Moving and Maneuvering 1
Cornerstone Electronics Technology and Robotics III
(Notes primarily from "Underwater Robotics – Science Design and Fabrication", an excellent book for the design, fabrication, and operation of Remotely Operated Vehicles ROVs)

- **Administration:**
    - Prayer
- **Basics of Moving a Vehicle through Water:**
    - Force and Vectors: A force may be thought of as any influence which tends to change the motion of an object. A force is a vector quantity. A vector quantity is defined as a quantity which has both magnitude and direction. To fully describe the force acting upon an object, you must describe both its magnitude and direction.

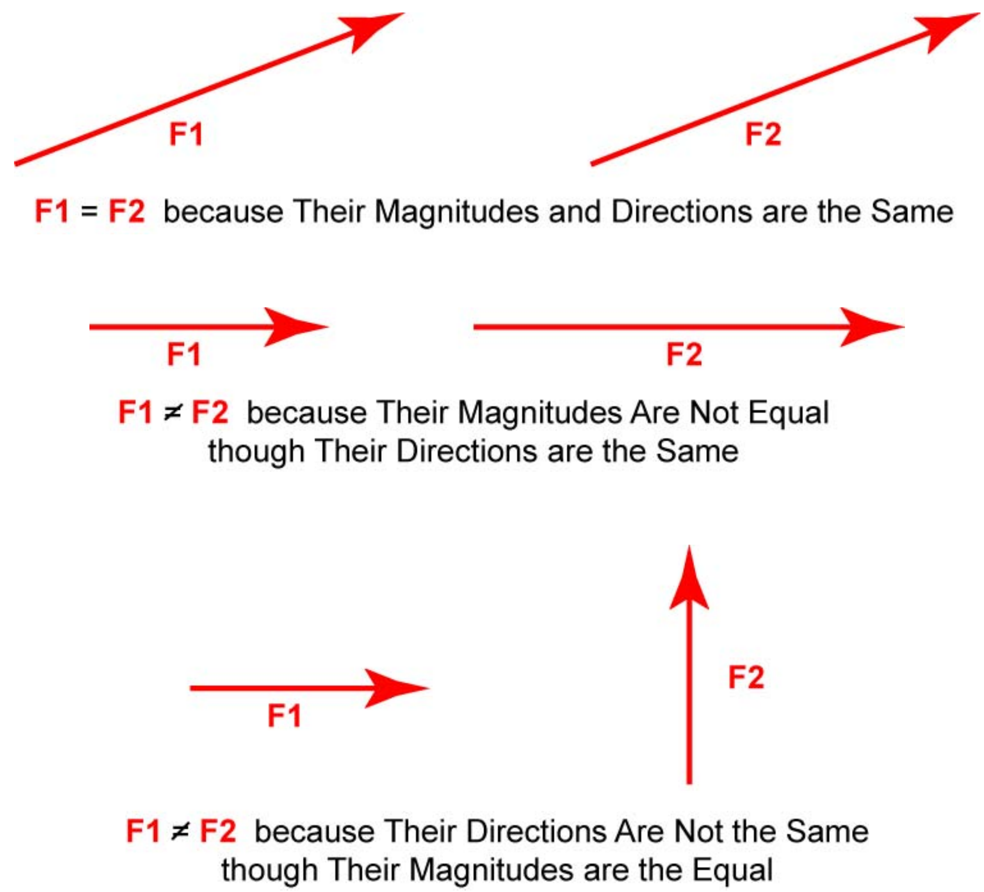


Figure 1: Forces Are Equal When Both Their Magnitudes and Directions Are the Same

- Addition of two vectors: The tail of each consecutive vector begins at the head of the most recent vector. The resultant vector (the net result of the addition of the given vectors) is then drawn from the tail of the first vector to the head of the last vector. The order of the vectors does not matter.

