Physics for K-12

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C O N N E X I O N S

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Why yet another course in physics?[1]

Answer to this question is vital to justify yet another course (book) on the subject, specially when, there exists brilliant books on the shelves, successfully meeting the requirement of schools. Understandably, each of these books / courses has been developed through a rigorous process, conforming to a very high level of standards prescribed by state education boards. Why then yet another course (book)? Matter of fact, this question had been uppermost in my mind before I undertook the commitment to take up this project. A good part of the reason lies in the basic nature of creative urge involved in writing and shaping a book. Besides, as an author, I had the strong conviction like others that a subject matter can always be treated in yet another way, which may be a shade different and may be a shade better than earlier efforts. This belief probably clinched my initiation into this project. Further :

1 : It is no wonder that books have been published regularly - many of which have contributed significantly to the understanding of the nature and natural events. Also, there is no doubt that there has been a general improvement in the breath and depth of the material and style of presentation in the new books, leading to a better appreciation among the readers about the powerful theories, propounded by great human minds of all time. However, one book differs to other in content, treatment, emphasis and presentation. This book is different on this count.

2 : Fundamental laws of physics are simple in construct. Take the example of Newton's second law : $\mathbf{F} = m\mathbf{a}$. This could not have been simpler. Yet, it takes great deal of insight and practice to get to the best of mechanics – a branch of physics, which is largely described by this simple construct. The simplicity of fundamental laws, matter of fact, is one of the greatest wonders of nature. Difficulty arises, mostly, from the complexity of the context of natural phenomena, which are generally culmination of a series of smaller events interwoven in various ways. The challenge here is to resolve complex natural phenomena into simpler components, which can then be subjected to the theories of physics. Resolution of complex natural phenomena into simpler components is an important consideration in physics. This book keeps this aspect of physics central to its treatment of the subject matter.

3 : Overwhelming and awesome reach of theories in physics, inadvertently, introduces a sense of finality and there is a tendency to take an approach towards the study of physics, which is serene and cautious – short of 'do_not_fool_around' kind of approach. This book takes calculated risk to play around with the hypotheses and theories to initiate readers to think deeper and appreciate physics with all its nuances. The book is structured and developed from the perspective of inquisitive young minds and not from the perspective of a matured mind, tending to accept theory at its face value. This shift in approach is the cornerstone of subject treatment in this book.

4 : Mathematics fine tunes physics laws and gives it a quantitative stature. Most of the extension of physical laws into the realm of application is possible with the intelligent use of mathematical tools at our disposal. Further, adaptation of physical laws in mathematical form is concise and accurate. Consider the magnetic force on a moving charge given by :

$$\mathbf{F} = q\ (\mathbf{v}X\mathbf{B})$$

The mathematical expression is complete and accurate. It tells us about both magnitude and direction of the magnetic force on the moving charge. Matter of fact, direction of force in relation to velocity of charge and magnetic field is difficult to predict without this formula. Either, we rely on additional rules like

[1] This content is available online at <http://cnx.org/content/m13249/1.13/>.

Fleming's left hand rule or interpret the vector quantities on the right hand side of the equation in accordance with rules concerning cross product of two vectors. The choice of mathematical vector interpretation is found to avoid confusion as Fleming's rule requires that we memorize direction of each of the vectors by a specific finger from the set of three fingers stretched in mutually perpendicular directions. There is great deal of uncertainty involved. You may forget to remember the correct hand (left or right), correct fingers (first, middle or thumb)and what each of them represents. On the other hand, vector interpretation has no element to memorize to predict the direction of magnetic force! Such is the power of mathematical notation of physical law.

In this sense, mathematics is a powerful tool and preferred language of expression in physics. Separate modules are devoted to describe mathematics relevant to physics in order to prime readers before these tools are used in the context of physics.

5 : The fundamental laws/ theories of physics are universal and result of great insight into the realm of physical proceedings. New constructs and principles are difficult to come by. The last defining moment in physics was development of the quantum physics by Erwin Schrodinger and Werner Heisenberg in the year 1925-26. Since then, there had been advancement in the particle physics and electronics, but no further aggregation of new theories of fundamental nature. Physics, however, has progressed a great deal in its application to other spheres of science, including engineering, medicine and information technology. This book assigns due emphasis to this aspect of applied physics.

