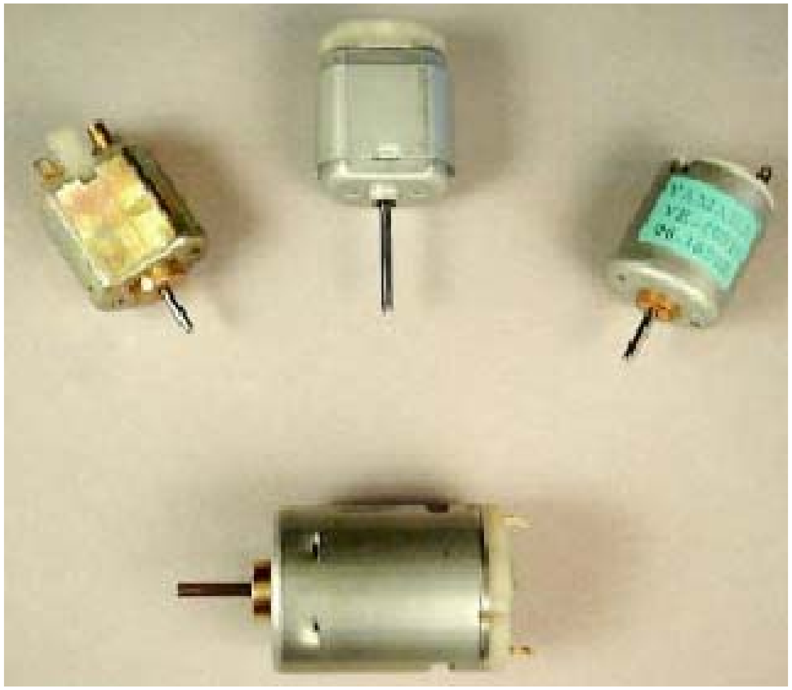
Motors

DC Motors

Direct Current (DC) Motors:

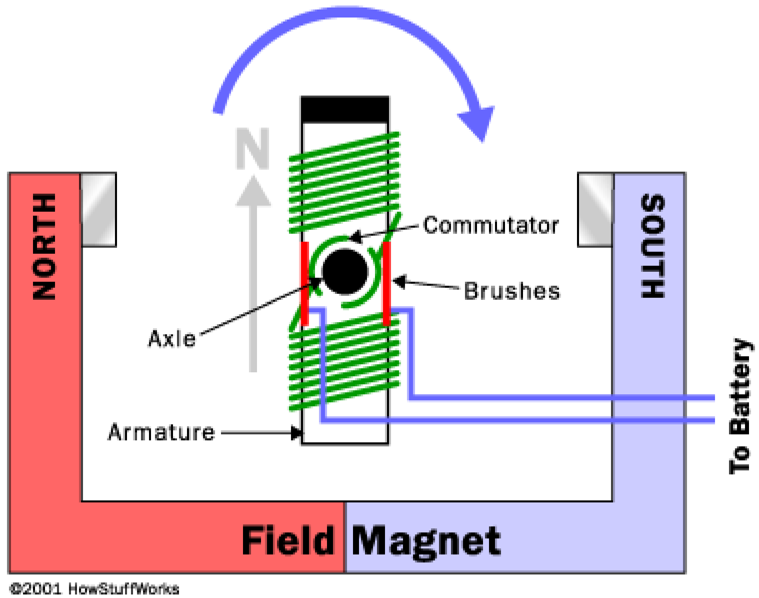
- Small, cheap, reasonably efficient, easy to use, ideal for small robotic applications
- Converts electrical energy into mechanical energy
- How do they work?
  - By running electrical current through loops of wires mounted on rotating shaft (*armature*)
  - When current is flowing, loops of wire generate a magnetic field, which reacts against the magnetic fields of permanent magnets positioned around the wire loops
  - These magnetic fields push against one another and the armature turns

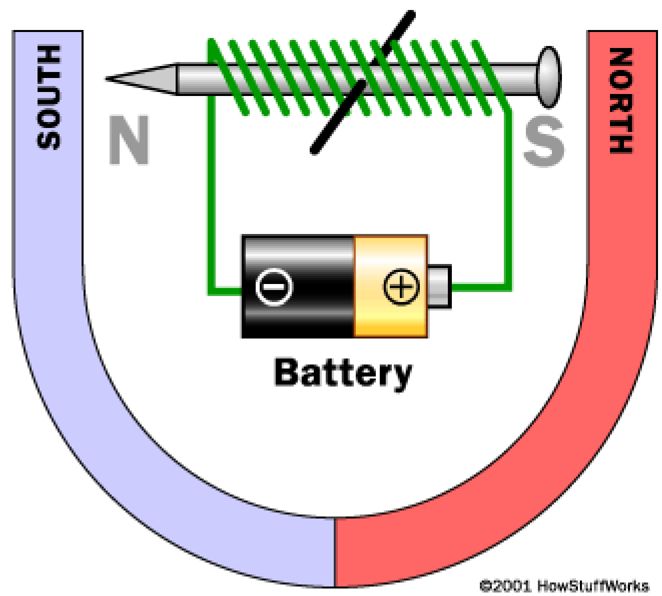


- Efficiency
  - Various limitations, including mechanical friction, cause some electrical energy to be wasted as heat
  - Toy motors: efficiencies of 50%
  - Industrial-grade motors: 90%

