Chapter 4: Newton's Laws of Motion

Dynamics: Study of motion *and* its *causes*.

- *Forces* cause changes in the motion of an object.

Force and Interactions

Definition ("loose"): A *force* is a push or pull exerted *on* one object *by* another object.

Two Broad Categories of Forces:

1. Contact Forces: Forces exerted *on* one object *by* another object *in contact with* the first object.

2. Field Forces: Forces exerted *on* one object *by* another object *not* in contact with the first object.
   - Gravity: only field force we will deal with in this course.

Four *Fundamental* Forces:

1. **Strong Nuclear Force**
   - Holds atomic nuclei together.

2. **Electromagnetic Force**
   - "Electromagnetic" = "Electric" + "Magnetic"
   - Responsible for electrical repulsion of like charges, attraction of unlike charges, e.g.

3. **Weak Nuclear Force**
   - Responsible for "decay" of radioactive nuclei.

4. **Gravitational Force**
   - Responsible for force of attraction between Earth and Moon, e.g.

➢ Which one of these *fundamental* ones are *contact forces*?

Inertia and Mass

Inertia: The tendency of an object to *resist* a change in its motion.

Mass: A measure of the degree to which an object resists a change in its motion. (A measure of the “amount” of inertia an object possesses.)

- *All* objects resist a change in their motion to *some* degree.

Newton's Laws of Motion

- Sir Isaac Newton (1642-1727)
- First published in *Philosophiae Naturalis Principia Mathematica*, 1687

Newton's First Law ("Law of Inertia"): An object acted upon by zero net force moves with constant velocity.

- "constant velocity" = constant *speed* in a constant *direction* (i.e., a *straight line*)

- If object was *at rest* to begin with, it will *stay* at rest; if it was *moving* to begin with, it will *stay* moving with *same* speed in *same* direction…. unless a net force acts on it.
  - In symbols: If $\sum \vec{F} = \vec{0}$, then $\vec{a} = \vec{0}$

- Net force = vector sum of all *individual* forces acting on the object:

$$\vec{F}_{net} = \sum \vec{F} = \vec{F}_1 + \vec{F}_2 + \cdots + \vec{F}_N \qquad (1)$$

Newton's Second Law: When a net force acts on an object (or a *system* of objects), the object (or system) *accelerates* with an acceleration that is directly proportional to the net external force and inversely proportional to the object's mass:

$$\vec{a} = \frac{\sum \vec{F}}{m} \tag{2}$$

$$\sum \vec{F} = m\vec{a} = m\frac{d\vec{v}}{dt} = m\frac{d^2\vec{r}}{dt^2} \tag{3}$$

This one vector equation really implies three separate equations:

$$\sum F_x = m\frac{dv_x}{dt} = m\frac{d^2x}{dt^2} \tag{4}$$

$$\sum F_y = m\frac{dv_y}{dt} = m\frac{d^2y}{dt^2} \tag{5}$$

$$\sum F_z = m\frac{dv_z}{dt} = m\frac{d^2z}{dt^2} \tag{6}$$

Notes:

1. Unit for force (SI): $\mathrm{kg} \cdot \frac{\mathrm{m}}{\mathrm{s}^2} \equiv \text{"Newton", N}$
2. In $\sum \vec{F} = m\vec{a}$, the $\sum \vec{F}$, the m and the $\vec{a}$ all refer to a *single* object. So we need to be careful to *isolate* this object ⇨"Free-Body Diagram"

Free-Body Diagrams (FBDs)

A proper FBD includes:

1. A sketch of the object whose motion you wish to analyze. Often, the object is represented simply by a *dot*. (There are good reasons for doing this which we will discuss later.)
2. All the forces acting *on* this object. No forces that this object exerts on other objects!!
3. Some kind of coordinate system (set of *x* and/or *y* axes).

...and not one single thing else!!

General Procedure for Solving Most Newton's Second Law Problems

1. Draw the FBD for the object whose motion you wish to analyze.
2. Resolve all forces into components.
3. Apply Newton's 2nd Law separately to the *x* and *y* directions. That is, write down:

$$\sum F_x = ma_x$$

$$\sum F_y = ma_y$$

- Fill in $\sum F_x$ and $\sum F_y$ from your FBD.
- Fill in the mass, if known.
- Fill in a_x and a_y, if known.

4. Solve the resulting simultaneous equations for whatever you're asked to find.

- You may have to use one or more “equations of constraint” to reduce the number of unknowns:

  - constant acceleration $\Rightarrow$ equations of kinematics with constant acceleration

  - “inextensible” strings (string does not stretch or go slack)

Mass and Weight

- Not the same! But *are related*.

Definition: The weight of an object is the net gravitational force on the object.

Note: Weight is a *force*! Unit: N, not kg!

To see how weight and mass related, just consider any object in *free-fall*. Newton's 2nd law gives:

$$\begin{aligned} \sum F_y &= ma_y \\ -w &= m(-g) \\ w &= mg \end{aligned} \tag{7}$$

So the *weight* is the mass *times* the acceleration due to gravity.

Newton's Third Law

Whenever one object (Object #1) exerts a force on a second object (Object #2), Object #2 exerts a force on Object #1, and these two forces are equal in magnitude, opposite in direction.

Symbolically, if we let $\vec{F}_{12}$ be the force that Object #1 exerts on #2 and $\vec{F}_{21}$ be the force that #2 exerts on #1, then 3rd law says:

$$\vec{F}_{21} = -\vec{F}_{12}$$

One of the forces in Newton's 3rd law sometimes called the "action" force. The other is then the "reaction."

So 3rd law says forces always come in *pairs*!

Note: The two forces in an action-reaction pair always act on *different objects*! So they *don't cancel*!

Tension

Definition: The tension in a rope (string, cable, etc.) is the force that the rope exerts on the objects attached to the *ends* of the rope.

- The tension always *pulls*, never *pushes*!

This fact follows directly from Newton's 3rd law.

Inertial Frames of Reference

A *frame of reference* (coordinate system) in which Newton's 1st law holds.

1st law says: If $\sum \vec{F} = \vec{0}$, then $\vec{a} = \vec{0}$.

Any *accelerating* frame is a *noninertial* frame.

Consider person on roller skates in railroad boxcar that accelerates from rest, for example.

As another example, consider bus rounding a curve.