6 : Various Boards of State Education prescribe well thought out framework and standards for development of physics text book for classroom teaching. This book emphasizes these standards and goals set up by the Boards.

What is physics?[2]

The word **physics** is derived from Greek word *fusis*, meaning nature or natural things. As such, physics is defined as that branch of science, which studies natural phenomena in terms of basic laws and physical quantities. The study is generally structured to satisfy queries, arising from the observed events occurring around our world. In this sense, Physics answers questions about universe and the way elements of universe interact to compose natural phenomena.

The underlying principles in physics are simple and general, but defining (basic) in nature. Elements and quantities used to describe natural phenomena are also general and basic. The whole of universe, as a matter of fact, can be considered to be comprising of two basic quantities : (i) matter and (ii) energy. For this reason, some physicists rightly define physics as the study of matter and energy.

Domain of physics

The domain of physics extends from the infinitesimal to the infinite and is largely undefined. At one end of the scale, there are quarks composing nucleons (neutrons and protons) and on the other end, there are galaxies, with sun-like stars as its constituents and a universe that we do not know much about.

In physics, domains are also defined in terms of various important attributes like speed, temperature and other physical quantities. In the domain defined by speed, we study both stationary objects and objects moving at very high speed, perhaps three – fourths of the speed of light. It is thanks to the extraordinary efforts of scientists in the last two centuries that we now know some of the important bounds of nature. For example, the upper limit of speed is the speed of light in a vacuum. Similarly, the lower limit of temperature is 0 K. These are some of the highlights of the development of our basic understanding of nature and its extent.

The uncertainty about the domain of physics stems from the fact that new experiments and discoveries continuously break the bounds (limits) set before. An example: for many years, the charge on the electron was considered the smallest amount of charge, but today after the discovery of quarks, we know that these carry lesser amounts of charge than that carried by electrons. Thus, the extent of physics is actually changing as we learn more and more about nature.

Generality

Theories of physics are extremely general, being the underlying governing principles of natural events extending to the whole universe. This aspect contrasts physics from other streams of science, which are often specific and sometimes localized. Generality of physics and its theories render physical laws to form the basic scientific framework upon which other branches of science are developed. Take the example of charged molecules called "ions" - a subject of investigation in Chemistry. Oppositely charged ions are glued together under the influence of an electrostatic force irrespective of the nature and type of ions and the atoms or molecules involved. The magnitude of this electrostatic force is secular in that its magnitude is determined by an inverse square law – whatever be the context and location.

[2]This content is available online at <http://cnx.org/content/m13250/1.16/>.

Simplification and unification

Simplification and unification have emerged as the basic trait of physics. There are only a few laws to define a wide variety of natural phenomena – a fact that underlines the simplification of governing laws in physics. On the other hand, unification of physical quantities and concepts is also prevalent. Take the example of matter and energy. They are now considered equivalent. The Special Theory of Relativity establishes the equivalence of these two quantities as $E = mc^2$. Further, this dual nature of matter highlights the wave (E energy) nature of particles (m mass), which underlies the concept of mass-energy equivalence. Similarly, the treatment of magnetism in terms of electrical charge is an example of unification of physical concepts.

Simplification can also be seen in the laws governing gravitation and electrostatics. Gravitational and electrical forces are conservative forces, determined by inverse square laws. The similarity of the forms of mathematical expressions is no coincidence, but a sure indication of the underlying nature of the universe, which emphasizes simplification :

$$F_G = \frac{Gm_1m_2}{4\pi r^2} \quad \text{.......... Gravitation Force}$$

$$F_E = \frac{q_1q_2}{4\pi\varepsilon_0 r^2} \quad \text{.......... Electrostatic Force}$$

Simplification and unification of physical quantities, concepts and laws are remarkable, suggesting more such cases – which are yet to be discovered. Consider the physical quantities: "mass" and "charge". There is as yet no relationship connecting these two fundamental quantities of physics. Similarly, the two major categories of forces known as nuclear and weak forces are not yet fully understood. Scientists are working to examine these unknown territories.

