Length

The way we have defined and measured length has taken many forms throughout history. At first the dimensions of parts of the body were used. Later these measures were enshrined as length artefacts such as metal bars. Today the SI unit of the metre is defined in terms of the speed of light, giving us a universal and absolute scale of length.

Early definition of the metre

The metre was first defined in 1791, as 'one ten millionth of the polar quadrant of the earth passing through Paris'. If you ran a piece of string from the North Pole through Paris to the equator, and then chopped it into 10 000 000 equal length pieces, each section would be one metre long. The team of surveyors that measured the part of the Polar quadrant between Dunkirk and Barcelona took six years to do it. This definition of the metre was realised practically with a bar of platinum metal.

The metre today

Since 1983, the metre has been internationally defined as the length of the path travelled by light in a vacuum during a time interval of 1/ 299 792 458 of a second. This definition is a major improvement on the original one, as it can be realised more simply and accurately using modern techniques. In addition the speed of light is generally regarded to be a universal constant of nature making it ideal as a length standard.

The definition of the metre can be used or realised in two different ways to measure length practically:
a) Time of flight – a pulse of light is sent over the length to be measured. The time it takes for the light to travel this distance multiplied by the speed of light (299 792 458 metres per second), gives the length in metres. As light is very fast, this method is easiest to apply over long distances. However, care has to be taken to account for gravitational field effects if using long distances across space.
b) Interferometry – the technique of interferometry allows a length to be measured in terms of the wavelength of light. By using a light source of known and stable wavelength, lengths up to 100 metres can be directly measured, with accuracies approaching 1 part in a thousand million.

Why do we need accurate length measurement?

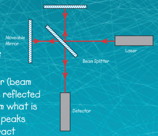
The need for accurate length measurement and definition is needed throughout the modern world. Much of industry and technology relies on length measurement. From the thread on a nut and bolt to precision machined parts in car engines down to tiny structures on microchips; all require an accurate international scale of length. This need is all the more important in the global economy, as without it for example, an aeroplane wing made in the United Kingdom would not fit a fuselage made in France.

At the start of the Twentieth Century 1,207 different combinations of nuts and bolts that supposedly were the same size were tested, but of these only 8% of them 'engaged sufficiently' to allow screwing up with a spanner.

"One small step..."

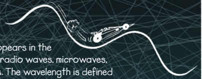
A good example of measuring a long distance by using the time of flight method is that of measuring the distance from the earth to the moon. In the 1970s Apollo astronauts placed mirror-like retroreflectors on the surface of the moon. A pulse of light sent from the earth can be bounced back from the moon and detected. Measuring the round trip time and multiplying by the speed of light gives the average distance as 384.4 million metres with an accuracy in the 2-3 cm range.

What is interferometry?



An interferometer is a device that enables one to measure a length in terms of the wavelength of light. An interferometer consists of a source of light of stable and known wavelength (usually a laser) and three reflecting surfaces. The light is split into two portions, by a partially reflecting mirror (beam splitter), which then travel separate paths to two mirrors where they are reflected back on themselves. The two beams recombine at the beam splitter to form what is known as an interference pattern which can be imaged by a detector. The peaks and troughs of the light waves in the two arms of the interferometer interact (or interfere) with one another forming the interference fringes. When one of the mirrors moves a distance equal to one half of the wavelength of the laser (about 0.3 millionth of a metre) one fringe is observed to cross the detector. By electronic counting and sub-dividing the fringes, lengths can be determined to accuracies of about one billionth of a metre, known as a nanometre.

Did you know?

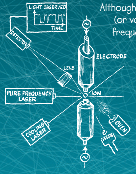


Light is one small section of the electromagnetic spectrum and appears in the form of a wave, like the ripples on a pond. This spectrum includes radio waves, microwaves, infrared light, visible light, X rays and cosmic rays, amongst others. The wavelength is defined as the distance between the peaks or troughs of the wave and is different for all the various forms of radiation. The wavelength of visible light is between 400 nanometres (blue) and 700 nanometers (red).

Wavelength standards

As interferometers measure length in terms of the wavelength of a laser, one needs to use a laser with a fixed and known wavelength. For best accuracy today, this is achieved using an iodine-stabilised helium-neon laser. When run under the recommended conditions the laser has a wavelength that is known to better than 0.000 000 000 000 000 02 metres. The laser is based on a standard red helium-neon laser often found in school science laboratories. Inside the laser, however, is a sealed tube containing a gas of iodine molecules. These molecules absorb the red light at very definite and fixed wavelengths. The laser can be automatically stabilised to one of these absorptions by monitoring the dependence of the power of the light leaving the laser as the laser wavelength is tuned past one of these absorptions. As all iodine molecules are the same the world over, an iodine-stabilised helium-neon laser built according to certain international guidelines, will have the same wavelength to within 0.000 000 000 000 000 02 metres anywhere on earth.

The future

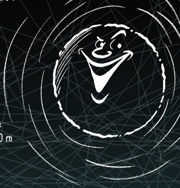


Ion trap frequency standard

Although the iodine-stabilised helium-neon laser provides a very stable optical frequency (or vacuum wavelength), it is already possible to build lasers with an optical frequency that is known around ten thousand times more accurately. The iodine-stabilised laser is limited because the iodine molecules are at room temperature and bang into each other, whizzing in and out of the laser beam. This allows them to absorb the light over a comparatively large range of frequencies. This problem can be solved by swapping the iodine molecules with atoms of a metal such as ytterbium or strontium. In one type of optical frequency standard, a single atom is given an electrical charge (making it into an ion) and then it is held in an ion trap. Once captured in the trap, it can be cooled down so that it is almost stationary. In a second type of trap, groups of atoms are cooled and trapped in a "lattice" structure. The atoms are trapped by using a high power laser beam. For both types of optical frequency standard, the cooling means that a much better frequency reference is provided since the atoms absorb over a frequency range that is only about one millionth that of iodine, giving the improved performance.

Date	Definition of the Metre	Accuracy of realization of the metre from the definition of the period
1791	Based on the quarter meridian of the earth	± 0.06 mm
1889	International Prototype Metre	± 0.002 mm
1960	First length quantum standard	± 0.000 007 mm
1983	Speed of light	± 0.000 000 7 mm
Today	Speed of light, with improved He-Ne laser accuracy	± 0.000 000 02 mm

Spectrum of Length

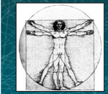


Earth/Sun mean distance
[~1.5×10^{11}m] 150 000 000 000 m

Distance to moon
[~3.8×10^{8}m] 380 000 000 m

Length of the Great Wall of China
[~2.4×10^{6}m] 2 400 000 m

Height of Everest ~8 848 m



Man ~1.8 m

Width of a human hair
[~8×10^{-5}m] 0.000 08 m

Typical size of cell
[~4×10^{-6}m]
0.000 004 m

H_2O Molecular diameter [~1×10^{-9}m]
0.000 000 001 m

Size of atom [~3×10^{-10}m]
0.000 000 000 3 m

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