Inside an Electric Motor

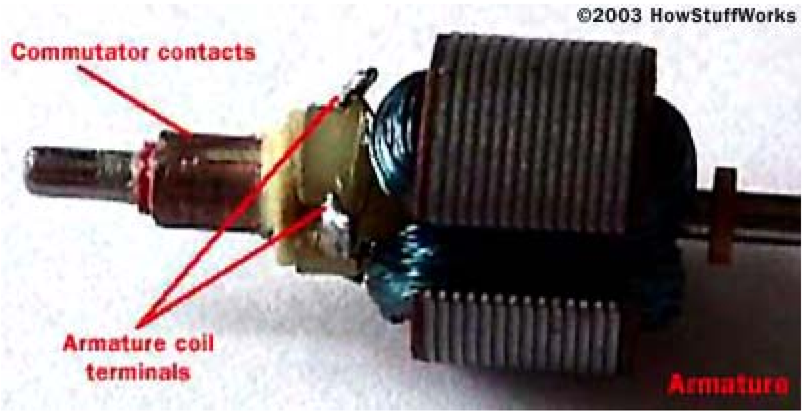
• Simple **two-pole DC electric motor**

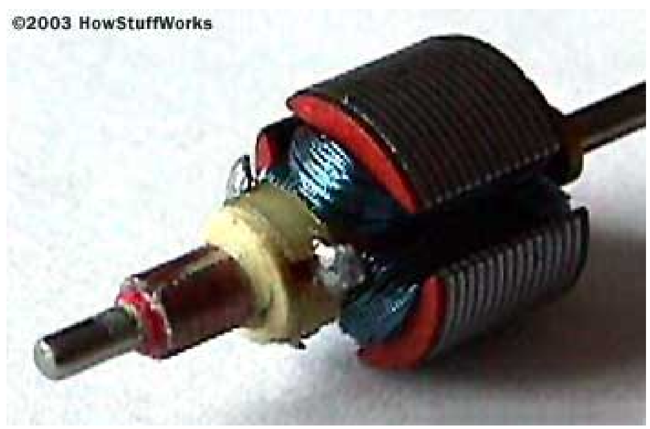




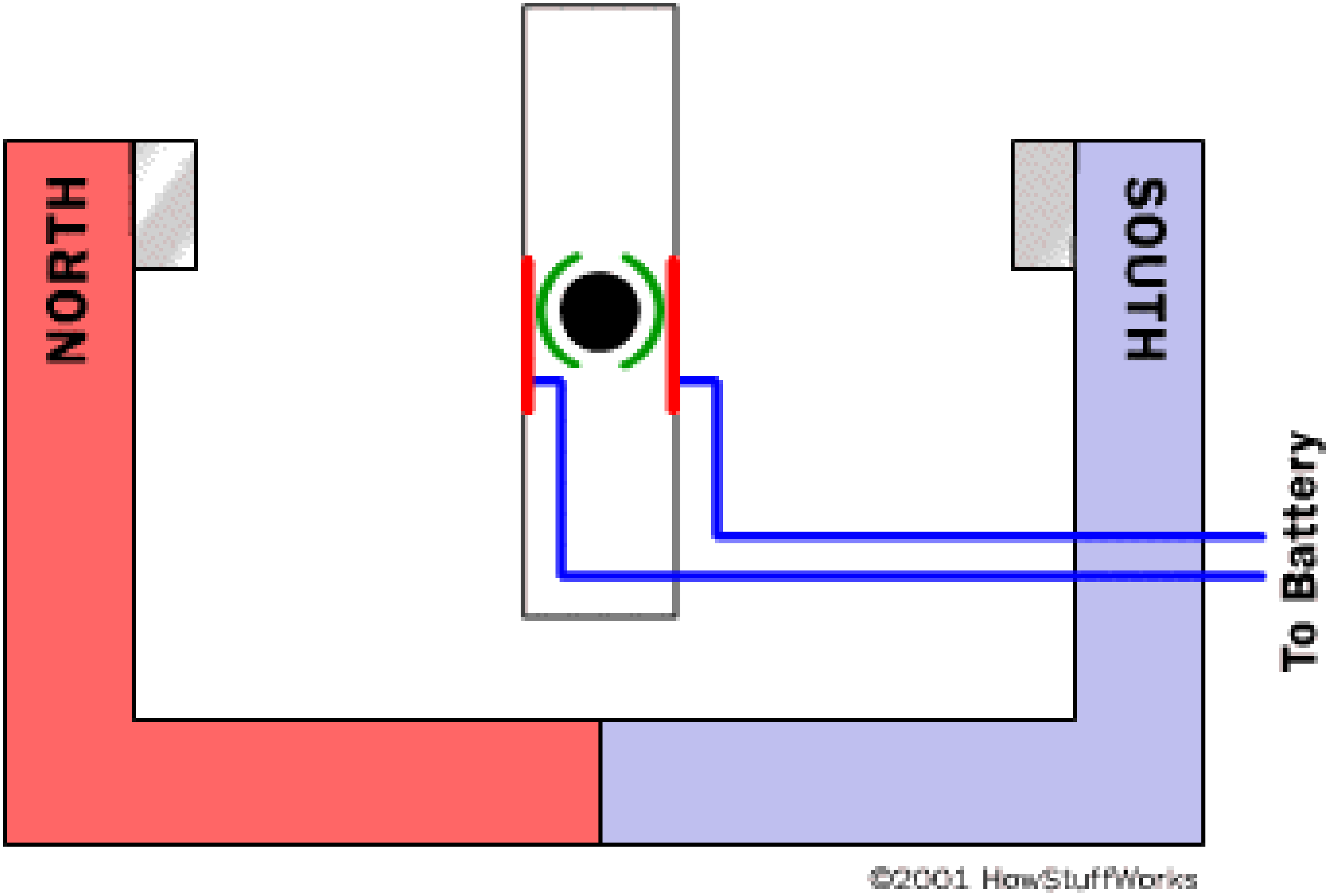
- The armature (or rotor) is an electromagnet,
- The field magnet is a permanent magnet
- Commutator
- Brushes
- Axle
- DC power supply of some sort