Scientific validation and experimental verification

The fundamental laws of physics are set against either too big or too small quantities, presenting a peculiar problem in establishing direct validation of basic theories in physics. Even today, there is not a single experimental set up which could directly verify Einstein's theory of relativity. For example, mass of an electron moving at two – third of the speed of light can not be measured directly. As we do not see the atom and its constituents, theories based on them are also not directly verifiable. We can not even verify Newton's first law of motion, which states that an object in the absence of net external force shall keep moving! We have seen all objects come to rest in the earth's frame of reference, when left unaided. This peculiarity, however, does not mean that these laws have not been validated as required for scientific studies.

It should be amply clear that scientific method for validation also includes inferences based on indirect measurements. In that sense, Einstein's special theory of relativity has been tested and verified by results obtained from the experiments involving motions of charged particles at great speed. Surprising is the exactness and accuracy of the results obtained. In the same context, accuracy of predications involving solar systems, satellites etc. have validated laws of gravitation.

Recasting and revalidating laws in the light of new revelations

Studies and experiments continue to bring new details and dimensions to our understanding of natural phenomena. New revelations recast old facts, hypotheses and theories. The relativity theory propounded by Albert Einstein, for example, revealed that Newton's laws of motions are basically a subset of more general theory. Similarly, Newton's hypothesis regarding velocity of sound was recast by Laplace, arguing that propagation of sound is adiabatic and not isothermal process as considered by Newton. His assertion was based on the experimental result and was correct. There are many such occasions when an incomplete or erroneous understanding of natural event is recast or validated when new facts are analyzed.

Domains of physical laws

There is an irresistible perception that physical phenomena are governed by a universal law - a fundamental law, which is valid at all dimensions and at all speeds. As against this historically evasive natural conjecture, our understanding and formulation are limited to domains of applicability. Newton's law works fine in our world, where dimensions are bigger than atomic size and speed is not exceeding 0.17c (speed of light, "c"). If the speed of an object exceeds this limit, the relativistic effects can not be ignored.

Consequently, we are currently left with a set of laws, which are domain specific. One law resigns in favor of other as we switch from one domain to another. The plot below approximately defines the domains of four major physical laws in terms of dimension and speed. Though, there are further subdivisions proposed, but this broader classification of applicability of natural laws is a good approximation of our current understanding about natural phenomena.

Domains of physical laws

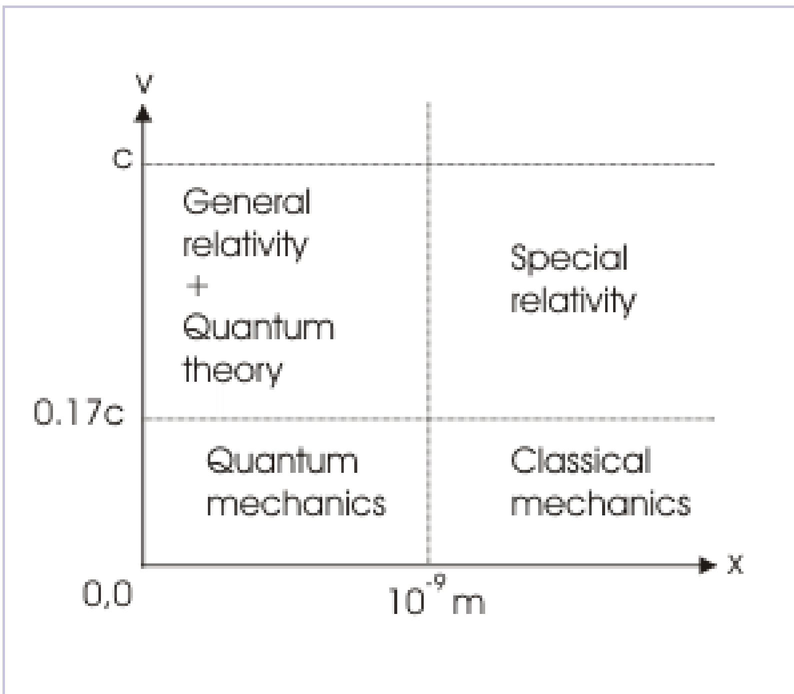

Figure 1: Approximation of domains in terms of speed and dimension.

The reduction of the special theory of relativity into classical mechanics at smaller speeds gives an indication that there may be a law which is the most general and, therefore, universal. At present, however, there is no such clear cut "deducibility" among other domain specific laws, which involves "quantum mechanics" or "general relativity". Unquestionably, unification of physical laws is the most fundamental question eluding all scientific investigation to this date.

