SCI 206: The Physics of How Things Work

Charles Shen

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Notes written from Stefan Idziak's lectures.

Feel free to email feedback to me at ccshen902@gmail.com.

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1.1 Inertia

Inertia states that a body in motion tends to remain in motion; a body at rest tends to remain at rest.

At any particular moment, you're located at a **position**—that is, it is a specific point in space.
Whenever a position is reported, it is always as a **distance** and **direction** from some reference point.

Position is an example of a vector quantity.
A **vector quantity** consists of both a magnitude and a direction; the **magnitude** tells you how much of the quantity there is, while the **direction** tells you which way the quantity is moving.

Velocity measures the rate at which your position is changing with time.
Its magnitude is your **speed**, the distance you travel in a certain amount of time,

$$\text{speed} = \frac{\text{distance}}{\text{time}}$$

and its direction is the direction in which you're heading.
A velocity of zero is special, because it has no direction.

When your velocity is constant and doesn't changes, you **coast**.

1.2 Newton's Law

Newton's First Law of Motion: an object that is not subject to any outside forces moves at a constant velocity, covering equal distances in equal times along a straight-line path.

The outside influences referred in the first law are called **forces**, a technical term for pushes and pulls.
An object that moves in accordance with Newton's first law is said to be inertial.

Mass is the measure of your inertia, your resistance to changes in velocity. Almost everything in the universe has mass.
Mass has no direction, so it's not a vector quantity.

It is a **scalar quantity**—that is, a quantity that only has an amount.

When something pushes on you, your velocity changes; in other words, you accelerate.
Acceleration, a vector quantity, measures the rate at which your velocity is changing with time.
Any changes in velocity is acceleration.

You accelerate in response to the **net force** you experience—the sum of all the individual forces being exerted on you.

$$\text{acceleration} = \frac{\text{net force}}{\text{mass}}$$
$$\text{net force} = \text{mass} \cdot \text{acceleration}$$
$$F_{net} = m \cdot a$$

This relationship is known as **Newton's Second Law of Motion**; the net force exerted on an object is equal to the object's mass times its acceleration. The acceleration is in the same direction as the net force.

Newton's Third Law of Motion: for every force that one object exerts on a second object, there is an equal but oppositely directed force that the second object exerts on the first object.

Forces that are directed exactly away from surfaces are called **normal forces**, since the term **normal** is used by mathematicians to describe something that points exactly away from a surface—at a right angle or perpendicular to that surface.

1.3 Weight and Gravity

Gravity is the physical phenomenon that produces attractive forces between every pair of objects in the universe.

Earth exerts a downward force on any object near its surface. That object is attracted directly toward the center of Earth with a force we call the object's **weight**. This weight is exactly proportional to the object's mass.
Weight is how hard gravity pulls on an object, and mass is how difficult an object is to accelerate.
We have

$$\text{weight} = \text{mass} \cdot \text{acceleration due to gravity}$$

In other words: you can lose weight by either reducing your mass or by going someplace, like a small planet, where gravity is weaker.
The Earth's acceleration due to gravity is $9.8N/kg$ or $9.8m/s^2$.

1.4 The Velocity of a Falling Ball

The current (present) velocity can be calculated as

$$\text{present velocity} = \text{initial velocity} + \text{acceleration} \cdot \text{time}$$
$$v_f = v_i + a \cdot t$$

1.5 The Position of a Falling Ball

The average velocity is exactly halfway in between the two individual velocities:

$$\text{average velocity} = \text{initial velocity} + \frac{1}{2} \cdot \text{acceleration} \cdot \text{time}$$

The present position can be calculated as the following:

$$\text{present position} = \text{initial position} + \text{initial velocity} \cdot \text{time} + \frac{1}{2} \cdot \text{acceleration} \cdot \text{time}^2$$
$$x_f = x_i + v_i \cdot t + \frac{1}{2} \cdot a \cdot t^2$$

1.6 Tossing the Ball Upward

The larger the initial velocity of the ball, the longer it rises and the higher it goes before its velocity is reduced to zero.
It then descends for the same amount of time it spent rising.
The higher the ball goes before it begins to descent, the longer it takes to return to the ground and the faster it's traveling when it arrives.