Inside an Electric Motor





Inside an Electric Motor



DC Motors

Properties:

- **Operating Voltage**
  - Recommended voltage for powering the motor
  - Most motors will run fine at lower voltages, though they will be less powerful
  - Can operate at higher voltages at expense of operating life
- **Operating Current**
  - When provided with a constant voltage, a motor draws current proportional to how much work it is doing
  - When there is no resistance to its motion, the motor draws the least amount of current; when there is so much resistance as to cause the motor to stall, it draws the maximal amount of current
  - *Stall current:* the maximum amount of operating current that a motor can draw at its specified voltage

DC Motors

Properties:

- **Torque**
  - – Rotational force that a motor can deliver at a certain distance from the shaft
    - The more current through a motor, the more torque at the motor's shaft
  - – Direct consequence of the electromagnetic reaction between the loops of wire in the motor's armature and the permanent magnets surrounding them
  - – Strength of magnetic field generated in loops of wire is directly proportional to amount of current flowing through them; torque produced on motor's shaft is a result of interaction between these two magnetic fields
  - – Often a motor will be rated by its *stall torque*, the amount of rotational force produced when the motor is stalled at its recommended operating voltage, drawing the maximal stall current at this voltage
  - – Typical torque units: *ounce-inches*; e.g., 5 oz.-in. torque means motor can pull weight of 5 oz up through a pulley 1 inch away from the shaft

DC Motors

Properties:

- **Power**
  - – Product of the output shaft's *rotational velocity* and torque
  - – Output Power Zero
    - • Case 1: Torque is zero
      - • Motor is spinning freely with no load on the shaft
      - • Rotational velocity is at its highest, but the torque is zero—it's not driving any mechanism (Actually, the motor is doing some work to overcome internal friction, but that is of no value as output power)
    - • Case 2: Rotational Velocity is zero
      - • Motor is stalled, it is producing its maximal torque
      - • Rotational velocity is zero
  - – In between two extremes, output power has a characteristic parabolic relationship

DC Motors

Motor Speed vs. Torque, Power:

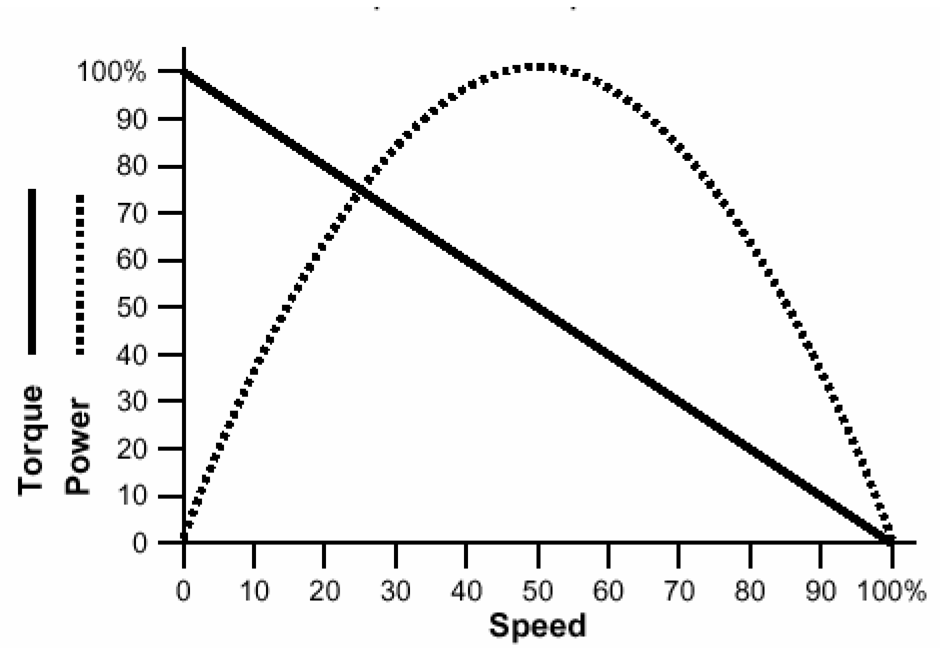
• **Solid line** shows the relationship between motor speed and torque

– At the right of the graph, the speed is greatest (100%) and the torque is zero; this represents the case where the motor shaft is spinning freely but doing no actual work

– At the left of the graph, the speed is zero but the torque is at its maximum; this represents the case where the shaft is stalled because of too much load

• **Dashed line** shows the power output, which is the product of speed and torque

– It is the highest in the middle of the motor's performance range, when both speed and torque are produced



Idealized Graph

DC Motors

Measuring Motor Torque:

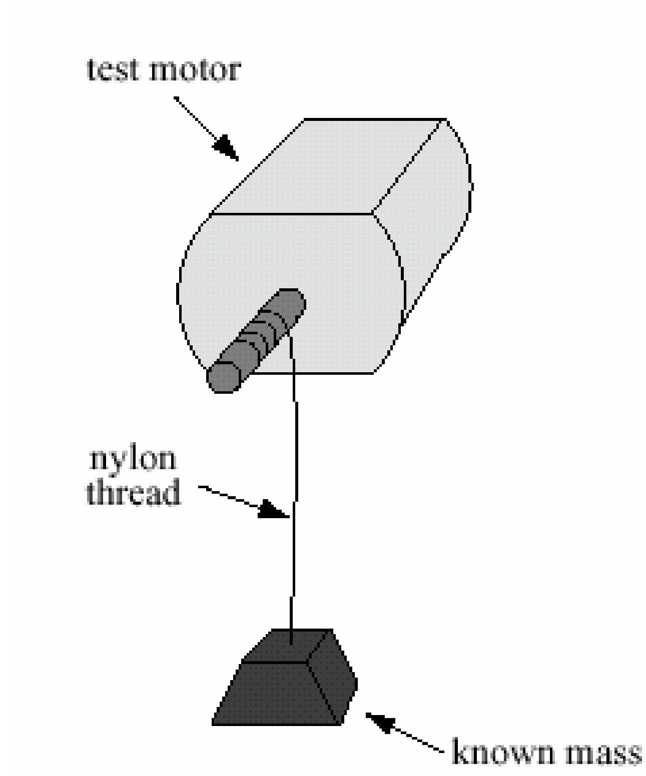
• Motor winds a nylon thread, which carries a known weight, around the motor shaft

• As the thread winds up around the shaft, like a bobbin, the effective radius of the shaft increases

• This process continues until the radius of the bobbin increases to a point where the motor can no longer lift the weight.

• When the motor stops turning, measure the radius of the bobbin

• **Stall torque = bobbin radius * mass**



Experiment:
Bobbin radius = 0.5 in.
Mass = 2 ounce
Torque = 1 ounce-inch

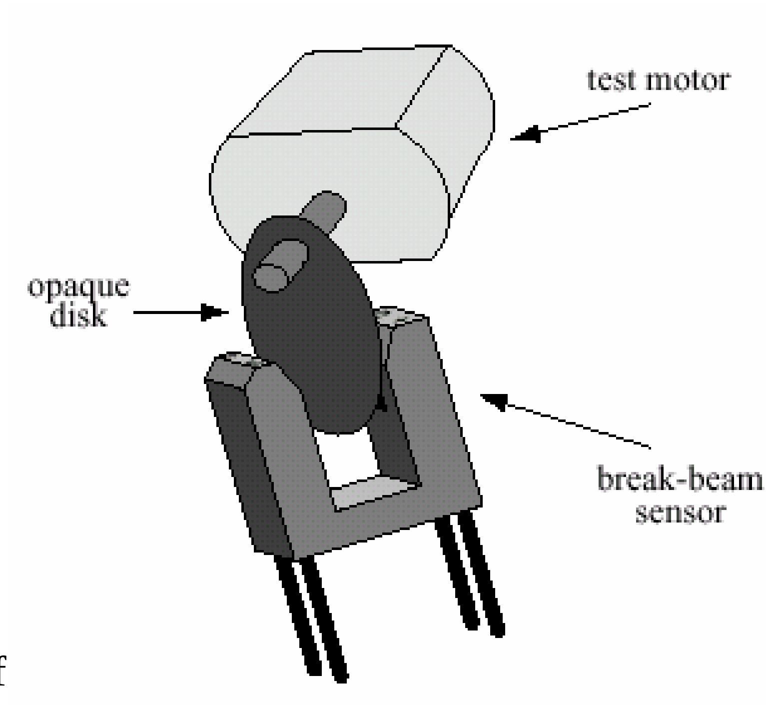
DC Motors

Measuring Motor's Top Speed in RPM:

• Opaque disk (light-weight) is mounted directly on the motor shaft

• *Break-beam opto-sensor* is positioned such that as the disk rotates, it interrupts the sensor's light beam once per revolution

• Most DC motors have unloaded speeds in the range of 3,000 to 9,000 revolutions per minute (RPM), which translates to between 50 and 150 revolutions per second. This is slow enough that a regular RCX analog input could be used, but it is possible that Interactive C would not be able to keep up with this rate.

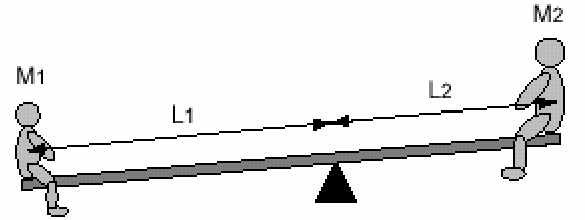


Experiment:
Use torque or RPM test to determine if motor is symmetric in both directions

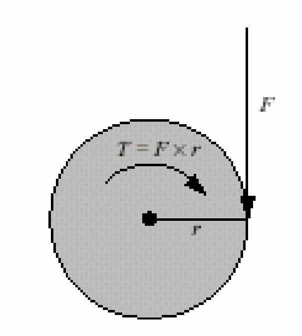
Gearing

- DC motors are high-speed, low-torque devices
- All mechanisms in robots, including drive trains and actuators, require more torque and less speed
- **Gears** are used to trade-off high speed of the motor for more torque
- Torque, or rotational force, generated at the center of a gear:

$$T = F \times r$$



Downward force is equal to weight times their distance from the fulcrum. Lighter people can displace heavier people simply by increasing their distance from the fulcrum.



The torque t—or, turning force—is the product of a force F applied perpendicularly at a radius r.

