter and energy are contained. At this stage, it is unimaginably hot. The universe started to expand and accordingly cooled down very rapidly. Around 10^{-43} s after the Big Bang, the universe cooled down to 10^{32} K (I know it is still unimaginably high temperature!). Within about 1 s, the universe cooled to 10^{9} K, and reached to the current temperature, 2.73 K after about 14 billion years after the Big Bang.

"... while the sources of heat were obvious the sun, the crackle of a fire, the life force of animals and human beings cold was a mystery without an obvious source, a chill associated with death, inexplicable, too fearsome to investigate."

Absolute Zero and Conquest of Cold

by T. Shachtman

Current technology can reach around 10^{-9} K (nanokelvin). It is 0.000,000,001 K above absolute zero. You can think of absolute zero like the speed of light in the sense that it is a barrier nature does not allow to go beyond and one can only reach as close as possible. As the temperature lowers close to absolute zero, nature reveals fascinating character, quantum nature which is so different from what we experience. Remember that when the length scale gets shorter in subatomic level, quantum physics is needed. If you lower temperature low enough, the quantum nature appears even in a macroscopic length scale.