Dynamics Explained in the Simplest, Most Comprehensive, and Modern Way

Let's start with the **Motion** first**:**
Quantities describing the motion of an object briefly are:

1. **Displacement:** Change of position Δx, means moving from point A to point B
2. **Velocity**: Rate of change of position or Displacement over time elapsed: $v = \frac{\Delta x}{\Delta t} = \frac{x2-x1}{\Delta t}$
3. **Acceleration**: Rate of change of Velocity versus time: $a = \frac{\Delta v}{\Delta t} = \frac{v2-v1}{\Delta t}$

All these quantities are **vectors**. A vector changes if its magnitude, direction, or both change.
Velocity changes if the object speeds up or slows down while moving in a straight line, or the moving object changes direction, or in all the above scenarios.

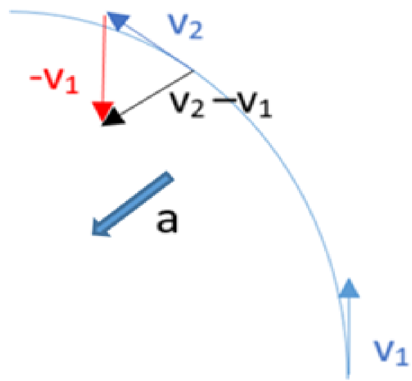


Figure 1: Velocity change and acceleration in a curved motion.

All these quantities describe motion in Kinematics. In dynamics, we calculate the acceleration and then apply it in kinematics to analyze an object's motion.
In summary, acceleration refers to a change in motion. Conversely, force changes the motion and causes acceleration; that's why we need to explore dynamics to deepen our understanding of force.

Forces

Force is a physical quantity that influences an object's motion in all aspects, meaning it causes acceleration. The fundamental principle is the Law of Inertia, also known as Newton's Second Law.

$$F_{net} = ma$$

* F_{net}: Sum, or Resultant force, in Newtons (N)
m: mass in Kg
a: acceleration in N/Kg in Dynamics, which is equivalent to m/s^2 in Kinematics

Different types of forces that need to be considered in this discussion are:

*F_a: **Applied Force**, (no expansion)

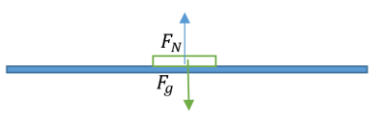
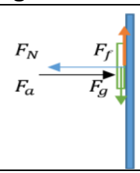
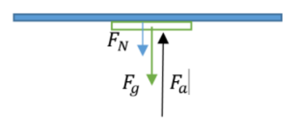
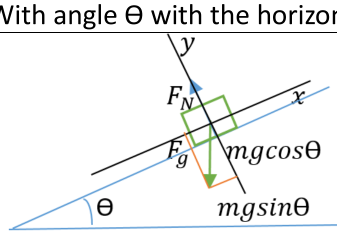
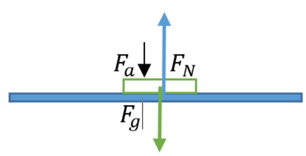
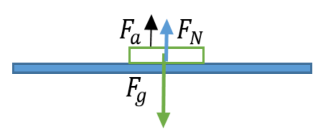
*$F_g = mg$: **Gravitational Force** (this will be expanded later)

***F_N: Normal Force**:

***F_N*: The complete definition of **Normal Force** is: <u>The Reactive Force of the solid surface, Normal to it, towards the object.</u>

Note 1: In physics and math, Normal is the line perpendicular to a surface, which means Normal is perpendicular to all lines lying in the surface.
Note 2: Reactive or Reaction force is the force that opposes the applied or active force. It is also referred to as a Passive, Reactive, or Resistant force**.**
For example, if you push the wall with 100 N, the wall will **resist** with an equal amount in the opposite direction (-100N).
Remember, saying that the "wall pushes you back" is not a meaningful interpretation because the wall or the floor cannot push; they only **resist** to precisely equal and opposite quantity.

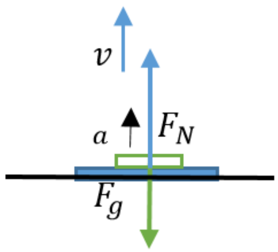
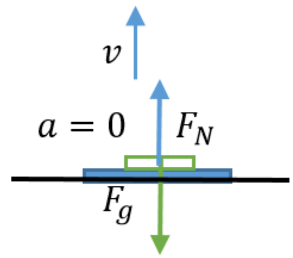
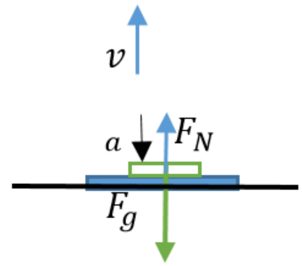
The normal force requires closer attention and a more detailed explanation. Based on the definition above, we examine several common cases, summarized in the table below, each accompanied by its corresponding **Free Body Diagram (FBD)**.

