Lecture 02 Measurement

This lecture gives you the same content as that in **Chapter 01 in Serway/Jewett's** textbook of "Physics for Scientists and Engineers with Modern Physics".

What is physics? Physics is about the background mechanisms of all phenomena around you. Until now, we have established many practical models using mathematics to express physical mechanisms. The first step to explore physics is to carry out measurements.

2.1 Classification of Physics

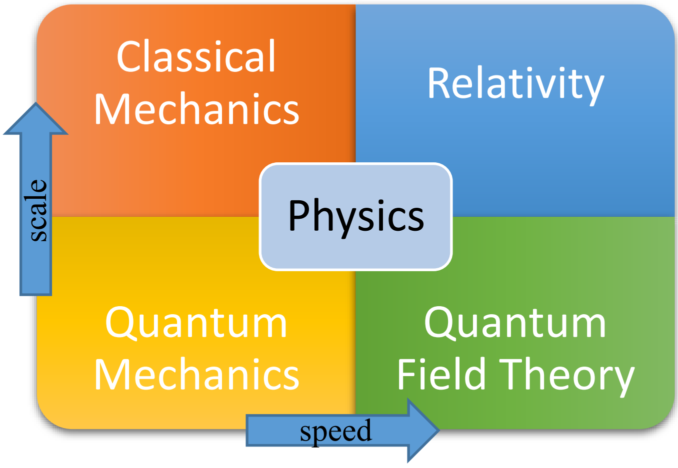


Figure 1. Classification of physics by the scale and the velocity of the objects.

Physics is commonly classified to classical mechanics and modern physics. They can be roughly separated by the time in the beginning of the 20th century. Classical physics consists of Newtonian mechanics, oscillations and waves, thermodynamics, electromagnetics, and optics. On the other hand, modern physics possesses the only two topics of quantum physics and relativity.

We can classify physics by using speed and scale. For a system moving in a high speed approaching the speed of light, the relativity shall be considered. For a system on the atomic scale, the wave nature and quantum mechanics shall be taken into account.

Measurements help us to study physics around us. What are measurements? Measurements are just the act of comparison. Comparing with a standard, we can estimate a number of that how many times of the standard are equal to the object under measurement. The measurement is expressed as the estimated number with the standard (named as a unit).

Classical Physics – It possesses the fundamental concepts of Galileo (1564-1642) and Newton's space and time. It includes Newtonian mechanics, rotation, fluid, oscillations and waves, thermodynamics, electricity and magnetism (James Maxwell), and optics.

Modern Physics – The application of special relativity and, particularly, quantum theory to microscopic systems is often referred to as modern physics. The microscopic systems could be atoms, molecules, and nuclei, which has led to a detailed understanding of solids, liquids, and gases around us.

Recording / Measurement – Compare with a standard length, mass, or time

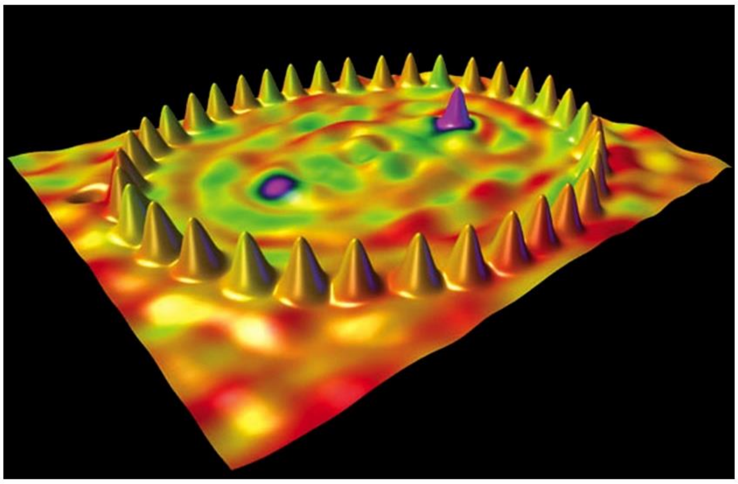


Figure 2. The concept of iron atoms placed on copper surface.