There is a long way to go

Our knowledge about nature is improving progressively with every passing day. Yet our so called understanding at any point of time is subject to new revelation and meaning. Most of the time, we come to realize that our understanding is mostly limited to our surrounding and the context of application. It may sound bizarre but it is a fact that we have yet not fully understood even the basic concepts like distance, mass and time. Theory of relativity attached new meaning to these terms. It may not be totally brazen to think that even relativistic improvisations be ultimately incomplete and inaccurate. Who knows ?

Chapter 1

Measurements

1.1 Units of measurement[1]

The study of science, including physics, is quantitative in nature. We study natural phenomena and events in terms of quantities, which can be measured. A measurement is basically observations to estimate a physical quantity. Its basic objective is to reduce uncertainty and to give definitive stature to the quantities being described.

The measurement of quantity is done by comparing it with some standard called "unit". A unit, therefore, is any division of quantity, which is accepted as one unit of that quantity. A quantity (Q) is expressed as the product of a number (number of times in comparison to the standard) and the name given to the unit or standard.

$$Q = nX\text{name of unit}$$

$$Q = nu$$

We can have a look at some of the physical quantities that we use in our everyday life: 5 kg of sugar, 110 Volt of electric potential, 35 Horse Power of an engine and so on. The pattern of all these quantitative expression follows the same construct as defined above.

1.1.1 System of units

Our earlier units have been human based (in the context of what we use in our daily life) and, therefore, varied from country to country and even from society to society. We had measure of length (foot) in terms of the length of a foot step as unit.

Relating units to immediate physical world is not wrong; rather it is desirable. What is wrong is that there are many units for the same quantity with no relative merit over each other. We are led to a situation, where we have different units for the same quantity, based on experiences in different parts of the world. These different units of the same quantity do not bear any logical relation amongst themselves. We, therefore, need to have uniform unit system across the world.

Further, it is seen that there are scores of physical quantities. If we assemble all quantities, which are referred in the study of physics, then the list will have more than 100 entries. Fortunately, however, most physical quantities are "dependent" quantities, which can be expressed as combination of other quantities. This fact leads us to classify quantities in two groups :

1. Basic or fundamental quantities

[1] This content is available online at <http://cnx.org/content/m15034/1.3/>.

2. Derived quantities

Basic or fundamental units are a set of units for physical quantities from which other units can be derived. This classification i.e. existence of basic quantities has a great simplifying effect. We are limited to study few of basic units; others (derived) are derived from them.

Here, we should also strike difference between "basic" quantity of a system of measurement to that of quantity of basic nature. The presence of length, mass and time in the basic category may give impression that all members are basic in nature. Neither it is required nor it is so. We can have a system of measurement with quantities, which are not basic in nature.

In modern SI unit system, for example, the electric current is included in the list of "basic" quantities. We, though, know that it is equal to time rate of charge. A quantity of basic nature in the universe is not derivable from other quantities, but current is. As such, current is not basic in nature. We could have included "charge" as the basic quantity instead. But, then there are other requirements of a basic unit like reproducibility and ease of measurement etc, which need to be taken into consideration.

As pointed out earlier, the basic units should be correlated to our immediate context. For example, a meter represents a length that we are able to correlate and visualize with the physical entities in our world. For example, we say that height of the room is 2.1 m – not something like $2.1X10^{-11}$ m.

Nature presents a kind of continuum, which ranges from very small to very large. Consider the dimensions of a nucleus ($\sim 10^{-15}$ m) and distance of the sun ($\sim 10^{11}$ m). The system of units, therefore, needs to have a scheme to express wide variations often seen in physical quantities.

Finally, the advancement in scientific studies has expanded scope of studies much beyond human physical existence. We study atoms at one hand and galaxies on the other. The quantities involved are ether so small or so big that the physical comparison with a real time measuring device may not be possible. For example, we can not think of going inside an atom and measure its radius with a scale. Inferred (indirect) measurements are, therefore, allowed and accepted in such situations.

1.1.1.1 Features of fundamental units

Following are the features/ characteristics of fundamental units :

- They are not deducible from each other.
- They are invariant in time and place (in classical context).
- They can be accurately reproduced.
- They describe human physical world.