<table>
<tr><td>F_N: The object sits on a horizontal surface or floor</td><td>F_N: The object is pushed against a vertical wall</td><td>F_N: The object is pushed against the ceiling</td></tr>
<tr><td>
</td><td>
</td><td>
</td></tr>
<tr><td>$F_N - F_g = 0, \quad F_N = F_g$</td><td>$F_N = F_a, \quad F_f = F_g$</td><td>$-F_N - F_g + F_a = 0$
$F_N = F_a - F_g$</td></tr>
<tr><td>F_N: The object sits on a ramp With angle ϴ with the horizontal</td><td>F_N: The object sits on a horizontal floor pushed down</td><td>F_N: The object sits on a horizontal floor, pulled up</td></tr>
<tr><td>
</td><td>
</td><td>
</td></tr>
<tr><td>$F_x = mgsinϴ$
$F_N = F_y = mgcosϴ$</td><td>$F_N - F_g - F_a = 0$
$F_N = F_g + F_a$</td><td>$F_N - F_g + F_a = 0$
$F_N = F_g - F_a$</td></tr>
</table>

Apparent weight *F_N of an object in a moving elevator

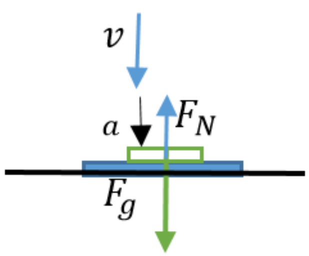
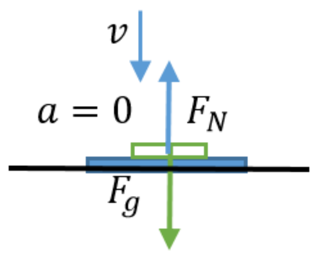
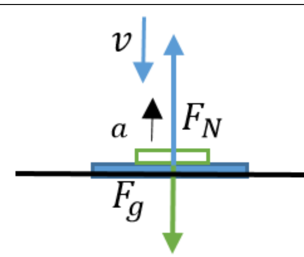
The weight of an object on a scale in an elevator can be determined by examining the normal force, which reflects the combined effects of gravity and the elevator's acceleration. The following diagrams provide a summary of different scenarios along with their corresponding free-body diagrams.

a. The elevator moves upward: it starts, then continues at a steady speed before coming to a stop.

Accelerating upward, level zero	Moving up at a constant speed	Decelerates to stop at the top
		
$F_N - mg = ma$ $F_N = mg + ma$	$F_N - mg = 0$ $F_N = mg$	$F_N - mg = -ma$ $F_N = mg - ma$

The object appears heavier at the bottom and lighter at the top of the trip.

b. The elevator moves down: it starts, then continues at a steady speed before coming to a stop.

Accelerating downward, at the top level	Moving down at a constant speed	Decelerates to stop at the lower level
		
$F_N - mg = -ma$ $F_N = mg - ma$	$F_N - mg = 0$ $F_N = mg$	$F_N - mg = ma$ $F_N = mg + ma$

Similarly, the object appears heavier at the bottom and lighter at the top of the trip.

*$\boldsymbol{F_f}$**:** The **Friction Force** is the resistance force between the surfaces of two objects in contact when <u>one slides over the other</u>. This force is proportional to the normal force and a constant μ, which represents the roughness of both surfaces and is referred to as the coefficient of friction. This force acts in the opposite direction of the **sliding motion**:

$$F_f = \mu . F_N$$

When an applied force ***Fa*** begins to move an object from rest, it must first overcome the **static friction** force, which depends on the **static coefficient of friction** (μ_s). Once the object is in motion, $\boldsymbol{F_f}$ opposes the motion by **kinetic friction**, which depends on the **kinetic coefficient of friction** (μ_k).

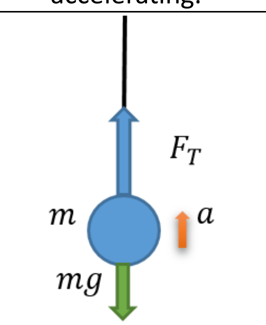
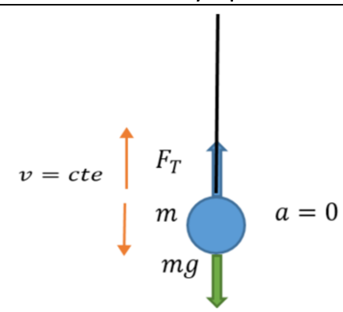
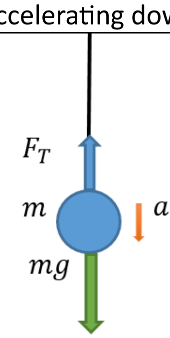
Since $\mu_s > \mu_k$, it takes more force to start the motion than to keep the object moving.

