Newton's Laws of Motion

The laws of dynamics, or the laws of motion, relate the acceleration of an object and the forces acting upon it. Newton recorded three laws:

Newton's First Law:

It was Galileo actually, who first enunciated the principle of inertia: An object in motion will continue in motion with a constant velocity (or an object at rest will remain at rest) unless it is acted upon by a net external force.

Thus a ship, for instance, having once received some impetus through the tranquil sea, would move continually around our globe without ever stopping; and placed at rest it would perpetually remain at rest, if in the first case all extrinsic impediments could be removed, and in the second case no external cause of motion were added.
-fron Galileo's 'Letters on Sunspots'

$$\text{If } \Sigma F = 0 \text{ then } a = 0$$

Newton's Second Law:

While the first law explains what happens to the motion of an object if no external forces act upon it, Newton's second law explains how the motion of an object changes when this is not the case, giving a specific way of determining how the velocity changes under the influence of external forces.

$$F = ma$$

The second law states that the acceleration of an object is directly proportional to the resultant force, i.e. the sum of forces, acting upon it and inversely proportional to its mass. The mass of an object is a quantitative measure of its inertia. The more massive an object, the more it resists a change of velocity (acceleration). A force is the outside influence producing such a change. In our experience we distinguish contact forces, such as the push of your hand against a door, and action-at-a-distance forces, such as gravity. This distinction is false, however, as the force of your hand against the door is acually due to repulsive electrical forces at the atomic level which are action-at-a-distance forces. Actually, there are only four known fundamental forces in nature: gravitational, electromagnetic, strong nuclear, and weak nuclear. The SI (International System) unit of force is the newton, which is defined as the force that produces an acceleration of 1 m/s^2 when acting on a 1-kg mass.

$$1\,N = 1\,kg \cdot \frac{m}{s^2}$$

Newton's Third Law:

The third law states that every action (force) is accompanied by an equal and opposite reaction (force). In other words, if two objects interact, the force exerted by the first on the second object is equal and opposite to the force exerted by the second on the first object.

$$F_{12} = {}^- F_{21}$$

Illustration of Newton's Laws in Uniform Circular Motion

We discussed uniform circular motion earlier in our treatment of kinematics. We shall continue that discussion here, revisiting the boy with his airplane, to show how each of Newton's three laws of motion apply in this case.

The first law:

In the illustration at right, we see what occurs when the string breaks. The airplane continues on its way with the same velocity (speed and direction) that were present at the moment it lost its string. There is no longer the force, provided by tension on the string, changing the direction of the velocity, accelerating the plane by keeping it flying in a circle. Of course we are neglecting resistance of the air and the force of gravity too, so you are imagining for an instant that in the same moment that the string broke the air disappeared and gravity was "turned off". In physics, we are always oversimplifying things! Do you see that the airplane could continue moving at the same speed and in the same direction indefinately with no forces acting upon it? For its velocity to change, in speed or direction, it would require the influence of an outside force, which is the point of the first law.
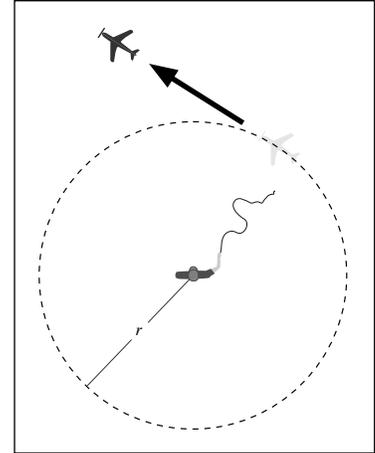
The second law:

In our discussion of uniform circular motion in kinematics, we discussed the existance of centripetal acceleration. "Centripetal" is a word whose parts mean "center-seeking".- The centripetal acceleration is a vector directed towards the center of the circle whose magnitude is given by the formula:

$$a_r = \frac{v^2}{r}$$

The above equation describes the kinematics. It says that the velocity of an object moving in a circle changes by an amount per unit time which depends on the speed of the object and the radius of the circle. The second law, $F = ma$, brings us into the realm of dynamics. It relates the acceleration to a force. If an object acclerates, there is a force acting on it. In the case of the boy with his airplane, the tension on the string supplies this, called the centripetal force, the magnitude of which the second law allows us to derive this expression:

$$F_r = ma_r = \frac{mv^2}{r}$$
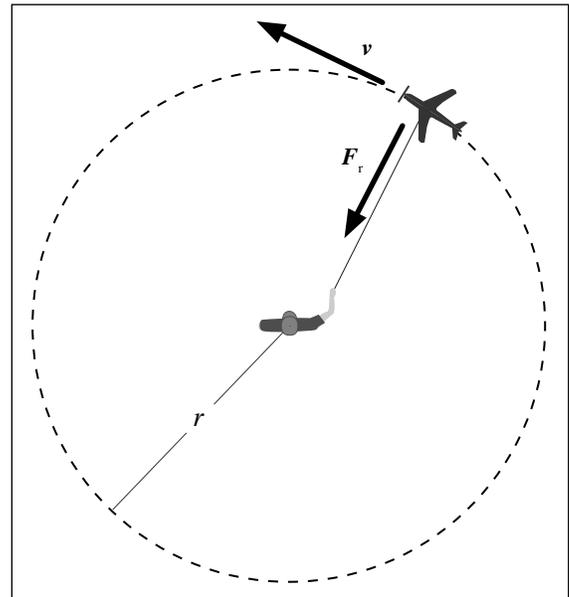
The third law:

According to the third law, a force cannot exist in isolation. The string exerts a force upon the airplane towards the center of the circle, and the airplane exerts a reaction force upon the string equal in magnitude but opposite in direction, called the centrifugal force.