Gearing

Meshing Gears

• When two gears of unequal sizes are meshed together, their respective radii determine the translation of torque from the driving gear to the driven one

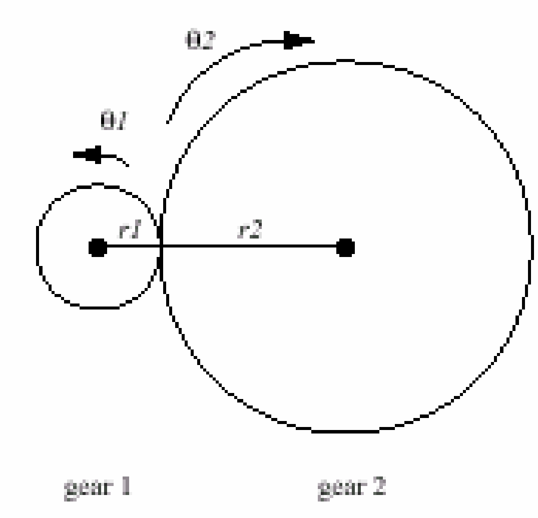
• This mechanical advantage is easiest understood from a “conservation of work” point of view

$$W = F \times d$$

$$W = T \times \theta$$

• Neglecting losses due to friction, no work is lost or gained when one gear turns another

• Example: Gear 1’s radius is one-third that of Gear 2. Their circumferences are also in a 3:1 ratio, so it take three turns of the small gear to produce one turn of the larger gear. Ratio of resulting torques is also 3:1.



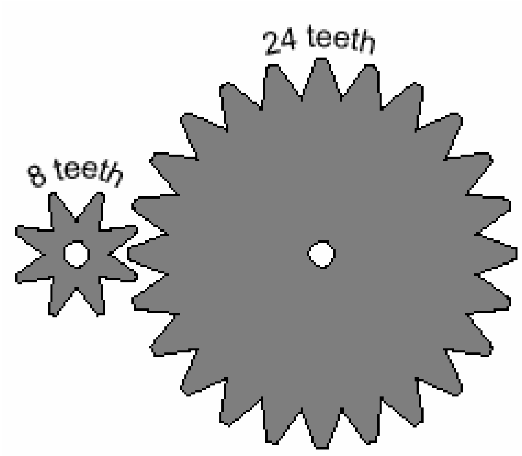
Gear 1 with radius r1 turns an angular distance of θ1 while **Gear 2** with radius r2 turns an angular distance of θ2.

Ratio of gear sizes determines ratio of resulting torques

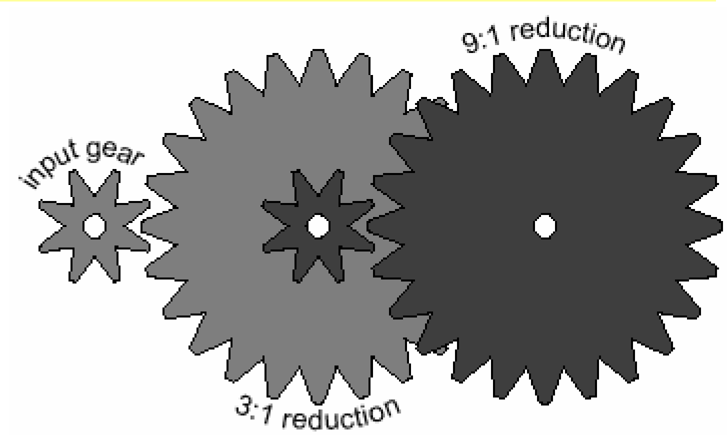
Gearing

Gear Reduction

- Small gear driving a larger one:
  - **torque increases**
  - **speed decreases**
- 3 to 1 Gear Reduction
  - Power applied to 8-tooth gear results in 1/3 reduction in speed an 3 times increase in torque at 24-tooth gear
- 9 to 1 Gear Reduction
  - By putting two 3:1 gear reductions in series—or “ganging” them—a 9:1 gear reduction is created
  - The effect of each pair of reductions is multiplied to achieve the overall reduction
  - Key to achieving useful power from a DC motor
  - With this gear reduction, the high speed and low torque is transformed into usable speeds and powerful torques



3 turns of left gear (8 teeth) to cause 1 turn of right gear (24 teeth)

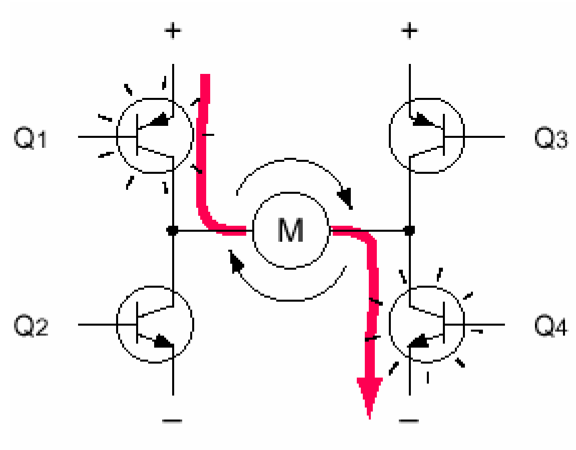


8-tooth gear on left; 24-tooth gear on right

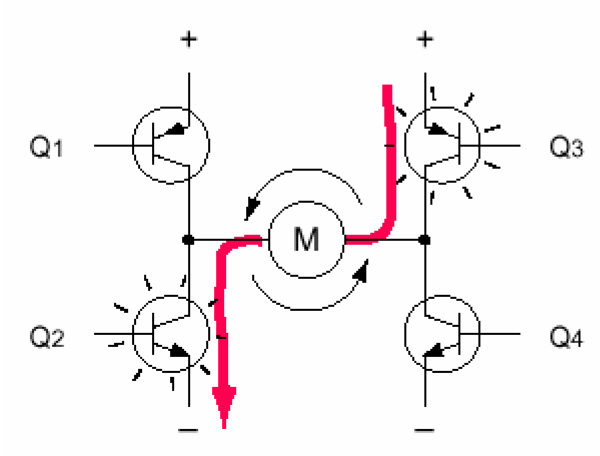
Electronic Control

H-Bridge Motor Driver Circuit

- Four transistors form the vertical legs of the H, while the motor forms the crossbar
- In order to operate the motor, a diagonally opposite pair of transistors must be enabled
- Transistors **Q1 and Q4 enabled**
  - Starting with the positive power terminal, current flows down through Q1, through the motor from left to right, down Q4, and to the negative power terminal
  - Results in motor rotating in a clockwise direction
- Transistors **Q2 and Q3 enabled**
  - Results in current flowing through the motor from right to left