Important: There are some Key Concepts on Friction and Motion commonly misunderstood:

1. **Walking:** When we walk, our feet push backward against the ground. According to Newton's third law, the ground reaction, in the form of static friction, moves us forward. So, in walking, friction acts in the direction of motion, not opposite to it, and helps us walk and run.
2. **Cars:** A car's tires rotate and push backward against the road. This is why **friction causes the acceleration**. Therefore, the frictional force is in the direction of motion.
3. **Rolling requires friction:** In rolling motion (like wheels or balls), the object is **not sliding** over the surface. Therefore, **static friction** is at play, not kinetic friction. Static friction allows the wheel or ball to roll without slipping. On a **frictionless surface**, a ball or wheel cannot roll; it would simply slide. Friction provides the necessary torque at the point of contact to initiate and sustain rolling on the road or surface.

*F_T: The **Tension Force** is a type of force transmitted through a rope, cable, chain, or cord. It is typically used to **pull objects**, and the medium (rope, chain, etc.) here is assumed to be theoretically massless and inextensible. Tension **changes the direction** of the applied force but **not its magnitude**, especially when using pulleys or redirecting systems. On horizontal or inclined surfaces, tension can be treated like any other force component acting along the direction of the rope.

For a hanging object, the different possible scenarios and their FBDs while it is moving up or down are summarized in the diagrams below:

The object is pulled up, accelerating.	Object moving up/down at a constant velocity up or down	The object is held, but accelerating down
		
$F_T - mg = ma$ $F_T = mg + ma$	$F_T - mg = 0$ $F_T = mg$	$F_T - mg = -ma$ $F_T = mg - ma$

*F_B: The **Buoyancy Force** and Archimedes' Principle
Any object wholly or partially submerged in a fluid experiences an upward force known as the **buoyant force**. According to Archimedes' Principle, this force is equal to the weight of the fluid displaced by the object. The origin of the buoyant force lies in the difference in fluid pressure at different depths. Pressure in a fluid increases with depth because it is proportional to the weight; therefore, the height of the fluid column above a given level, plus atmospheric pressure, P_a.

Since pressure is defined as $P = \frac{F}{A}$, and density $\rho = \frac{m}{V}$, the net force on a submerged object results from the pressure difference between the top and bottom surfaces.

$$P = \frac{mg}{A} = \frac{\rho V g}{A} = \rho g h$$

Where: $V = hA$, is the volume of the object submerged (equal to the volume of the fluid displaced), A is the cross-sectional area of the object parallel to the fluid surface, and h is the height of the fluid on top.

The buoyant force F_B is the net upward force exerted by the fluid, acting in opposition to gravity.

$$F_B = \rho_{Fluid} \rho V g$$

Where: F_B is the Buoyancy force (N)

ρ The density of the fluid (Kg/m^3)

V The volume of the liquid displaced by the submerged part of the solid object in (m^3)

g: The gravitational constant in N/Kg or m/s^2

The difference in pressure from the bottom to the top level of the object is:

$$P_1 - P_2 = \rho g h_1 - \rho g h_2$$

Note: Since we are calculating the pressure difference, the atmospheric pressure cancels out.

On the other hand, the force of gravity applied to the object can be written as:

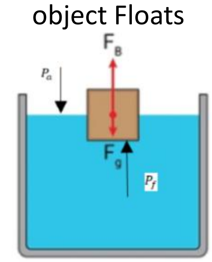
$$F_g = mg = \rho_{Object} V g$$

The upward force (buoyant force) is equal to the weight of the displaced fluid:

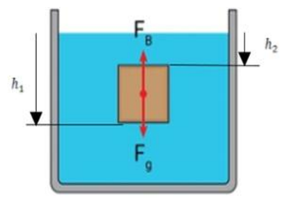
$$F_B = \rho_{Fluid} . V . g$$

Depending on the density of the object compared to that of the fluid, the object can float, suspend, or sink.