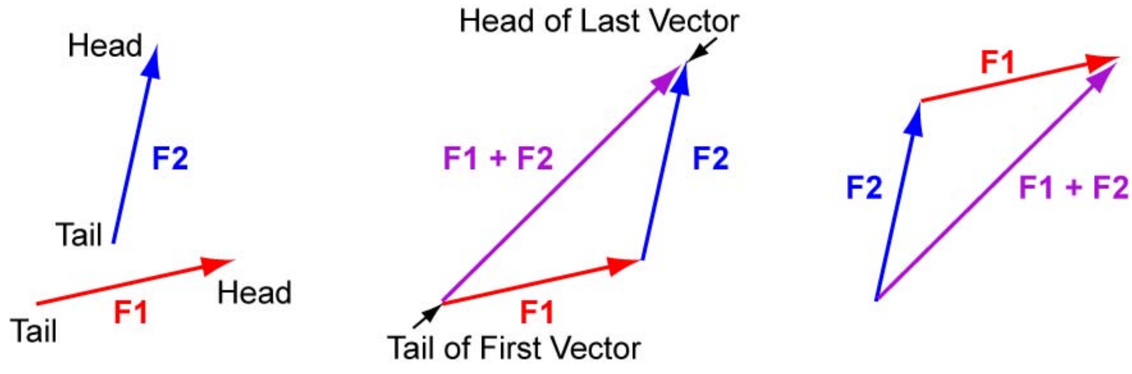


Figure 2: Adding Vectors

Figure 3: Two Forces Cancel Each Other and the Net Result (F1 + F2) = 0
Also Called Balanced Forces

- Newton's First Law of Motion: Newton's First Law states that an object will remain at rest or in uniform motion in a straight line unless acted upon by a net external force.

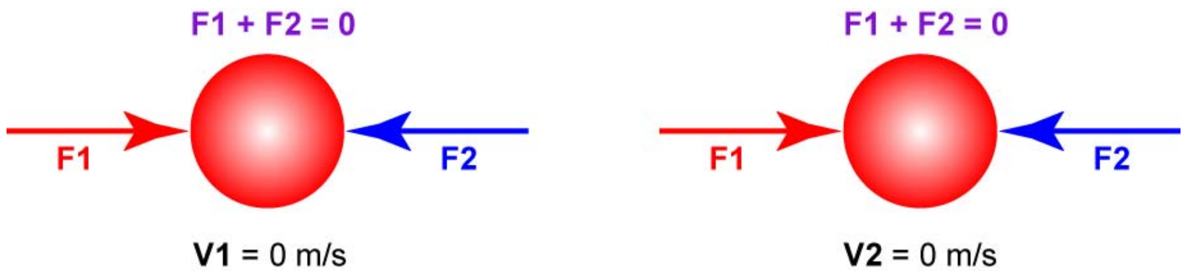


Figure 4: If All the Forces Acting on an Object Are Balanced (Net Force = 0) and the Object is at Rest, then the Object Remains at Rest (V1 = V2 = 0 m/s)

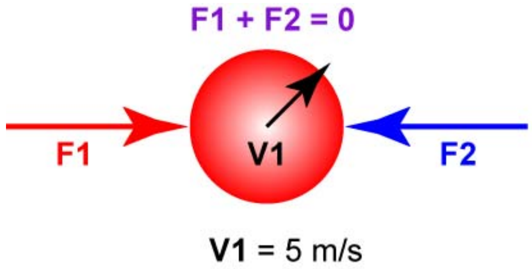


Figure 5: If All the Forces Acting on an Object Are Balanced and the Object is in Motion, the Object Maintains the Same Speed and Direction over Time (V1 = V2)

    - In terms of underwater vehicle control, a vehicle will maintain a constant speed and direction if all of the forces acting on it are in balance (net force equals zero).
    - Perform Moving and Maneuvering 1 Lab 1 – Newton's First Law of Motion
- Newton's Second Law of Motion:
    - The net force acting on an object equals the mass of the object multiplied by the acceleration of the object. It is written as:

$$\mathbf{F} = m \times \mathbf{a}$$

Where:

F = the sum of all of the forces acting on an object
m = the constant mass of the object
a = acceleration of the object
(acceleration is the rate of change of velocity with respect to time; broadly*:* change of velocity)
F and **a** are vector quantities. Also, the directions of the force and acceleration are the same.

This equation is a vector equation meaning that it not only accounts for the size of the force and acceleration, but it also tracks the direction of the force and direction of the acceleration.

Figure 6: The Larger the Force, the Larger the Acceleration

    - Newton's First Law of Motion is a special case of his Second Law; acceleration equals zero because the net force acting on the mass is equal to zero.
    - Force calculator: http://www.ajdesigner.com/phpforce/force_equation.php

    - Applying Newton's Second Law to vehicle control, a vehicle will change speed and/or direction if there is an imbalance of all the forces acting on it (net force does not equal zero).
    - Perform Moving and Maneuvering 1 Lab 2 – Newton's Second Law of Motion
  - Newton's Third Law of Motion:
    - The third law states that for every action (force) in nature there is an equal and opposite reaction. This means that for every force there is a reaction force that is equal in size, but opposite in direction. That is to say that whenever an object pushes another object it gets pushed back in the opposite direction equally hard.