Figure 2 shows a concept of imaging the waves and iron atoms on atomically flat copper surface. How can the scientist determine the size of the elliptical structure constructed by atoms? The answer is just a measurement by comparison. The scientists build up the atomic microscope. They then make a standard pattern with a periodic pattern structure of several microns in length. They determine the length scale of the standard pattern by using a calibrated optical microscope. They then measure the standard pattern and calibrate the new-built atomic microscope. All measurements are done by comparison.

2.2 Standards of Length, Mass, and Time

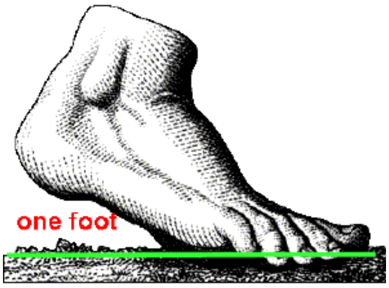
To get a number for the measurements, we need standards for comparison. In physical

measurements, there are three basic measurements, including length, mass, and time. All other units of measurements can be derived from the three basic measurements. It is commonly used to measure according to the international standard – the international system of units (abbreviated as SI). In this unit system, the three standards, meter, kilogram, and second, are used in measurements.

If other units different from the SI units are used in measurements, we may need a calculation of unit conversion. Here we introduce the unit conversion between the English system and the SI unit.

The Unit Conversion for The English System:

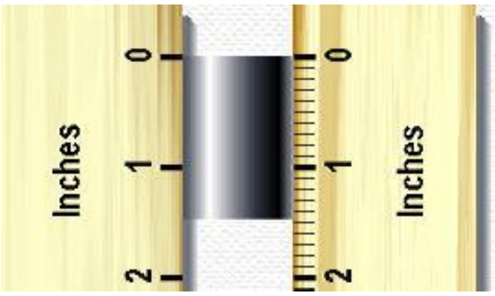
1 inch = 2.54 cm, 1 ft = 30.48 cm
1 mi = 1.609 km
1 lb = 0.454 kgw
1 atm = 14.7 lb/in.^{2} (PSI) = 760 mmHg = 101325 Pa (N/m^2) ~ 1 kgw/cm^2



The English measurement units grew out of the creative way that people measured for themselves. Familiar objects and parts of the body were used as measuring devices. For example, people measured shorter distances on the ground with their feet. The concepts are still used today. For example, a boy scout shall learn to measure his surround natural objects by using his height, his length of arm or his hands.

The Standard of Length:

Distance traveled by light in a vacuum during a time of 1/299 792 458 second. Give the correct length measurement for the left and the right rulers.



The Standard of Time:

Atomic clock: 9 192 631 770 times the

period of oscillation of radiation from the cesium-133 atom.

Radio Controlled Exact Set Atomic Projection, Alarm and Wall Clocks from Oregon Scientific, Casio, La Crosse Technology and more.
Radio controlled clocks or "Atomic Clocks" keep perfect time by automatically synchronizing to the radio signal emitted from the U.S. Atomic Clock in Colorado. Radio controlled clocks reset daily to the split second, and adjust automatically to Daylight Savings Time, Leap Year and Time Zone Changes.

Scientists have manufactured the world's smallest atomic clock, with inner machinery about the size of a grain of rice. Requiring very little power to run, the device loses only one second every 300 years and could one day provide precise timekeeping for portable applications such as wireless communication devices and Global Positioning System (GPS) receivers. Like other atomic clocks, the new design relies on the natural vibrations of cesium atoms, which “tick” 9.2 billion times each second. John Kitching of the National Institute of Standards and Technology and his colleagues trapped cesium vapor inside a chamber that is probed by a tiny laser, resulting in two electromagnetic fields. The team then adjusted the fields until the difference between them equaled that of the energy levels within the cesium atoms, causing the atoms to stop absorbing or emitting light. An external oscillator was then stabilized against the natural resonance frequency of cesium. “The real power of our technique is that we're able to run the clock on so little electrical power that it could be battery operated and that it's small enough to be easily incorporated into a cell phone or some other kind of handheld device”, explains Kitching. “And nothing else like it even comes close as far as being mass producible.”

