Chapter 15

Newton's First Law of Motion

15-1 Prelude

1. From Kinematics:
   (i) To start from rest and acquire a velocity v_f or simply v, we need acceleration a.
   Unless otherwise stated, acceleration a will always be uniform or constant.
   (ii) To start from one velocity, say v_o to another velocity, say v, (where v_o can be smaller or larger than v), we need acceleration a.
   (iii) While travelling at some velocity v, to come to a complete stop, we need acceleration a.

15-2 Newton's Laws

Newton's extensive theoretical and empirical work, associated with massive ingenuity led him to develop three laws, known as the Laws of Motion. These were published in the year 1687 and have, since, stood the test of time, in the face of astronomical advances in science and technology and the way we chase scientific advancements. There have been, no doubt, advances in our understanding of nature (relativity, quantum mechanics and the like) but for our everyday life on the earth including (but not limited to) travelling to the moon and beyond, we use Newtonian Mechanics only (surprised?). Some topics (from our everyday life) that may use these new (modern) developments in physics, are beyond the scope of this textbook.

We begin by enunciating Newton's first law, followed by the concepts, that the law presents to us.

15-3 Newton's First Law of Motion: The Enunciation and the Concepts.

The Enunciation

Every object in the universe tends to continue to stay in its state of rest or (state of) uniform motion in a straight line, unless it is compelled to change that state by the application of a net force, F_{net}.

(that was easy!)

15-4 The Concepts

The law introduces four fundamental concepts that are the building blocks of dynamics. These are: (i) equilibrium, (ii) inertia, (iii) momentum, and (iv) net force.

(a) Equilibrium

Equilibrium spells the state of being neutral to activities of all kinds, to be doing exactly nothing (to be a couch potato, perhaps); to be staying put and being immune to unforced changes. First law states that both, the state of rest and the state of uniform motion in a straight line, qualify to be recognized as *equilibrium* states. The *state of rest* portrays all of the above characteristics. It can, therefore, be safely agreed that the *state-of-rest* is in fact a **state of equilibrium**. This is quite acceptable to all and sundry and no one ever raises an eyebrow.

The same is not so obvious for the uniform motion, in a straight line. If the *state of uniform motion in a straight line* were to be a *state of equilibrium*, then an object once set in uniform motion in a straight line (on a flat surface), should continue to move for ever and ever. This does not happen. It is a common observation that an objects set in uniform motion, slows down and eventually comes to a complete stop. Newton stated that the only reason it stopped was the presence of friction or other similar factors. If these were eliminated, objects once set in motion, on flat surfaces, will continue to move indefinitely in a straight line, with uniform speeds.

Consider, for example, a puck. If we kick a puck on a flat floor, it will slide to some distance and then stop. If we put oil on the floor thereby reducing friction, and kick the puck in exactly the same manner as before (i.e. imparting it the same uniform motion, as before), the puck will slide for a much larger distance. It will probably slide an even larger distance on ice. Thus as friction gets less and less, the puck covers larger and larger distances. In the limit, if friction were to become zero, the puck will keep sliding forever.

I guess you still do not believe me.

Having succumbed to logic-based pressures, we surrender and recognize both: (i) *state of rest*, and (ii) *state of uniform motion in a straight line,* as *states of equilibrium* and do hereby confer upon them all the privileges and responsibilities of the *state of equilibrium*, as described below:

(1) The object is either not moving at all or is moving by traversing equal lengths in equal intervals of time, in a straight line. The x-axis (or the y-axis or the z-axis) of the observer's reference frame may be aligned with this straight line.

(2) Forces neutralize one another, in each of the three modes, considered individually. There is as much effort to pull the object (say) to the right as there is to pull it to the left; etc. (Think of a scoreless game of tug-of-war.).

15-5 ***(b) Inertia***

Concept of *inertia* stems from the words ***tends to continue to stay in its state of rest,*** of the law. We find that there is an inherent tendency on the part of the object to resist a change from its *state of rest*. This *tendency* is not merely a wishful thinking on the part of the object (*oh, how I wish I could stay in this state!*), it is a real thing. These words **imply** that the object not only has the ability (to resist a change of state), but it also has the capability to exercise this ability fully.

The above mentioned ability and capability has been given the name *inertia.* Thus Newton's first law of motion recognizes *inertia* as a basic characteristic of all material things in our universe.

Inertia of an object is intimately related to its mass. It is a common experience that an object of larger mass is more stubborn and offers greater resistance to attempts of dislodging it or disturbing it from its state of rest. To demonstrate the above, let us take a tennis ball and a bowling ball and place both of them *at rest* on a table. We then make an effort to move them from rest (one at a time) by using our little finger. We shall be able to move the tennis ball rather easily but we will not be able to say the same for the bowling ball. We will probably think twice before pushing a bowling ball with our delicate little finger. The rather large difference in the magnitude of effort necessary to mobilize the respective balls from rest, will help you understand inertia and its dependence on mass.