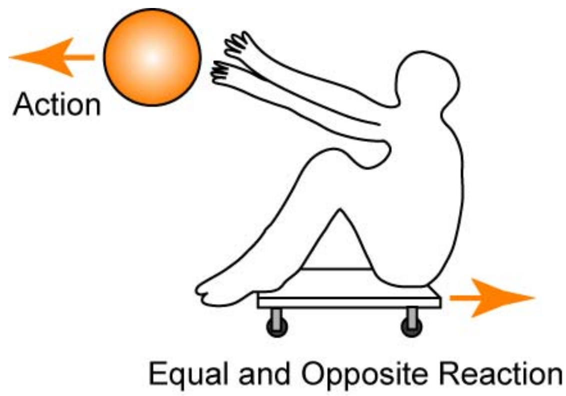


Figure 7: When You Push the Medicine Ball Backward, the Medicine Ball Pushes You Forward

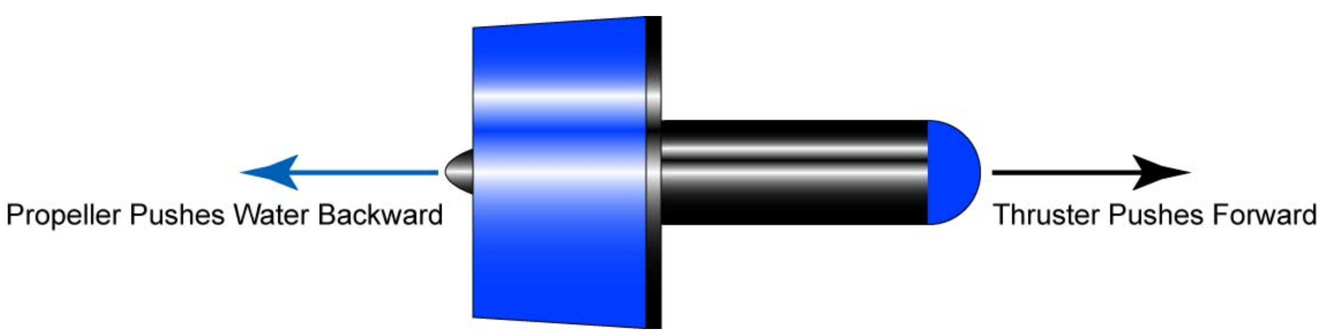


Figure 8: Likewise, when a Thruster's Propeller Pushes the Water Backward, the Water Pushes the Thruster Forward

    - To propel a vehicle in one direction, it must push something with equal force in the opposite direction.

- The Five Forces that Control Motion of an Underwater Vehicle:

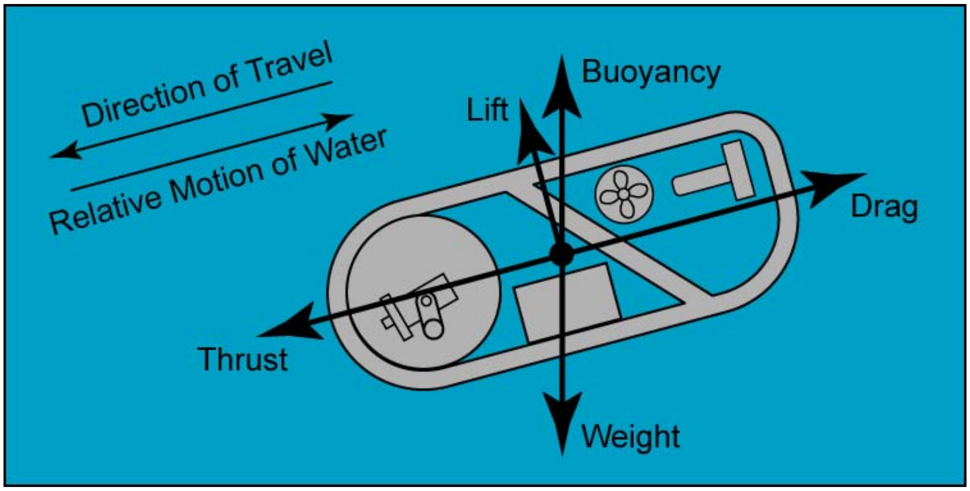


Figure 9: Five Forces that Control a Moving Underwater Vehicle

- Drag: The resistance to the motion of an object passing through a fluid. It is the component of hydrodynamic force parallel to the relative motion of water.
  - In water, drag tries to make a vehicle do whatever the water is doing. If the water is still, drag will attempt slow and stop the vehicle. In moving water, drag will try to carry the vehicle along with the prevailing current.
  - Drag:
    - Limits the maximum speed of a vehicle
    - Plays a significant part in steering a vehicle
    - Consumes most of the energy to power an underwater vehicle
  - Drag must be overcome with the vehicle's propulsion system. This is normally accomplished by the propellers on the thrusters.
  - Drag will be further discussed later in this lesson.
- Weight: The downward force caused by the relationship between the vehicle's mass and gravity. The downward force is always acting straight down.
- Buoyancy: The upward force exerted by the fluid on a body that is immersed. The buoyant force always acts straight upward.
- Thrust: A propulsive force normally produced by a thruster's propeller. Thrusters are mounted in such a way as to push a vehicle in the desired directions for navigation.
- Lift: The component of hydrodynamic force perpendicular to the relative water. Lift only exists when there is relative motion between the vehicle and water. Lift always acts perpendicular to the vehicle's motion. Lift can also act downward or even sideways depending upon the geometry of the vehicle. The effects of lift increase with vehicle speed; lift is inconsequential for slow-moving ROVs.

- Combining Forces:
  - The net force referred to in Newton's laws is the summation of all of the forces acting on an object. The net force working on an underwater vehicle is the resultant force when the five forces just covered are added together.
  - Each of the five force groups is made up of a collection of individual forces of that same type. For example, the total buoyant force is sum of all the individual buoyant forces of each part. As demonstrated in Lesson 9, Buoyancy, Stability, and Ballast 1, these individual buoyant forces can be combined to form one equivalent force acting at the center of buoyancy. The challenge during the design phase is to keep track of all of the forces a vehicle will produce in a systematic manner.
  - Fortunately, some of the force groups can be thoughtfully ignored when considering the forces that affect the motion of a small ROV.
    - Since a ROV is typically designed to be neutrally buoyant, the weight and buoyancy cancel each other.
    - ROVs are typically slow movers so lift can be safely overlooked.
    - This leaves only two force groups to be concerned about that have a substantial impact on the motion of the ROV: drag and thrust.

- **Estimating Thrust Requirements:**
  - In outer space, drag is insignificant and a uniform thrust produces a uniform acceleration and a uniform increase in speed.
  - However, in water, drag is considerable and an even thrust yields a very short period of acceleration and then constant speed.
    - According to Newton's first law, speed must be constant if thrust and drag are balanced.

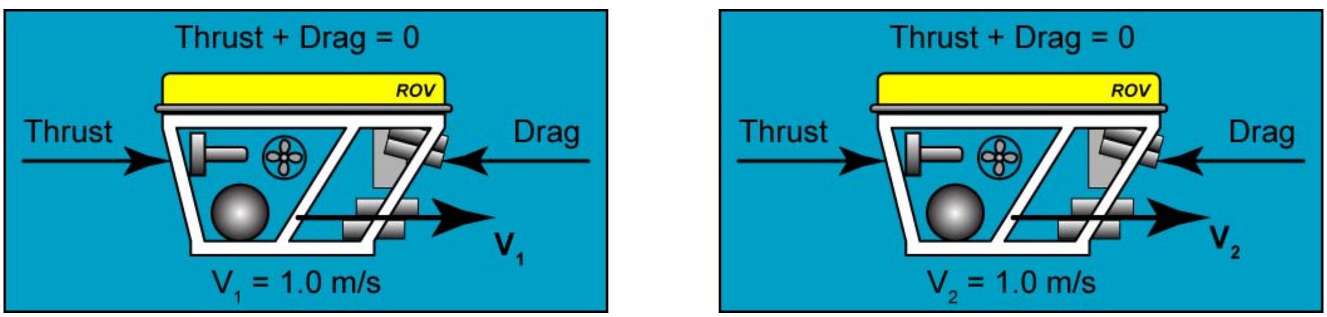


Figure10: As in Figure 5, if All the Forces Acting on an ROV Are Balanced and the ROV is in Motion, the ROV Maintains the Same Speed and Direction over Time (V1 = V2)

    - Drag increases with speed and decreases with streamlining.
  - To calculate thrust required for an underwater vehicle, drag must be estimated; since drag is dependent upon speed, the maximum speed of the vehicle must be known.

- Theoretical Approach for Estimating Drag:
    - A mathematical method to estimate drag at different speeds for vehicles of various shapes and profiles.
    - Skin friction drag (viscous drag): Drag caused by layers of the fluid sticking each other and to the object moving through a fluid. More surface area means more of the object is in contact with the fluid, which means more drag.
    - Profile drag (form drag or pressure drag): The portion of the drag force that is due to the inertia of the fluid — the resistance that it has to being pushed aside.

