LECTURE 10: Newton's laws of motion

Select LEARNING OBJECTIVES:

i. Understand that an object can only change its speed or direction if there is a net external force.
ii. Understand that the first law describes an equilibrium condition.
iii. Understand that departures from the first law's equilibrium condition leads to the arrival of the second law which attempts to explain the cause of this departure.
iv. Understand that being at rest and moving with a constant velocity are equivalent.
v. Understand that forces are used to describe the interaction between two objects.
vi. Understand that forces are used to describe the cause of the departure from the first law's equilibrium condition.
vii. Understand that force pairs are equal in magnitude, no matter how large the mass difference is between the two interacting objects.
viii. Understand that the third law is an empirical law, along with the second law, which further illustrates that a force is the description of an interaction between two objects.

TEXTBOOK CHAPTERS:

- Giancoli (Physics Principles with Applications 7th) :: 4-1, 4-2, 4-3, 4-4, 4-5
- Knight (College Physics : A strategic approach 3rd) :: 4.1, 4.4, 4.5, 4.7
- BoxSand :: Forces (Newton's First Law, Newton's Second Law, Newton's Third Law)

WARM UP: What is a force?

Classical mechanics stems from three astonishing laws of motion as realized by Isaac Newton in 1687, and published in Philosophiæ Naturalis Principia Mathematica. Before continuing on to restate these laws, I think it is a good idea to ask the question, why are Newton's laws are called laws? Simply put, empirical observations lead to three separate and distinct phenomena, which over the centuries have never been seen to deviate from their original predictions within the realm of classical mechanics.

1st law:

An object moving with a constant velocity will continue to movie with the same speed and in the same direction unless the interaction(s) with another object(s) produces a net external force.

We define force in the 2nd law section

If we find ourselves in some location where the 1st law is valid, then we say that we are in an inertial reference frame. Thus an inertial reference frame is one in which Newton's 1st law is valid. How do we know if the 1st law is valid in this location that we are at? We do experiments. Galileo Galilei performed some of the first experiments which confirmed his theories about the natural tendencies of objects. Galileo proposed dropping objects from the top of a mast on a sailboat while the boat was moving at a constant velocity in smooth waters. He noticed that the object landed at the bottom of the mast, not behind it as the previous consensus at the time would predict. Presumably nothing was acting on the object in the horizontal direction after it was released from the top of the mast, yet it still continued forward with the same velocity of the ship, resulting in the observed location of the object at the bottom of the mast, directly below where it was released from. You can perform similar experiments to determine if you are residing in an inertial reference frame.

We will typically place coordinate systems on Earth, which is not necessarily an inertial reference frame due to its rotational motion. However, we will see in later chapters that considering Earth as an inertial reference frame is a very good approximation for most scenarios that we will encounter in our studies in this course.

So what does the 1st law really mean, and why is it the 1st law not the 2nd or 3rd? Well, the first law sets the stage, so to speak. It describes a state of equilibrium (i.e. rest or constant velocity) for which objects seem to obey. Once we have established an inertial reference frame (i.e. confirmed we are in a location that the 1st law seems to hold true), if we notice any departure from this state of equilibrium, then we must seek to explain these new observations; herein enter the 2nd law.

2nd law

Newton's 2nd law of motion is a recapitulation of Newton's interpretation for what causes a departure from equilibrium which is defined by the 1st law. Newton used the idea of a force, as a physical quantity which is responsible for the departure from equilibrium. The 2nd law can be thought of as a cause-effect linear response function, in which a force (an interaction between objects) causes an effect, an acceleration that is scaled by a the mass of the object of interest. The 2nd law of motion is summarized below:

The vector summation of all the external forces acting on a system is equal to the mass of the system times the acceleration of the center of mass of the system.

Mathematically, this is written as:

$$\sum \vec{\mathrm{F}}_{\mathrm{ext}} = m_{sys}\, \vec{a}_{com}$$

Algebraically rearrange the above equation and notice that the acceleration of the object is inversely proportional to the mass of the object; for a given/fixed net force, if the mass is large then the resulting acceleration is smaller compared to if the mass was smaller. Thus, we often view mass as a measure of inertia, the tendency of an object to resist an acceleration (i.e. a change in velocity).

Like the 1st law, (and really any law for that matter), the 2nd law is based off of empirical observations.

It is important to note, and often overlooked, that the second law applies to systems which reside in an inertial reference frame. That is to say, you must have invoked the 1st before you can apply the 2nd law. Again, this drives home the idea that the naming of the 1st and 2nd law was not arbitrary, the former actually must be valid first, before the latter is applied.

Just like kinematics, we will still work under the point particle approximation until otherwise noted. Thus we do not need to worry about the center of mass just yet. In the following lectures, we will explore applications of Newton's 2nd law by analyzing various systems.