Mass of a material object is normally defined as the *quantity of matter* that is present in that material object. Newton's first law links this *quantity of matter* to a more basic aspect of materialism: ***inertia.*** In the light of such compelling evidence, we now interpret *quantity of matter* as *inertia* of a material object.

The definition of mass in terms of inertia is an example of scientific ingenuity. We discovered a certain property of mass: *resisting a change of state.* From this property, we evolved a new term: *inertia*. We shall improve upon this term by calling it *linear inertia*. This is because Newton's first law *only* acknowledges linear motion; i.e. motion in a straight line. It does not recognize motion along a non-linear or curved path.

Linear Inertia is synonymous with *mass* and also with *quantity of matter.* The M.K.S. unit is kg. We represent mass in an equation by the letter m or M.

15-6 (c) Momentum

Having recognized inertia as the embodiment of tendency to *continue to stay in its state of rest*, we ask an intelligent question. What about the tendency of the object to continue to stay in its *state of uniform motion* (in a straight line, of course)? Will the object exhibit the *same* tendency for the state of uniform motion, as it does for the state of rest?

The answer is an unequivocal *No*!

We find that the ability of the material object to resist a change, is *greater* when in motion than when at rest. In fact the *resistibility* increases with speed. The larger the speed, the larger is the object's resistibility. Consider a bowling ball that rolls slowly on the floor. You may stop it by placing your hand in front of the ball. If the ball is moving faster, you would need to make a larger effort to stop it. If this bowling ball is on its way to demolish the pins, in a bowling alley, you will not dare to place your hand in front of it.

We find that the *resistibility* is linked to the speed of the object. The functionality of what we call *inertia* is now changing. Newton interpreted this attribute of inertia as the *Quality of Inertia*.

Defining Momentum

From the above discussion, we conclude that *Quality of Inertia* is directly proportional to velocity. In order to give proper recognition to this aspect of inertia, we need to assign a specific name to it. This name is *momentum*. We define *momentum* as the product of linear inertia (mass m in kg) and linear velocity $\boldsymbol{v}$ in m/s. Writing $\boldsymbol{p}$ for momentum:

$$\boldsymbol{p} = m\boldsymbol{v} \qquad \text{..........(1)}$$

Because $\boldsymbol{v}$ is a vector, $\boldsymbol{p}$ is also a vector entity. The unit of momentum is $kg.m/s$.

The word momentum is not new for us. We often use it for many non-scientific situations as well. Consider, for example, a movement (such as *Tea Party*). As the movement spreads, we say that it is gaining momentum. We shall leave you to see the similarities in the two cases.

Another possible name could have been *dynamic inertia.* Objects at rest have *static inertia* and those in motion have *dynamic inertia.*

15-7 (d) Net Force $\boldsymbol{F}_{net}$

The fourth and the last concept that the first law provides us with, is the concept of *net force*. Please note that the first law recognizes three types of changes of state:

(i) from state of rest to state of uniform motion

(ii) from one state of uniform motion to another state of uniform motion

(iii) from state of uniform motion to state of rest

The law then tells us that all of the above listed changes of state, can only be effected by the application of a *net force*. The law reads "..........*unless compelled to change that state by the application of a* ***net force,*** $\boldsymbol{F}_{net}$".

15-8 But: What is "Force" $\boldsymbol{F}$?

We feel that we do not owe it to you to explain what a force is, or to define it for you. It is too obvious and too familiar an entity and is used millions of times everyday. Every action begins with the application of a force. We apply a force to move our eyebrows or lift a finger, to walk, to sit down or stand up, etc. Every little (or big) thing we do, or is done for us, requires the application of a force. A table-top exerts a force to support a book or a hair-pin. A thread of a spider's web, or a chain exerts a force to support the spider (or its prey) or a chandelier. We also exert a force to send a satellite into orbit and to keep the moon circling around the earth.

What is "Net Force" $\boldsymbol{F}_{net}$?

A force is a vector entity. If a number of forces act on an object all at the same time, we must combine them vectorially to get the resultant force. This resultant force is the *net force* $\boldsymbol{F}_{net}$. Net force, in this case, is a totally different force and not any of the original forces. If, however, only one force is acting on the object then this single force, in itself, will be the $\boldsymbol{F}_{net}$.

15-9 Net Force & Acceleration

Please note that the kinds of change of state, described in Section 15-1 (prelude) and those described above (Section 15-7) are identical. This is *very* interesting. Kinematics tells us that for *all* kinds of changes of state ***acceleration*** must be present. The first law, on the other hand, tells us that for *exactly the same set of changes of state*, ***net force*** must be present. We conclude:

Acceleration $\boldsymbol{a}$ *and Net Force* $\boldsymbol{F}_{net}$ *are intimately related to one another.*

15-10 Second Thoughts.....
Velocity or Momentum?