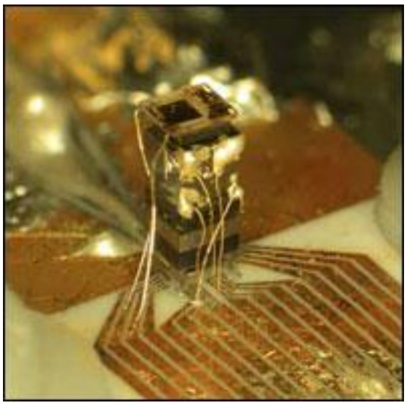
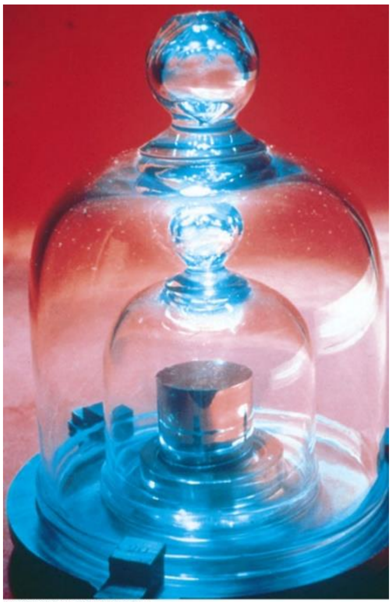


Image: NIST

The Standard of Mass:

Kilogram is defined as the mass of a specified platinum-iridium alloy cylinder kept at the International Bureau of Weights and Measures at Sevres, France.



Basic Information of The World:

Length:

One light year is 9.46×10^{16} m.

The mean radius of the Earth is about 6400 km that is also expressed as 6.4×10^{6} m.

The diameter of a hydrogen atom is about 10^{-10} m. It’s radius is 0.529 angstroms.

The diameter of a proton is about 10^{-15} m.

Mass:

The average value of human’s height is 70 kg.

The mass of a hydrogen atom is $1 * 10^{-3}$ kg / $6.02 * 10^{23} = 1.67 * 10^{-27}$ kg.

Time:

One day is $8.64 * 10^4$ s.

Some Abbreviation for Units of Measurements

Number	Name	Number	Name
10^{-3}	mili	10^3	Kilo (k)
10^{-6}	micro	10^6	Mega (M)
10^{-9}	nano	10^9	Giga (G)
10^{-12}	pico	10^{12}	Tera (T)
10^{-15}	femto	10^{15}	peta
10^{-18}	atto		

For example, when we talk about the thickness of the graphene, we say 0.3 nm. When we talk about the size of a hard disk, we use the units of mega (M) or giga (G) bytes.

Density and Atom Mass

The density is defined as mass of an object divided by its volume, denoted as $\rho = m / V$. Here we show densities of several important elements:

Gold: $19.3 * 10^3$ kg / m^3 = 19.3 g / cm^3

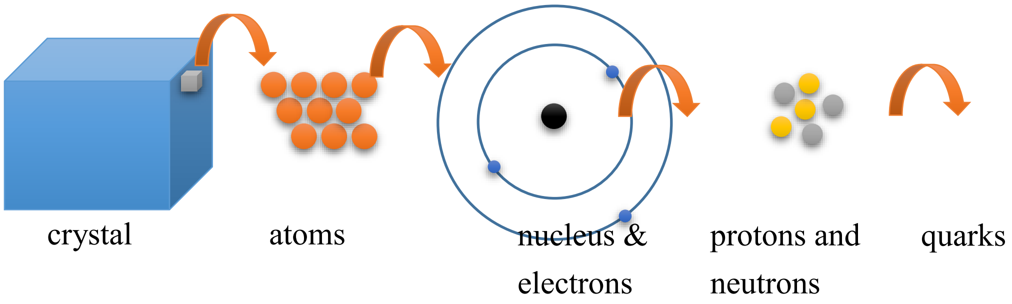
Lead: $11.3 * 10^3$ kg / m^3 = 11.3 g / cm^3

Copper: $8.93 * 10^3$ kg / m^3 = 8.93 g / cm^3

Aluminum: $2.7 * 10^3$ kg / m^3 = 2.7 g / cm^3

Example: A solid cube of aluminum has a volume of 0.200 cm^3. It is known that 27.0 g of aluminum contains $6.02 * 10^{23}$ atoms. How many atoms are there in the cube?