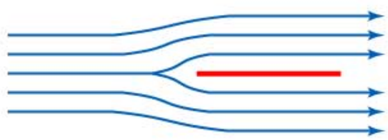
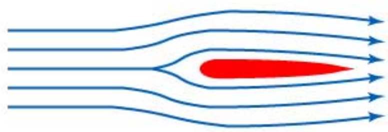
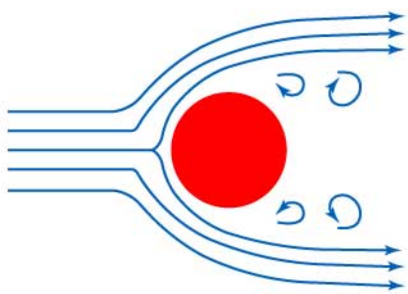
Shape and Fluid Flow	Skin Friction Drag	Profile Drag
	100%	0%
	~90%	~10%
	~10%	~90%

Figure 11: Geometric Shapes and Their Relative Drag

    - For larger and faster underwater vehicles, profile drag dominates, especially vehicles that are not streamlined, such as ROVs.

- When profile drag is significantly greater than skin friction drag, the following equation can be used to estimate the total drag:

$$D = \frac{1}{2} \rho C_d A U^2$$

Where: D = Drag in newtons
ρ = Fluid density in kg/m^3
C_d = Drag Coefficient (no units)
A = Frontal Area in m^2
U = Speed through fluid in m/s

- Empirical Approach for Estimating Drag:
  - This approach works by measuring the force needed to pull a vehicle through water at different speeds.
  - The empirical approach gives accurate drag data with minimal calculations.

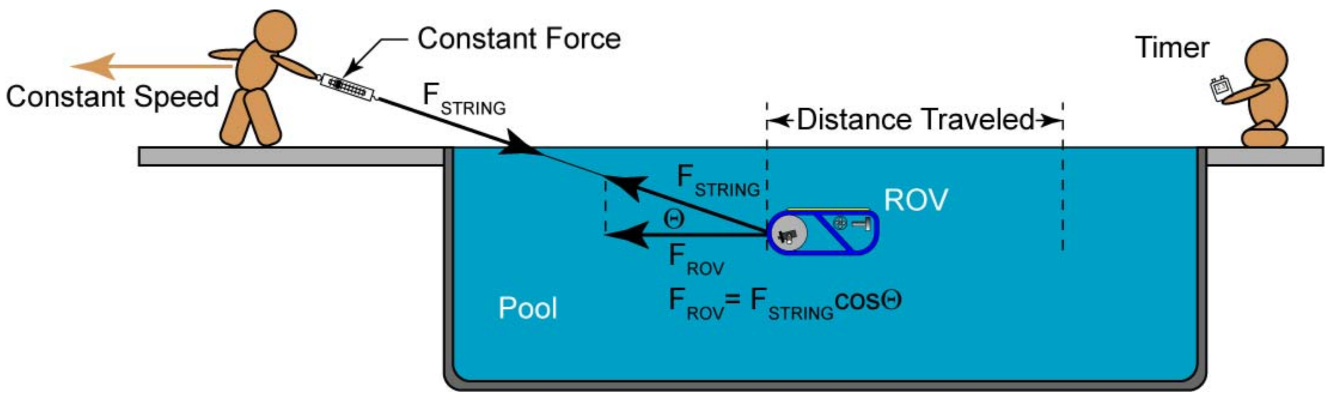


Figure 12: Measuring Drag Empirically Using a Pull Type Spring Scale

  - Pull the ROV through the water with a constant pulling force and measure the time it takes to transverse a given distance. Repeat at several speeds. Plot the speed vs. the pulling force and determine the force (thrust) needed to create the desired speed of the ROV.
  - Refer to page 314 in the textbook for tricks to increase the accuracy of the results.

- **Producing Thrust:**
  - The most popular method to generate thrust in an underwater vehicle is with a propeller.
  - The energy used to turn the propeller in an underwater vehicle is electrical energy. Electrical energy can come from the surface to the submerged vehicle through a tether or the vehicle can carry its own electrical energy stored in batteries.
  - Electric Thruster is a waterproof motor with a propeller attached to the output shaft.