1.1.2 International system of units

Its short name is SI system, which is an abbreviated form of French equivalent "Systeme Internationale d' units". As study of science became more and more definitive and universal, it was felt to have a system of units, which can be refereed internationally. The rationales for adopting SI system as international system are two fold. First, this system is based on the powers of 10. Second, there is a well structured prefixes to represent range of measurements associated with a physical quantity.

The "power of 10" makes it easy to change smaller to bigger unit and vice versa. A mere shift of "decimal" does the job.

12.0 mm (smaller) = 1.20 cm (bigger)

Equivalently, we multiply the given quantity with 10 raised to positive integer to obtain the measurement in terms of smaller unit; and divide it with 10 raised to positive integer to obtain the measurement in terms of bigger quantity.

Finally, SI system has a set of prefixes for a given unit to represent smaller or bigger quantities. This set of "prefixed" represents a predefined factor in terms of the power of 10. We should remind ourselves that all of these prefixes are applicable uniformly to all quantities.

Prefix factors

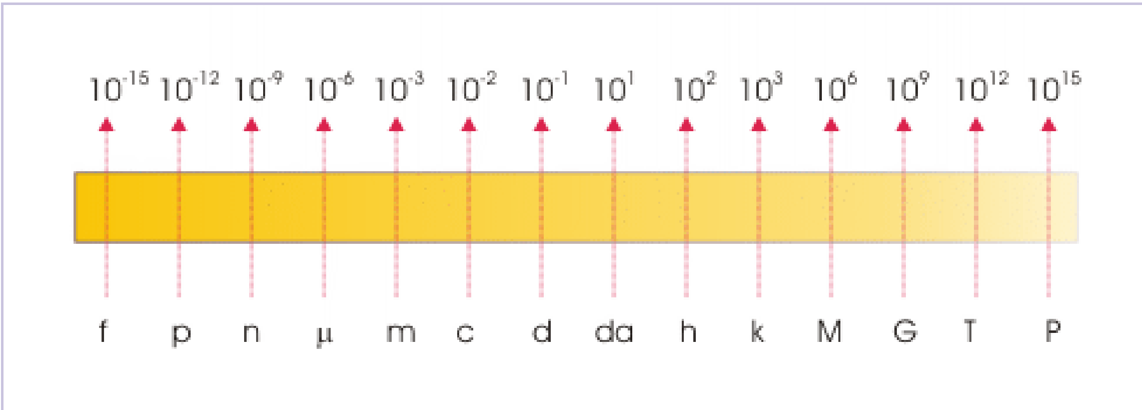

Figure 1.1: The factors are powers of 10.

Femto(10^{-15}), pico(10^{-12}), nano(10^{-9}), micro(10^{-6}), milli(10^{-3}), centi(10^{-2}), deci (10^{-1}), deka (10^{1}), hector(10^{2}), kilo(10^{3}), mega(10^{6}), giga(10^{9}),tera(10^{12}),peta(10^{15})

Note that except for few prefixes in the middle, the powers of the factor differs by "3" or "-3".

1.1.2.1 Basic units

The seven basic quantities included in SI system of measurement are :

1. Length
2. Mass
3. Time
4. Current
5. Temperature
6. Amount of substance (mole)
7. Luminous intensity

The corresponding seven basic units with their symbols are defined here (as officially defined):

1: meter (m) : It is the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 of a second.

2: kilogram (kg) : It is equal to the mass of the international prototype of the kilogram. The prototype is a platinum-iridium cylinder kept at International Bureau of Weights and Measures, at Severes, near Paris, France.

3: time (t) : It is the duration of 9, 192, 631, 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium - 133 atom.

4: ampere (A) : It is is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 m apart in vacuum, would produce between these conductors a force equal to $2X10^{-7}$ newton per meter of length.

5: kelvin (K) : It is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water.

6: mole (mol) : It is the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon 12.

7: candela (cd) : It is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency $540X10^{12}$ hertz and that has a radiant intensity in that direction of $1/683$ watt per steradian (measure of solid angle).

1.1.2.2 MKS system of units

MKS is an abbreviation of **M**eter, **K**ilogram and **S**econd. These three quantities form the basic set of units in MKS system. Clearly, it is a subset of SI system of units. As we can realize, mechanics - a branch of physics - involves only length, mass and time. Therefore, MKS system is adequate to represent quantities used in mechanics.