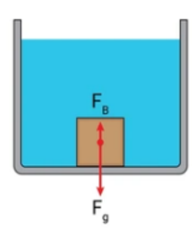
$\rho_{Object} < \rho_{Fluid} \Rightarrow F_B < F_g$
object Floats



$\rho_{Object} = \rho_{Fluid} \Rightarrow F_B = F_g$
Object Suspends



$\rho_{Object} > \rho_{Fluid} \Rightarrow F_B > F_g$
Object Sinks



***F_x*: Elastic Force,** or the force stored in a spring: This is a force opposite and proportional to the stretch of the spring, expressed by **Hook's law:**

$$F_x = -k\Delta x$$

Where: k is the spring constant in N/m, and Δx represents the spring stretch in meters.
While a mass *m* in Kg is attached to one end of a massless spring (Ideal case), by applying Newton's 2[nd] law to the mass m:

$$F_{net} = F_x \qquad \text{or} \qquad -k\Delta x = ma$$

$$m\frac{\Delta^2 x}{\Delta t^2} + k\Delta x = 0$$

The solution of this second-order differential equation, which is the foundation of oscillation or Simple Harmonic Motion SMH is a sinusoidal function like:

$$x(t) = x_0 cos\omega t$$

Where: *X(t)* is the position of the vibrating object as *a* function of time
X_0 is the initial stretch, known as the Amplitude of Oscillation
ω is the frequency of the vibration in Radian/S, which is equal to:

$$\omega = \sqrt{k/m} = 2\pi f = \frac{2\pi}{T}$$

With the frequency *f* in Hertz, and the Period of oscillation in seconds

$$T = 2\pi\sqrt{\frac{m}{k}}$$

***F_c*: Centripetal Force**: Uniform circular motion can be described as the motion of an object in a circle at a constant speed under the influence of a Force *F* directed toward the center *C* with a steady magnitude. As the object circulates, it constantly changes its direction. Since the velocity vector follows the object's motion, it remains tangent to the circle with center *C* and radius *R*. Given that the force *F* is a radial vector, it is always perpendicular to the velocity vector at any instant.

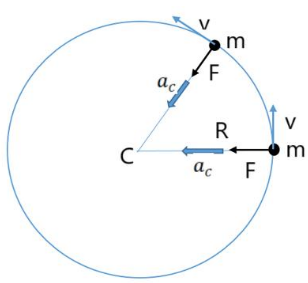


Figure: 2

According to Figure 1, explained in the introduction about Kinematics, the object experiences an inward acceleration. In the case of uniform circular motion, the acceleration vector remains constant in magnitude but continuously changes direction. The acceleration vectors are called radial, pointing toward the center in the direction of the applied force, which is called a_c, Centripetal Acceleration.
To adapt Newton's Second Law to circular motion, Figure 2:

$$F_{net} = ma$$

We rewrite it as F_c, uniform circular motion:

$$F_c = ma_c \qquad \text{With:} \qquad a_c = \frac{v^2}{r}$$

Fc is the net centripetal force, and a_c It is the Centripetal, sometimes called Radial acceleration.

The velocity in uniform circular motion in (m/s) can be expressed as:

$$v = \frac{2\pi r}{T} = 2\pi r f$$

Where *T* is the Period of revolution in seconds (s), and *f* is the Frequency of revolution in Hz (1/s).

Depending on the application, use one of the following formulas to find the centripetal acceleration:

$$a_c = \frac{v^2}{r} = \frac{4\pi^2 r}{T^2} = 4\pi^2 r f^2$$

Forces exerted by a field

It has been both theoretically proven and experimentally verified that similar objects interact by creating a field around themselves. Subsequently, the field generated by one object applies a force on the other, and vice versa. This theory has been discussed in detail in my previous paper, "How to present the 3 fundamental concepts in Physics today."

Gravitational Force:** The Gravitational field "g" produced by one mass in N/Kg, applies a force ***F in (N) to another mass "m" in (Kg): $F_g = mg$

Electric Force:** The Electric Field "E" produced by one Charge in N/C, applies a force ***F in (N) to another charge "q" in (Coulombs): $F_e = qE$

Magnetic Force:** The Magnetic Field "B" produced by one Moving Charge in N/C, applies a force ***F in (N) to another charge in motion "qv" in (C.m/s) $F_B = qvxB$

***Drag Force:** The resistive force acting against an object's motion through a fluid (such as air or water). It depends on: the fluid's density (ρ), the object's velocity (v), the object's cross-sectional area (A), and a dimensionless coefficient called the drag coefficient (Cd), depending on the object's shape.

$$F_D = \frac{1}{2}\rho A v^2 C_d$$

***Trust Force:** Also known as thrust, it is the force produced by a rocket engine to lift and accelerate the rocket. Thrust depends on the fuel flow rate and the rate of mass loss, which are beyond the scope of this paper.