- **Introduction to DC Electric Motors:**
  - Electric motors convert electrical energy into mechanical energy to turn a shaft.
  - Electrical motors do not need oxygen to operate, a clear advantage over gasoline or diesel engines.
  - Types of Motors - AC and DC:
    - AC motors: A motor operating on alternating current that flows in either direction (AC current). AC motors are more commonly used in industry than DC motors but do not operate well at low speeds.
    - DC Motors: A type of motor that runs on direct current. DC motors have better speed control and higher torque than AC motors.
      - DC motors are generally used in battery-operated devices.
      - Many run at lower voltages than AC motors making them safer to operate.
  - Types of DC Motors:
    - Brushed DC Motors: A class of motors that has a piece of current conducting material (usually carbon or graphite) which rides directly on the commutator and conducts current from the power supply to the armature windings.
      - Least expensive and most common of the small DC motors
      - Operating details for a brushed DC motor are covered later in this lesson.
    - Brushless DC Motor: Electric motors powered by direct current (DC) electricity and having electronic commutation systems, rather than mechanical commutators and brushes.
      - Limitations of brushed DC motors overcome by brushless DC motors include lower efficiency and susceptibility of the commutator assembly to mechanical wear and consequent need for servicing, at the cost of potentially less rugged and more complex and expensive control electronics.
    - Stepper and Servo DC Motors: Motors made for precise control of the shaft rotation angle.
    - Gear Motors: A gearhead and motor combination to reduce the speed of the motor to obtain the desired speed or torque. Gearhead is the portion of a gear motor, which contains the actual gearing which converts the basic motor speed to the rated output speed.

- Brushed DC Electric Motor Parts:
  - Permanent magnets: Two magnets that remain magnetized after the electricity is turned off.
  - Armature coils: Coil windings where the magnetic polarity changes. The windings are wound around an iron core to increase the reaction with the permanent magnets. Part of the rotor assembly.
  - Commutator: Contains two or more segments to receive the electricity that is then sent to the armature coils. The commutator rotates with the armature coils and is part of the rotor.
  - Brushes: Contacts that press against the commutator to make connection between the power source and the armature coils.
  - Shaft: Transmits rotational energy to perform work.