This distinction between mechanics and rest of physics is hardly made in recent time. We can, therefore, completely do away with MKS nomenclature in favor of SI system.

1.1.3 Conversion of units

Despite endeavor on world level for adoption of SI unit, there are, as a matter of fact, wide spread variation in the selection of unit system. Engineering world is full of inconsistencies with respect to the use of unit system. We often need to have skill to convert one unit into another. We take a simple example here to illustrate how it is done for the case of basic quantity like mass.

Let us consider a mass of 10 kg, which is required to be converted into gram - the mass unit in cgs unit (Gaussian system). Let the measurements in two systems are " $n_1 u_1$ " and " $n_2 u_2$ " respectively. But, the quantity, "Q", is "10 kg" and is same irrespective of the system of units employed. As such,

$$Q = n_1 u_1 = n_2 u_2$$

$$\Rightarrow n_2 = \left(\frac{u_1}{u_2}\right) n_1$$

$$\Rightarrow n_2 = \left(\frac{1\text{ kg}}{1\text{ gm}}\right) n_1$$

$$\Rightarrow n_2 = \left(\frac{10^3\text{ gm}}{1\text{ gm}}\right) 10$$

$$n_2 = 10^4$$

$$Q = n_2 u_2 = 10^4\text{ gm}$$

The process of conversion with respect to basic quantities is straight forward. The conversion of derived quantities, however, would involve dimensions of the derived quantities. We shall discuss conversion of derived quantities in a separate module.

1.2 Dimensional analysis[2]

We are familiar with dimensions of motion and motion related quantities. Often, we specify the description of physical process by numbers of coordinates involved – one, two or three. It indicates the context of motion in space. The dimension of physical quantities follows the same philosophy and indicates the nature of the constitution of quantities. In other words, dimension of a physical quantity indicates how it relates to one of the seven basic/ fundamental quantities. Basic quantities are the seven dimensions of the physical quantities.

[2]This content is available online at <http://cnx.org/content/m15037/1.8/>.

Dimensions of a physical quantity are the powers with which basic quantities are raised to represent it. The dimension of a physical quantity in an individual basic quantity is the power with which that basic quantity is raised in the dimensional representation of physical quantity. We should be clear here that the dimension is not merely a power, but a combination of basic quantity and its power. Both are taken together and hence represented together. We may keep in mind that units follow dimensional constitution. Speed, for example, has dimension of 1 in length and dimension of -1 in time and hence its unit is m/s.

A pair of square bracket is used to represent the dimension of individual basic quantity with its symbol enclosed within the bracket. There is a convention in using symbol of basic quantities. The dimensions of seven basic quantities are represented as :

1. Mass : [M]
2. Length : [L]
3. Time : [T]
4. Current : [A]
5. Temperature : [K]
6. Amount of substance : [mol]
7. Luminous Intensity : [cd]

We can see here that there is no pattern. Sometimes we use initial letter of the basic physical quantity like "M", sometimes we use initial letter of basic unit like "A" and we even use abbreviated name of the basic unit like "mol".

1.2.1 Dimensions of derived quantities

The dimensions of derived quantities may include few or all dimensions in individual basic quantities. In order to understand the technique to write dimensions of a derived quantity, we consider the case of force. The force is defined as :

$$F = ma$$

Thus, dimensions of force is :

$$\Rightarrow [F] = [M]\,[a]$$

The dimension of acceleration, represented as [a], is itself a derived quantity being the ratio of velocity and time. In turn, velocity is also a derived quantity, being ratio of length and time.

$$\Rightarrow [F] = [M]\,[a] = [M]\left[vT^{-1}\right] = [M]\left[LT^{-1}T^{-1}\right] = \left[MLT^{-2}\right]$$

We read the dimension of force as : it has “1” dimension in mass, “1” dimension in length and “-2” dimension in time. This reading emphasizes the fact that the dimension is not merely a power, but a combination of basic quantity and its power.

1.2.2 Dimensional formula

The expression of dimensional representation is also called “dimensional formula” of the given physical quantity. For brevity, we do not include basic dimensions, which are not part of derived quantity, in the dimensional formula.

$$\text{Force}, [F] = \left[MLT^{-2}\right]$$

$$\text{Velocity}, [v] = \left[LT^{-1}\right]$$