Q1 and Q4 enabled



Q2 and Q3 enabled

Electronic Control

Enable and Direction Logic

• Critical that transistors in either vertical leg of “H” are never turned on at same time

– If Q1 and Q2 were turned on together, current would flow straight down through the two transistors

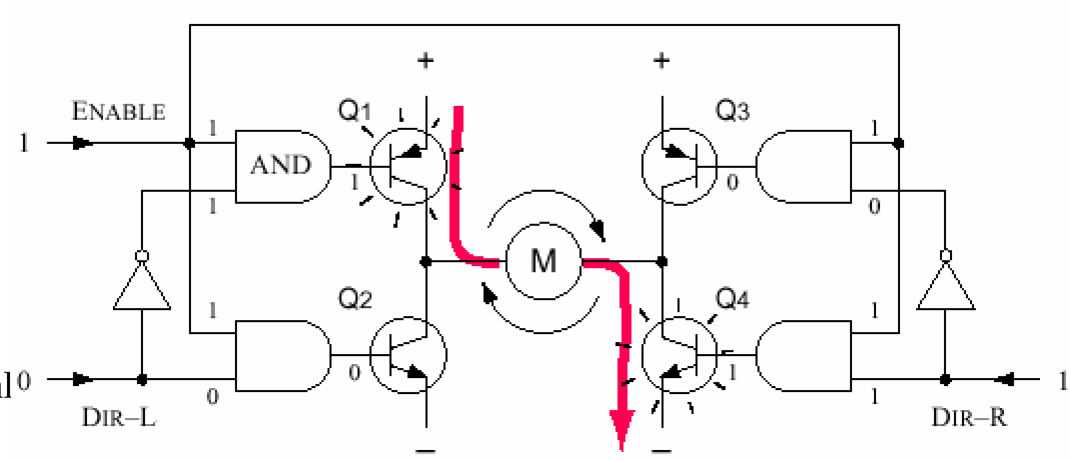
– There would be no load in this circuit other than the transistors themselves, so the maximal amount of current possible for the circuit would flow, limited only by the power supply itself or when the transistors self-destructed

• Actual circuit has hardware to facilitate control of transistor switches

– Add four AND gates and two inverters

– AND gates accept enable signal that allows one signal to turn whole circuit on/off

– Inverters ensure that only one transistor in each vertical leg of the H is enabled at any one time



DIR–L =0, DIR–R=1, enable signal =1: Q1 and Q4 turn on, and current flows through the motor from left to right

DIR–L =1, DIR–R=0, enable signal =1: Q2 and Q3 turn on, and current flows through the motor from in the reverse direction

Electronic Control

Active Braking

• What happens if both direction bits are the same state, and the enable bit is turned on?

– *Effectively, both terminals of motor are connected together*

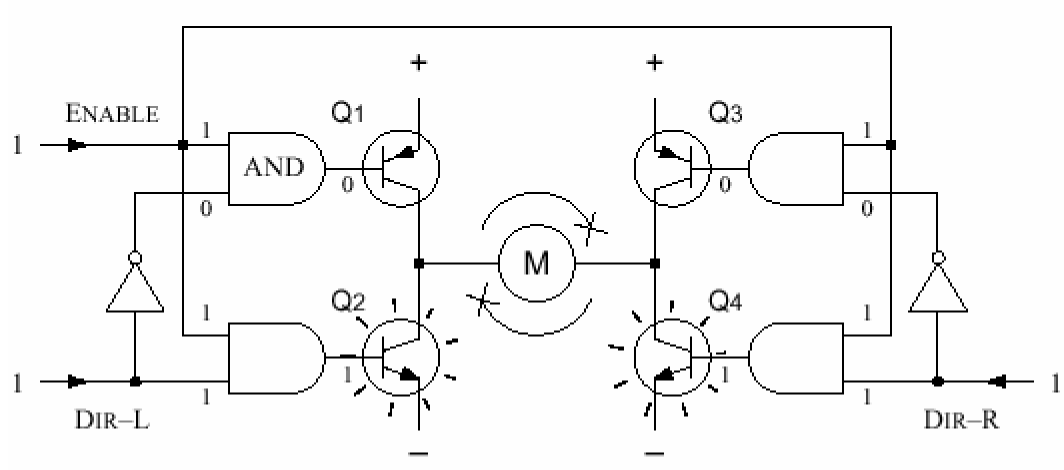
• Motor acts as a generator, creating electricity

–If there is a load connected to the motor, then the motor resists being turned proportional to the amount of the load

– When the motor terminals are grounded through the transistors, it is as if the motor were driving an infinite load

– Transistors in the H-bridge act as a wire connecting the motor terminals— the infinite load

• Final result: circuit acts to actively brake the motor's spin; transistors absorb the energy generated by the motor and cause it to stop. If, on the other hand, none of the transistors is active, then the motor is allowed to spin freely; i.e., to coast