Forces as interactions

Through our everyday experiences, we might be able to draw the conclusion that "objects seem to interact with other objects". For example, when you hold an apple in your hand, the apple does not pass through your palm, rather it rests in your hand. You also notice a sensation in your palm, that is your sense of touch letting you know that an apple is in your hand. Both these observations indicate that your hand and the apple are interacting with each other in some manner. It is this interaction that is the cause of departures from the 1st law's definition of equilibrium. ***A force is a mathematical construct that is used to described an interaction between two objects***.

Forces are vectors! If an object (e.g. a book resting on a table) is interacting with multiple objects, we can define a "net force" to represent the multiple interactions that the object is experiencing. The net force is just a vector summation of all the forces acting on the object (i.e. we are accounting for all the interactions the object is experiencing). But remember, when you add forces together you must follow vector addition rules as outlined in lecture 02.

We will use the following notation when working with forces:

$$\vec{F}^{\text{type}}_{\text{agent on object}}$$

An example is the following:

$$\vec{F}^{g}_{E1}$$

Which is read as, "the force of gravity from the earth acting on object 1".

3rd law

Newton's 2nd law introduced us to the idea of using forces to describe the interaction between two objects. As it turns out, the magnitude of the force that describes this interaction between two objects is the same for both objects. This is summarized by the following statement:

Every action has an equal and opposite reaction.

Which can be mathematically written as:

$$\left|\vec{F}_{12}\right| = \left|\vec{F}_{21}\right|$$

We call these two forces, "force pairs".

Thorough careful experiments and observations, Newton deduced that whenever one object exerts a force on a second object, the second object simultaneously exerts a force equal in magnitude and opposite in direction on the first object. When combined with the 2nd law, we will have amazing predictive capabilities when attempting to describe the motion of objects.

Comments on Newton's laws of motion

It is important to note that all three of Newton's laws of motion are separate laws, formed from empirical observations, they were not derived from anything else. Also, no one law of motion can be derived from another. However, all three laws are consistent with each other, for example: Looking at the 2nd law, if the net force acting on an object is zero, then the acceleration of the center of mass of that object is also zero, which means that the velocity of the object is constant; the object is at rest or constant velocity which is our 1st law. This should not surprise you, since the 2nd law is valid only after we have already established that the 1st law holds true in the reference frame we are working in. So the 1st law was not derived from the 2nd in this scenario, it was only shown to be consistent with what we already knew. Be wary, often times you will see other sources "derive" one law from the other, but really what is being done in those sources is just showing that all the laws are all consistent with one another. Simply put, if you could derive one law from the other, then why have more than one?

Summary

Newton's 1st law of motion is a definition for what equilibrium is.

Newton's 2nd law describes the cause-effect mathematical relationship, identifying forces as the cause and acceleration as the effect.

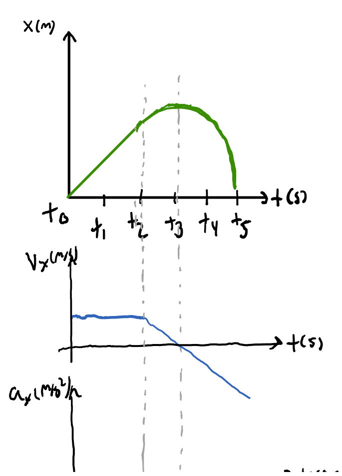
Newton's 3rd law proposes that two objects interacting with one another do so in a symmetric way, (i.e. the magnitude of force from object 1 on object 2 is the same as the magnitude of force from object 2 on object 1).

PRACTICE: A force is...

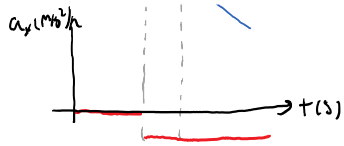
(1) equal to mass times acceleration.
(2) an interaction between two objects.
(3) dependent on the mass of the object.
(4) dependent on the acceleration of the object.
(5) dependent on the velocity of the object.
(6) only involving one object.
(7) always making objects accelerate.

PRACTICE: The figure below shows a graph of position vs time for an object moving along a straight line. During which time intervals is the net force on the particle zero?

$\Sigma \vec{F} = \vec{0} \Rightarrow \vec{a} = \vec{0}$



So $\Sigma \vec{F} = \vec{0}$ between $t_0 \rightarrow t_2$



So $\Sigma\vec{F}=\vec{0}$ between $t_0 \rightarrow t_2$

Conceptual questions for discussion

1) You are riding in a car. The driver suddenly applies the brakes and you are pushed forward. What pushed you forward?
2) The acceleration of a particle is zero as measured from an inertial frame of reference. Can we conclude that no force acts on the particle?