1.7 Energy

The capacity to make things happen is called **energy**, and the process of making them happen is called **work**.
Energy and work are both physical quantities, meaning that both are measurable.

Physical **energy** is defined as the capacity to do work.
Physical **work** refers to the process of transferring energy.

Energy is what's transferred, and work does the transferring. The most important characteristic of energy is that it's conserved. In physics, a **conserved quantity** is one that can't be created or destroyed but that can be transferred between objects or, in the case of energy, be converted from one form to another.

When you throw a ball, it picks up speed and undergoes an increase in **kinetic energy**, energy of motion that allows the ball to do work on whatever it hits.
When you list a rock, it shifts farther from Earth and undergoes an increase in **gravitational potential energy**, energy stored in the gravitational forces between the rock and Earth that allows the rock to do work on whatever it falls on.
Potential energy is energy stored in the forces between or within objects.

1.8 Doing Work

To do work on an object, you must push on it while it moves in the direction of your push.
This relationship can be expressed as the following:

$$\text{work} = \text{force} \cdot \text{distance}$$
$$W = F \cdot d$$

If you're not pushing or it's not moving, then you're not working.

Energy has no direction. It can be hidden as potential energy.
Kinetic energy is the form of energy contained in an object's motion.
Potential energy is the form of energy stored in the forces between or within objects.

1.9 Gravitational Potential Energy

$$\text{gravitational potential energy} = \text{mass} \cdot \text{acceleration due to gravity} \cdot \text{height}$$
$$U = m \cdot m \cdot h$$
$$The\ higher\ it\ was, the\ harder\ it\ hits.$$

A ramp provides **mechanical advantage**, the process whereby a mechanical device redistributes the amount of force and distance that go into performing a specific amount of mechanical work.

1.10 The Seesaw

Overall movement of an object from one place to another is called the **translational motion**.

A seesaw does not experience translational motion, it does turn around the pivot in the center, and thus it experiences a different kind of motion.

Motion around a fixed amount (which prevents translation) is called **rotational motion**.

The concepts and laws of rotational motion have many analogies in the concepts and laws of translational motion.

1.11 The Motion of a Dangling Seesaw

Rotational inertia states that a body that's rotating tends to remain rotating; a body thats not rotating tends to remain not rotating.

At any particular moment, the seesaw is oriented in a certain way—that is, it has an **angular position**. It describes the seesaw's orientation relative to some reference orientation.

Angular velocity measures the rate at which the seesaw's angular position is changing with time.

Its magnitude is the **angular speed**, the angle through which the seesaw turns in a certain amount of time,

$$\text{angular speed} = \frac{\text{change in angle}}{\text{time}}$$

and its direction is the axis about which that rotation proceeds.

The seesaw's **axis of rotation** is the line in space about which the seesaw is rotating.

Torques is a technical term for twists and spins; its SI unit is *newton-meter* $(N \cdot m)$.

Newton's First Law of Rotational Motion

A rigid object that is not wobbling and is not subject to any outside torques rotates at a constant angular velocity, turning equal amounts in equal times about a fixed axis of rotation.

1.12 The Seesaw's Center of Mass

There is a special point in or near a free object about which all of its mass is evenly distributed and about which it naturally spins—its **center of mass**.
The axis of rotation passes right through this point so that, as the free object rotates, the center of mass doesn't move unless the object has an overall translational velocity.

The point around which all the physical quantities of rotation are defined is the **center of rotation** or pivot.
For a free object, the natural pivot point is its center of mass.
For a constrained object, the best pivot point may be determined by the constraints.

1.13 How the Seesaw Responds to Torques

The **rotational mass** is the measure of an object's *rotational* inertia, its resistance to changes in its *angular* velocity; also known as **moment of inertia**.
An object's rotational mass depends both on its ordinary mass and how that mass is distributed within the object.
The SI unit for rotational mass is *kilogram-meter²* ($kg \cdot m^2$).

An object's rotational mass depends on how far its mass is from the axis of rotation, so its rotational mass may change when its axis of rotation changes, even if it's rotating about its center of mass.
Less torque is required to spin a tennis racket about its handle (racket's mass is fairly close to the axis and the rotational mass is small) than to flip the racket head-over-handle (both the head and the handle are far away fro m the axis and the rotational mass is large).

