5.1: Newton's Three Laws

Newton's classical theory of physics is based on the three following laws:

- **Law 1**: An object will remain in its state of motion, be it at rest or moving with constant velocity, unless a net external force is exerted on the object.
- **Law 2**: An object's acceleration is proportional to the net force exerted **on the object**, inversely proportional to the mass of the object, and in the same direction as the net force exerted on the object.
- **Law 3**: If one object exerts a force on another object, the second object exerts a force on the first object that is equal in magnitude and opposite in direction.

The three statements above are sufficient to describe almost all of the natural phenomena that we experience in our lives. Concepts such as energy, center of mass, torque, etc, which you may have already encountered, are derived naturally from these three laws. In order to build models to describe specific experiments or observations using Newton's Laws, one needs to understand the two main mathematical concepts that are introduced by the theory: force and mass. A few comments on each of the three laws are first provided before the concepts of force and mass are developed further.

Newton's First Law

Newton's First Law is often referred to as the law of inertia which was originally stated by Galileo. The first law is counter-intuitive, as our experience is that if you push a block on a table and let it go, it will eventually stop. Indeed, Aristotle proposed that the natural state of objects is to be at rest. As a result of Newton's theory, we now understand that if you model a block sliding on a table, one must include a force of friction between the table and the block that acts to slow it down; a sliding block is thus not in a situation where no net external force is exerted on the object.

Newton's First Law is useful in defining what we call an "inertial frame of reference", which is a frame of reference in which Newton's First Law holds true. A frame of reference can be thought of as a coordinate system which can be moving. For example, if a train is moving with constant velocity, we can consider the train as an inertial frame of reference since objects in the train would follow Newton's First Law for observers that are in the train. If a train passenger placed an object on a table, they would observe that the object does not spontaneously start moving; if they slide an object on a frictionless table, they would observe that it keeps on sliding at constant velocity.

However, if the train is accelerating forwards, then an object placed on a frictionless table would appear, for observers in the train's frame of reference, to be accelerating in the direction opposite to that of the train, and violate Newton's First Law. An accelerating train is thus not an inertial frame of reference. To an observer on the ground, looking into the accelerating train through a window, the object placed on the table would appear to move with the same constant velocity as when it was placed on the table (the velocity of the train at the instant the object is placed on the table). In a similar way, when you are in a car, Newton's First Law holds if the car is going at constant velocity, but if the car goes around a curve (and thus accelerates even its speed is constant), you will find that all objects in the car suddenly appear to be pushed towards the outside of the curve, in conflict with Newton's First Law; this is because the accelerating car is not an inertial frame of reference and Newton's First Law is thus not expected to hold.

Newton's First Law thus allows us to define an inertial frame of reference; Newton's Three Laws only hold in inertial frames of reference.

Exercise $5.1.1$

You are in an elevator accelerating upwards.

A. The elevator is an inertial frame of reference.
B. The elevator is not an inertial frame of reference.

Answer

B.

Newton's Second Law

Newton's Second Law is often written as a vector equation:

$$\sum \vec{F} = m\vec{a}$$

where $\sum \vec{F}$ is the vector sum of the forces exerted on an object, $\vec{a}$ is the acceleration vector of the object, and m is the "inertial mass" of the object. As we will see, a force is represented by a vector, and the sum of the force vectors on an object is often called the "net force". Recall that using vectors to write an equation is just a shorthand for writing the equation out for each component. In three dimensions, this would thus correspond to three independent scalar equations (one for each component of the force and acceleration vectors):

$$\sum F_x = ma_x$$
$$\sum F_y = ma_y$$
$$\sum F_z = ma_z$$

Newton's Second Law is the foundation for Classical Physics, in which we seek to quantitatively describe the motion of any object. The motion of an object is fully specified by its acceleration as long as we know the position and velocity at a specific point in time. That is, by knowing the position and velocity of the object at a point in time and its acceleration, we can describe its motion both in the future and in the in past; we call Classical Physics a deterministic theory (as opposed to, say, Quantum Mechanics, which would only tell us the probability that a particle would be at some particular position in the future). The right-hand side of Newton's Second Law thus contains the kinematic description of the object; if we know the acceleration, we know everything about the motion of the object.

The left-hand side of the equation contains all of the "dynamics" to describe the object; force is the tool that Newton introduced in order to be able to determine the acceleration of an object. Newton's Second Law thus tells how to determine the kinematics of an object by using the concept of forces; it relates the dynamics to the kinematics. Having already covered kinematics, we will now focus on understanding dynamics and how to develop models that allow us to calculate the net force on an object. The inertial mass, m, is a specific property of an object that tells us how large an acceleration it will experience based on a given net force. Thus, objects with different masses will experience different accelerations if subject to the same net force.

Exercise 5.1.1

Object 1 has twice the inertial mass of object 2. If both objects have the same acceleration vector.

A. The net force on both objects is the same.
B. The net force on object 1 is twice that on object 2.
C. The net force on object 1 is half of that on object 2.

Answer

B.

Newton's Third Law

Newton's Third Law relates the forces that two objects exert on each other. It is important to understand that the forces that are mentioned in the Newton's Third Law are exerted on *different* objects. If object A exerts a force on object B, then object B will also exert a force on object A. The two forces have the same magnitude but opposite directions. Sometimes, the forces are called "action" and "reaction" forces, although this is misleading, because it makes it sound like the reaction force is "in response to" some voluntary action force. However, inanimate objects can exert forces, and so this can lead to needless confusion as to which force is the reaction force.

It does not matter which force you choose to call the action (reaction) force. If a block is pushing down on a table (action force), then the table is pushing up on the block (reaction force). However, one could just as well say that the table is pushing up on the block (action force) so the block is pushing down on the table (reaction force). It does not matter which force you call the action force. This can be confusing, because if you choose to push on a wall (exerting an action force), then the wall exerts a force on you (the reaction force). If you choose not to push on the wall (exerting no force), then the wall does not exert the reaction force. This leads to people thinking that the reaction force is in response to an action force exerted by a sentient being, which is not the case. You can call the force that you choose to exert on the wall the reaction force and Newton's Laws will still work just as well!

Newton's Third law often leads to confusion when Newton's Second Law is applied. Recall that Newton's Second Law involves the sum of the forces on a particular object (the "net force" on that object). The **two forces that are mentioned in Newton's Third Law are not exerted on the same object**, so they would never appear together in the sum of the forces from Newton's Second Law, and they never cancel each other.

Exercise 5.1.3

You push a heavy block in the North direction. The block is twice as heavy as you are. Which statement is true?

A. The block exerts half of the force on you, in the North direction.
B. The block exerts the same force on you, but in the South direction.
C. The block exerts double of the force on you, in the South direction.
D. The block is inanimate and thus does not exert a force on you.

Answer

B.