Weight: An Application of the Second Law

On an object at or near the earth's surface, the force of gravity produces an acceleration, g, approximately equal to 10 m/s^2 directed towards the center of the earth. The force itself is termed the weight of the object. It is a vector whose expression is given by:

$$W = mg$$

The Normal Force

When an object possessing a certain weight is at rest, i.e. not accelerating, such as the book on the table in the illustration below, it means that there is another force present opposing the force of gravity. This is the normal force, N, provided by the resistance of the table to any downward motion of the book. Even though in this case the normal force is equal and opposite to the force of gravity, it is not the reaction force as predicted by the third law of motion. The reaction force in this case would be the force of gravity exterted by the book upon the earth, W' (not shown).
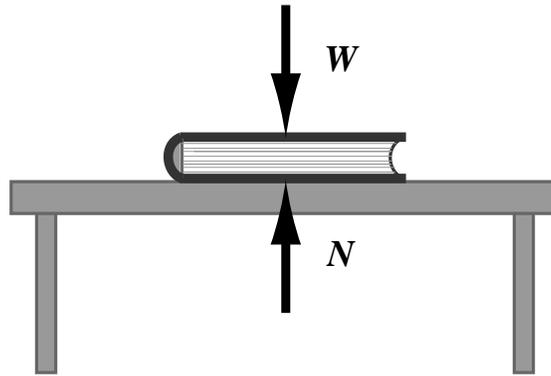
The Inclined Plane

Upon an inclined plane, the weight of an object, mg, may be resolved into two vector components, one parallel to the planar surface and one perpendicular. The normal force in this case is less in magnitude than the total weight. It is equal in magnitude to the component of the gravitational force perpendicular to the planar surface, $mg \cos \theta$. The perpendicular component of the weight and the normal force are equal in magnitude in opposite directions. The object is in static equilibrium in the direction perpendicular to the planar surface, there being no net force in that direction. There is, however, a net force of magnitude $mg \sin \theta$ parallel to the plane. If there is no friction, the object will move down the plane with acceleration of magnitude $g \sin \theta$.
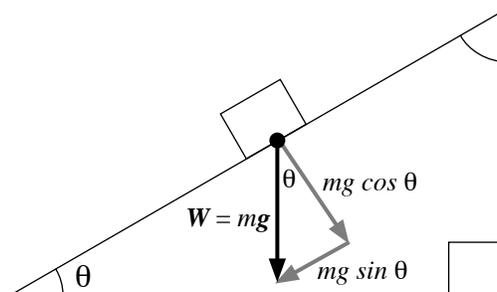
Forces of Friction

Looking again at our inclined plane and block, let's examine the situation where the plane is not frictionless. Friction is the force of resistance to motion because of the interaction of an object with its surroundings. The surface of the plane resists the sliding of the block with a force, F_k, opposition to the direction of motion. The illustration below represents all the forces that are acting on the block. (Notice the new vector, F_k.) Such an illustration is called a free-body diagram. We can see from our free body diagram of the block that the resultant force in the direction parallel to the plane has magnitude equal to $mg \sin \theta - F_k$.

Block sliding down an inclined plane against friction.
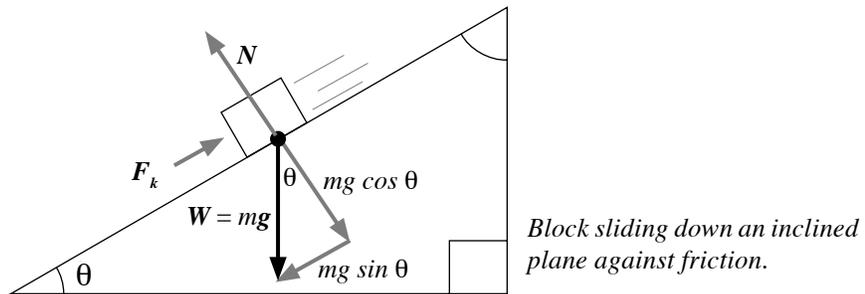
Kinetic Friction and Static Friction

Two types of frictional forces are distinguished. The first, static friction, applies to objects at rest; kinetic friction applies to objects in motion. The distinction arises because the frictional force which must be overcome to set-off motion, F_s, is greater than the frictional force which exists during the time of motion, F_k. The magnitudes of both F_s and F_k are proportional to the normal force:

$$F_s \leq \mu_s N \qquad\qquad F_k = \mu_k N$$

The symbols μ_s and μ_k are called the coefficients of static and kinetic friction respectively. They are determined experimentally for different combinations of surfaces. To understand the reason that the expression for F_s contains the "less than or equals" sign, imagine pushing a brick on the sidewalk: You begin by pushing lightly and the brick does not move. As you slowly increase the force you apply, the opposition force, F_s, increases, equaling out your force. When you reach the threshold and the brick is about to slide, at that point $F_s = \mu_s N$. The equals sign qpplies just when the brick is on the verge of slipping.