When something exerts a torque on an object, its angular velocity changes; i.e. it undergoes angular acceleration.
The **Angular acceleration** measures the rate at which the *angular* velocity is changing with time; The SI unit is *radian per second²* ($1/s^2$).
It's analogous to acceleration, which measures the rate at which an object's *translational* velocity is changing with time.
Just as with acceleration, angular acceleration involves both a magnitude and a direction. An object undergoes angular acceleration when its angular speed increases or decreases or when its angular velocity changes direction.

If an object experiences several torques at once, it undergoes angular acceleration in response to the **net torque** it experiences, the sum of all the individual torques being exerted on it.

$$\text{angular acceleration} = \frac{\text{net torque}}{\text{rotational mass}}$$

The relation is also known as **Newton's Second Law of Rotational Motion**.

$$\text{net torque} = \text{rotational mass} \cdot \text{angular acceleration}$$

Spinning a marble is much easier than spinning a merry-go-round.

This law does not apply to nonrigid or wobbling objects, because nonrigid objects can change their rotational masses and wobbling ones are affected by more than one rotational mass simultaneously.

1.13.1 Summary

1. Your angular position indicates exactly how you're oriented
2. Your angular velocity measures the rate at which your angular position is changing with time
3. Your angular acceleration measures the rate at which your angular velocity is changing with time
4. For you to undergo angular acceleration, you must experience a net torque
5. The more rotational mass you have, the less angular acceleration you experience for a given torque

1.14 Forces and Torques

A force can produce a torque and a torque can produce a force.

Nothing happens if you push on the seesaw exactly where the pivot passes through it; there's no angular acceleration!
If you move a little away from the pivot, you can get the seesaw rotating, but you have to push hard.
You do much better if you push on the end of the seesaw, where even a small force can start the seesaw rotating.
The shortest distance and the direction from the pivot to the place where you push

on the seesaw is a vector quantity called the **lever arm**; in general, the longer the lever arm, the less force it takes to cause a particular angular acceleration.
The torque is proportional to the length of the lever arm; i.e. you obtain more torque by exerting force farther from the pivot or axis of rotation.

When your force is directed parallel to the lever arm, it produces no torque.
To produce a torque, your force must have a component that is perpendicular to the lever arm and only that perpendicular component contributes to the torque.

The torque produced by a force is equal to the lever arm times that force, where we include on the component of the force that is perpendicular to the lever arm.

$$\text{torque} = \text{lever arm} \cdot \text{force perpendicular to the lever arm}$$

When twisting an unyielding object, it helps to use a long wrench.

1.15 Balancing and Unbalancing the Seesaw

When a child sits on one end of the seesaw, the child's weight produces a torque on the seesaw about its pivot. Gravity is ultimately responsible for that torque, so it can be referred to as *gravitational* torque.

A *balanced* seesaw experiences no overall gravitational torque about its pivot.
If nothing twists it, the balanced seesaw is inertial—the net torque on it its zero.
When the children aren't fidgeting, the seesaw is rigid and wobble-free, so it rotates at constant angular velocity, in according to Newton's first law of rotational mass. If it's motionless, it stays motionless. It it's running, it continues turning at a steady pace.

Two children with unequal weight can also balance the seesaw by sitting at different distances from the pivot. A heavier child should sit closer to the pivot, and vice versa.

With two children on the seesaw, it has a considerable weight but that weight produces no torque on the seesaw about its pivot.
Because the seesaw's **center of gravity**, the effective location of the seesaw's overall weight, is located at the pivot.
With the center of gravity located at the pivot, gravity has no lever arm with which to produce a torque on the seesaw about the pivot.

Any object or system of objects has a center of gravity—the effective location of its overall weight.
While center of gravity is a gravitational concept and center of mass is an inertial concept, the two conveniently coincide; the seesaw's center of gravity and its center of mass are located at the same point. That coincidence stems from the proportionally between an object's weight and its mass near Earth's surface.

1.16 Levers and Mechanical Advantage

2 Resonance

Indices