2.3 Matter and Model Building



It's not difficult to find crystals around us. Crystals are always in the solid phase rather than in liquid or gas forms. Inside the crystal, we can find the basic unit of atoms. Further zooming in, we can find nucleus and electrons in atoms. If we go further, we will find protons and neutrons in a nucleus. According to high energy experiments, protons are constructed by quarks. There are six kinds of quarks: up, down, strange, charmed, bottom, and top quarks.

2.4 Dimensional Analysis

$v_f = v_i + at$

v has a dimension of L / T

a has a dimension of L / T^2

Quantity	Symbol	Dimension
Area	A	L^2
Volume	V	L^3
Speed	v	L/T
Acceleration	a	L/T^2
Force	f	ML/T^2
Pressure	p	M/LT^2
Density	d	M/L^3
Energy	E	ML^2/T^2
Power	P	ML^2/T^3

Example: We know that the centrifugal acceleration is related to two physical quantities, radius and velocity. Can we us the unit of the three physical quantities to find out their relationship?

$a = kr^n v^m$, $\frac{L}{T^2} = L^n \left(\frac{L}{T}\right)^m$ → $n + m = 1$, $m = 2$

$$a_r = kr^{-1}v^2 = k\frac{v^2}{r}$$

2.5 Conversion of Units

$15.0in. = (15.0in)(\frac{2.54cm}{1in}) = 38.1cm$, $240km = (240km)\left(\frac{1mi}{1.61km}\right) = 149mi$

Example: A car is traveling with a speed of 38.0 m/s. Is the driver exceeding the speed limit of 75.0 mi/h?

$38\frac{m}{s} = 38\frac{m}{s}\frac{1mi}{1609m}\frac{3600s}{1h} = 85\frac{mi}{h}$

2.6 Estimates and Order-of-Magnitude

Calculation

1. Express the number in scientific notation, with the multiplier of the power of ten between 1 and 10.
2. If the multiplier is less than $\sqrt{10} = 3.162$ (the square root of ten), the order of magnitude of the number is the power of ten in the scientific notation. If the multiplier is greater than 3.162, the order of magnitude is one larger than the power of ten in the scientific notation.

$10^2 \times 10^3 = 100 \times 1000 = 100000 = 10^5$, $N_A = 6.02 \times 10^{23}$, $0.0086 \sim 10^{-2}$

Example: In 12g of carbon, there are N_A carbon atoms. If you could count 1 atom per second, how long (in years) would it take to count the atoms in 1 g of carbon?

$6.02 \times 10^{23} / 12 / 1(atom/s) / 86400 / 365 = 1.59 \times 10^{15}$

2.7 Significant Figures

The significant figures include the first estimated digit.

Rule: multiplication & division – The number of significant figures in the result of multiplication or division is no greater than the least number of significant figures in any of the factors.
2.00 * 6.10 = 12.2
2.00 * 6.112 = 12.2
2.00 * 6.1 = 12

Rule: addition & subtraction – The result of addition or subtraction of two numbers has no significant figures beyond the last decimal place where both of the original numbers had significant figures.
1.001 + 0.003 = 1.004
1.001 + 0.2 = 1.201=1.2

Measurement	**Number of Significant Digits**	**Distance between Markings on Measuring Device**
142.7 g	4	1 g
103 nm	3	10 nm

2.99798×10^8 m	6	0.0001×10^8 m

Example: A rectangle has a length of 3.21±0.02 m and a width of 2.8±0.1 m. Please calculate the area.

$$(3.21 \pm 0.02)(2.8 \pm 0.1) = (3.21)(2.8) \pm (0.02)(2.8) \pm (0.1)(3.21)$$

$$= 8.988 \pm 0.377$$

$$= 8.988 \pm 0.377$$

$$= 9.0 \pm 0.4$$