In an equilibrium state, velocity is uniform. As the momentum is *mass x velocity* and mass never changes for a given object, so if velocity is uniform, the momentum must also be uniform. Can we, therefore, replace *uniform velocity* by *uniform momentum*? The answer is ***yes***! There is no reason why not. It is our prerogative to use either one. The units will of course be different: *m/s* for velocity and *kgm/s* for momentum. That should pose no problem. However, as the term *momentum* hadn't been invented when the first law was enunciated, we will not make any modification in the wordings of the first law.

15-11 The Old Activity Diagram

We reproduce here the activity diagram used in Chapter 5, to define acceleration:

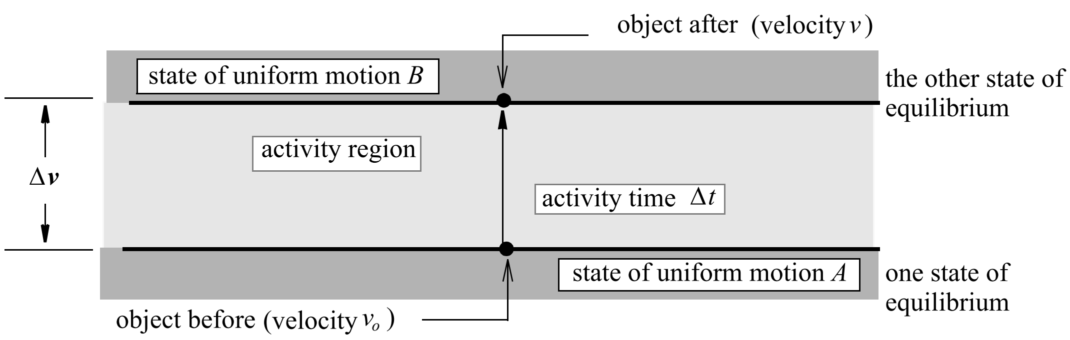

Fig (1) The Old Activity Diagram

15-12 The New Activity Diagram

The *second thoughts* of Section 15-10, encourage us to be adventurous and replace *velocity* by *momentum*, thereby producing a modified activity diagram. This is shown below. To keep up with the discussions of Chapter 14, we are including the *activity distance* also in this diagram.

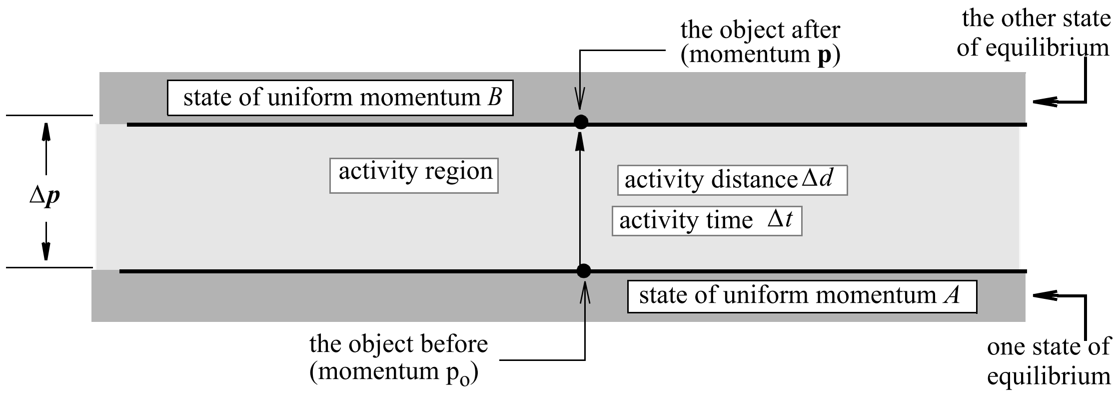

Fig (2) The New Activity Diagram

The target object experiences a change of momentum of magnitude $\Delta \boldsymbol{p}$, as it moves from one equilibrium state to another. According to the first law, the agency that transports the target object from state of equilibrium of uniform momentum p_o to the state of equilibrium of uniform momentum p is net force $\boldsymbol{F}_{net}$. Incorporating the agency into our activity diagram, we get:

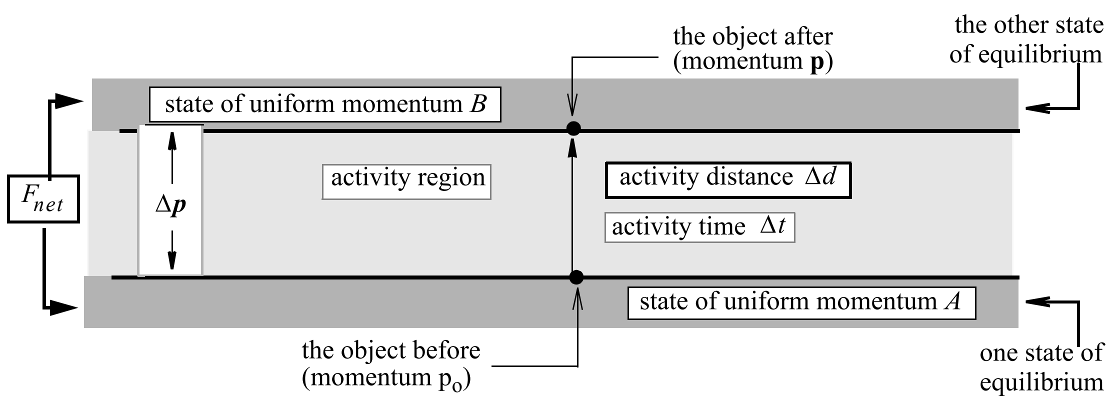

Fig (3) he Comprehensive Activity Diagram

Finally, we shall separate out the two modes of crossing the activity region for further study of each one of the two possibilities.

(a) Time Dependent Mode

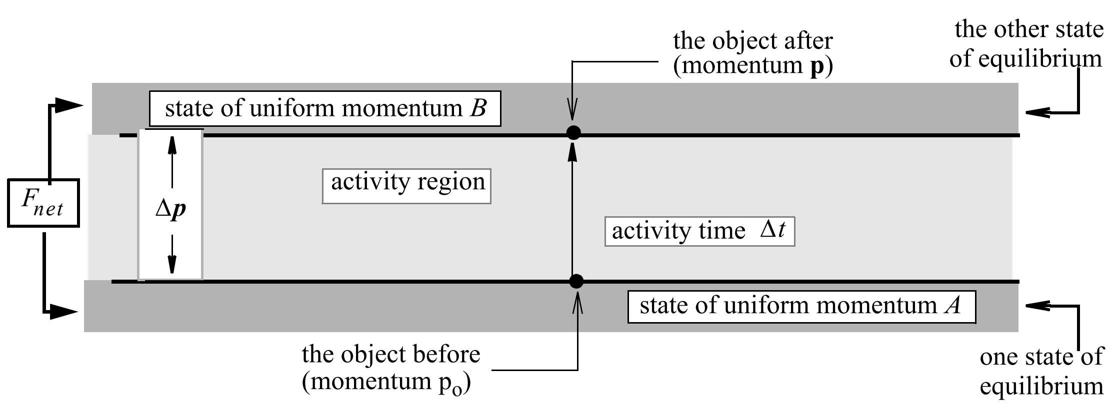

Fig (4) Monitoring Time of Travel

(b) Time Independent Mode

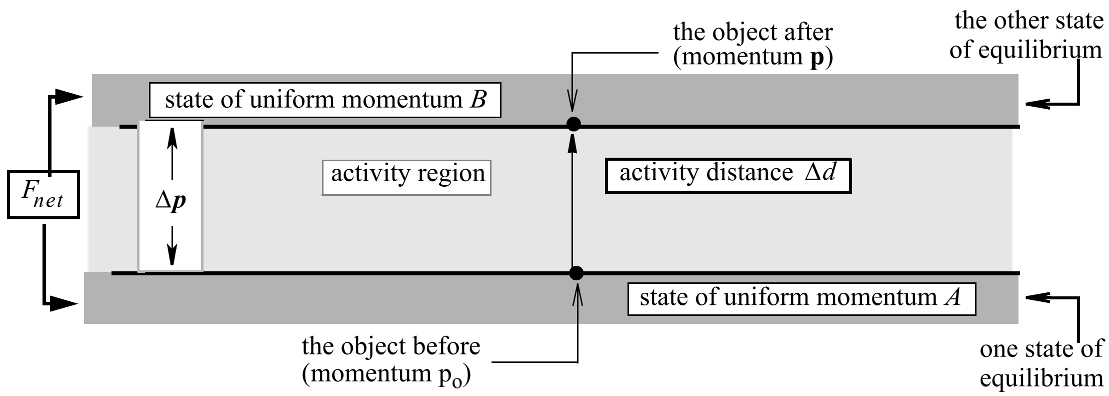

Fig (5) Monitoring Distance of Travel

15-13 Net Force and Momentum

Without much ado, we rewrite the conclusion from section 15-9 as:

Momentum p and Net Force F_{net} are intimately related to one another.

15-14 What Intimate Relationship?

The details of this relationship are specified in Newton's Second Law of Motion