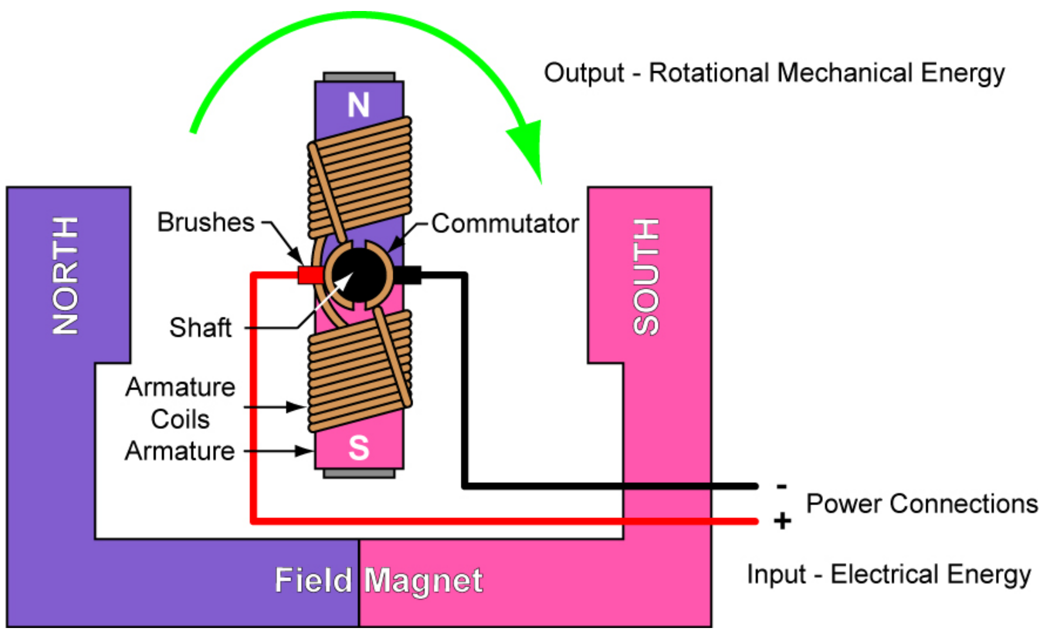


Figure 13: Parts of a Basic Brushed DC Motor

- **Simple Rotation Sequence for a Basic Brushed DC Motor:**

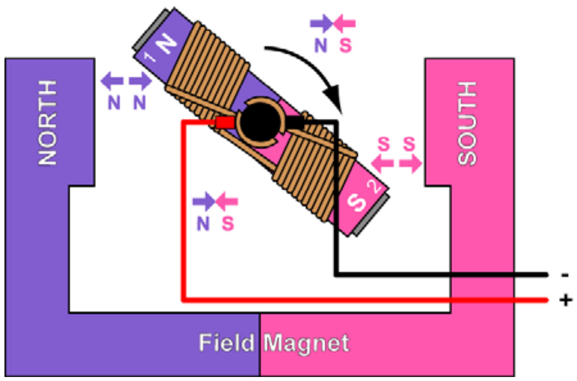


Figure 14

When current flows through the armature coils, magnetic fields are generated around each end of the coils (Ends 1 and 2). The coils function as electromagnets. The north magnetic field that is generated in End 1 of the coil is pushed away from the north permanent magnet (like poles repel) and drawn toward the south permanent magnet (opposite poles attract) causing rotation. Likewise, the south magnetic field that is generated in End 2 of the coil is pushed away from the south permanent magnet and drawn toward the north permanent magnet also causing rotation.

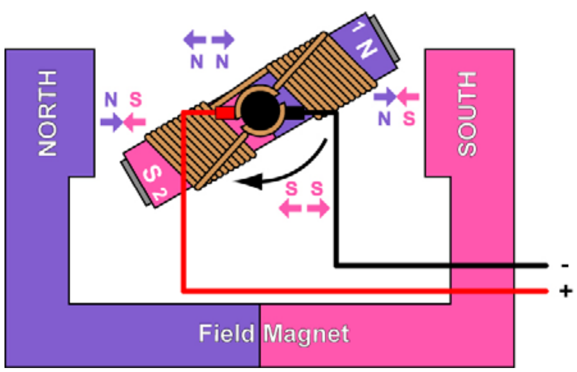


Figure 15

The magnetic fields in the armature coils are still the same causing the attraction and repulsive forces to continue. Notice the small gap in the commutator – the direction of the current through the coils is about to change once the brushes come in contact with the other side of that gap.

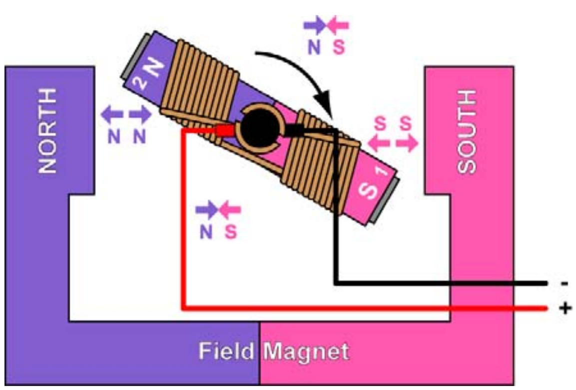


Figure 16

When the armature rotates past the horizontal alignment, the commutator reverses the direction of current through the coils, reversing or flipping the magnetic fields of the coils. End 1 is now the south pole; End 2 is now the north pole.

The process then repeats.

See: http://pcbheaven.com/wikipages/How_DC_Motors_Work/, and http://www.magnet.fsu.edu/education/tutorials/java/dcmotor/index.html

- **Introduction to Propellers:**
    - A propeller is a mechanical device having two or more blades radiating from a central hub that is rotated to produce a propelling force (thrust) to propel a ship, aircraft, etc. The blades are shaped so as to thrust water or air in a desired direction when spinning.
    - Parts of a Propeller:

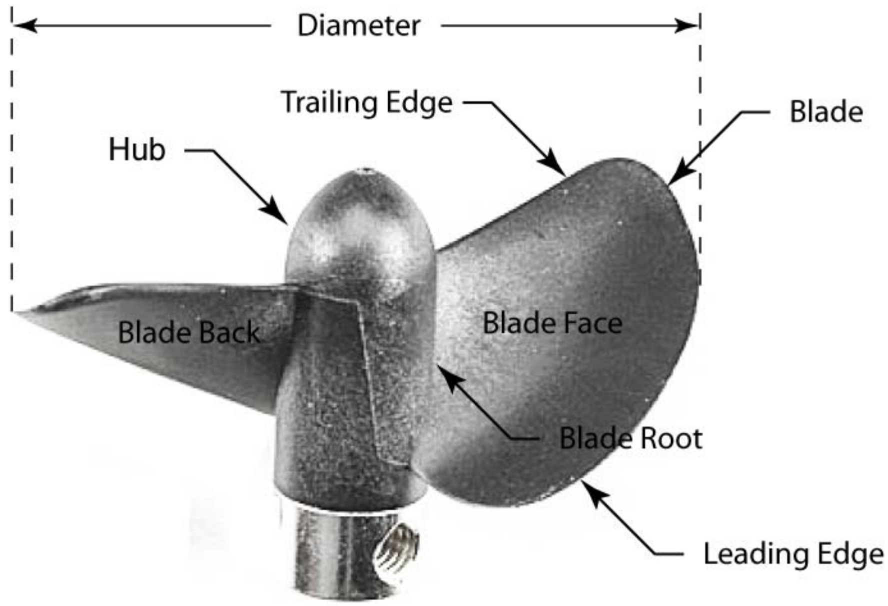


Figure 17: Parts of a Right-Handed Propeller

- Propellers have an airfoil shape to increase pressure on the face side of the blade.
- Propellers generally produce less thrust in reverse than in the forward direction. When a propeller reverses its direction of rotation from forward to reverse, the airfoil shape does not perform as well as in the forward direction.
- Properties of Propellers:
    - Diameter: The diameter of the circle formed by the tips of the blades rotation.
    - Pitch: Pitch is actually the distance that the propeller will move forward through the water in one complete revolution.

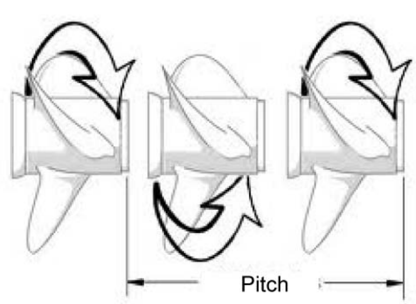


Figure 18: The Pitch of a Propeller Making One Revolution
(From: http://outboard-boats.com/Propeller_pitch_explained.html)

- Number of Blades:
  - Propellers used in water generally have two to seven blades, with three or four most common.
  - Props with fewer blades require less power to generate a given thrust.
  - Props designed with more blades are capable of pushing harder at lower speeds.
- Blade Shape:
  - Ratio of length to width: Short, wide blades are used in water while aircraft employ long narrow blades.
- Material:
  - Small blades normally come in metal or plastic.
  - Metal blades are more durable.
  - Plastic blades are lighter and less expensive.
- Handedness:
  - Right-handed prop: A prop that travels forward when rotation clockwise when viewed from the rear.
  - Left-handed prop: A prop that travels forward when rotation counterclockwise when viewed from the rear.

Figure 19: Left-Handed and Right-Handed Propellers

  - Prop walk is the slight tendency for the vehicle to move sideways when a prop is turning. If right-handed and left-handed props are mounted side by side on two shafts, prop walk is canceled.
  - Be careful to match the correct prop with the correct motor when you have RH and LH props. Placing a right-handed prop on a motor that should be equipped with a left-handed prop will produce thrust in the opposite of the intended direction.
- Mounting the Prop to the Motor Shaft:
  - Securing the propeller to the motor shaft depends upon the manufacturer of the prop. The hub may have a treaded shaft or a slip shaft and you may have to fabricate a coupler to join the motor to the propeller.

- Ducted or Non-ducted Props:
    - A ducted propeller is a propeller fitted with a nozzle.
    - It is used to improve the efficiency of the propeller by directing the fluid straight backward rather than sideways off the tips of the propeller blades.

Figure 20: Ducted Propeller
From:http://www.williammaloney.com/Aviation/USSSalem/SeehundGermanMidgetSubmarine/index.htm

- Ducted propellers are used at low speeds; at high speeds, the drag from the duct negates the increase thrust efficiency.
- The efficiency of a propeller can be further improved using a Kort nozzle. It is shaped like a foil to give added thrust to a propeller.

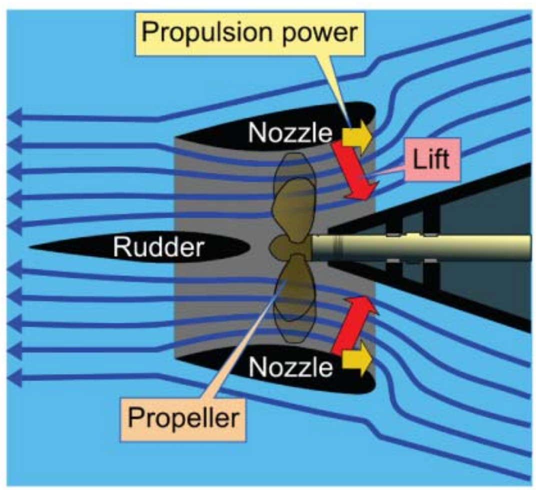


Figure 21: Kort Nozzle
From: http://www.rcgroups.com/forums/showthread.php?t=444813&page=23

- **See Moving an Maneuvering 1 labs at:** http://cornerstonerobotics.org/curriculumyear3.php