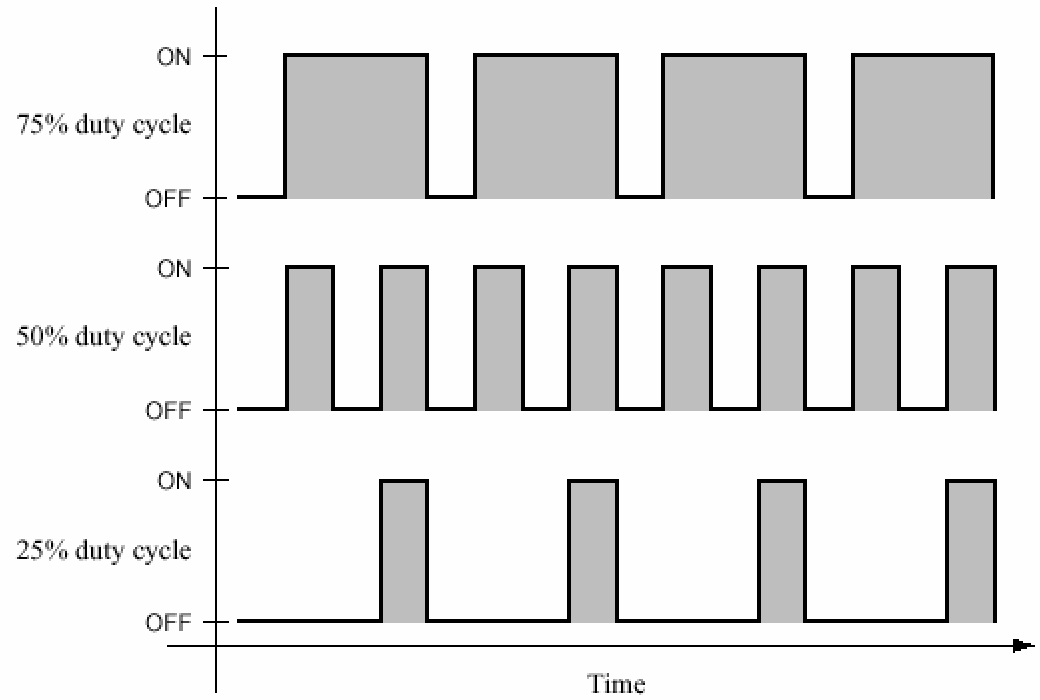
Both direction bits are one and the enable bit is turned on causing transistors **Q2 and Q4** to be activated. This causes both terminals of the motor to be tied to the voltage supply less the voltage drop of the transistor (0.6v).

Contemporary **electric car** designs incorporate circuitry to convert the the drive motor into a generator for recharging the main batteries when braking. This way, the power stored in the car's motion is recovered back into electrical energy. The **active braking** doesn't apply enough force to replace conventional brakes, but it can significantly extend the electrical car's operating range.

Electronic Control

Speed Control

- ***Pulse Width Modulation* (PWM)**
  - – The H-bridge circuit allows control of a motor’s speed simply by turning the drive transistor pair on and off rapidly
  - – *Duty cycle*—proportion between “on time” and “off time”—determines fractional amount of full power delivered to motor
  - – Commonly used in practice: simpler to build circuits that switch transistors on and off than to supply varying voltages at the currents necessary to drive motors
  - – Tends to be fairly linear (25% duty cycle yields pretty close to one-quarter of full power)
- **Reducing the voltage applied to the motor**
  - – Giving a motor 1/4 of its normal operating voltage typically would result in much less than 1/4 of nominal power, since the power increases approximately as the square of the voltage



PWM works by rapidly turning the motor drive power on and off. Waveforms shown would be connected directly to the enable input. Three sample **duty cycles** are shown: a 75%, a 50%, and a 25% rate. The frequency used in PWM control is generally not critical. Over a fairly wide range, from between 50 Hz and 1000 Hz, the motor acts to average the power that is applied to it.

Servo Motor

Specifications

- Specialized motor for turning to a specific position
- Components:
  - – DC motor
  - – Gear reduction unit
  - – Shaft position sensor
  - – Electronic circuit that controls the motor’s operation
- “Servo” - capability to self-regulate its behavior, i.e., to measure its own position and compensate for external loads when responding to a control signal
- Widely used in hobby radio control applications:
  - – RC cars: position the front wheel rack-and-pinion steering
  - – RC airplanes: control the orientation of the wing flaps and rudders

Futaba S148 Servo Motor with Mounting Horns ($17.00)

- Positioning applications:
  - – Shaft travel is restricted to 180 degrees
  - – Input waveform specifies desired angular position of output shaft
  - – Electronics measure current position
  - – If different from desired position, servo is turned on to drive the shaft to the desired position

Servo Motor

Servo Control

• Most hobby servo motors use a standard three wire interface:

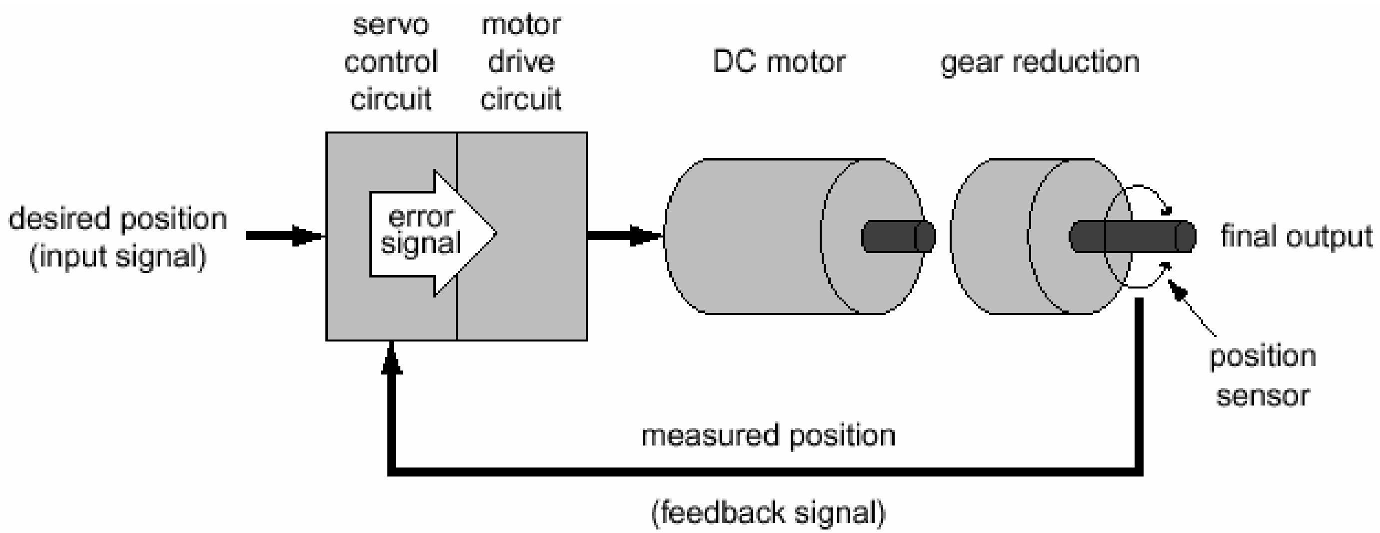
– Power

– Ground

– Control Line

• Power supply is typically 5 to 6 v

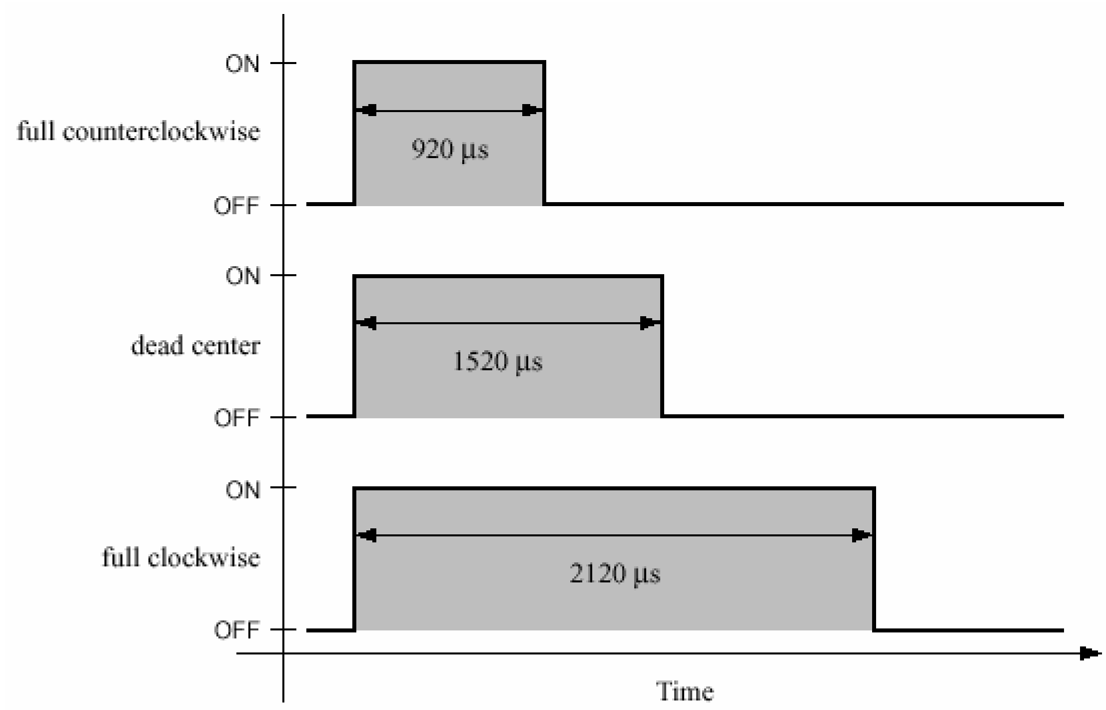
The **input** to the **servo motor** is desired position of the output shaft. This signal is compared with a **feedback signal** indicating the actual position of the shaft (as measured by position sensor). An **“error signal”** is generated that directs the motor drive circuit to power the motor. The servo’s gear reduction drives the final output.



Servo Motor

Servo Control Signal

- Control line uses a **PWM scheme** for encoding the position signal
- Servo PWM method is different from the speed control PWM
  - Speed control PWM: **overall duty cycle** (i.e, percentage of on-time) determines the speed of the motor
  - Servo PWM: **length of the pulse** is interpreted to signify control value
- Waveforms' length:
  - **920 μs** - full counterclockwise
  - **1520 μs** - center position
  - **2120 μs** - full clockwise



Three sample waveforms for controlling a servo motor

Servo Motor

Servo Control Signal

• To complete the servo control, all that one must do is periodically repeat the individual control pulses

• Servo turns off when pulses stop

• For **Futaba servo motors**, the recommended interval between control pulses is 14 to 20 ms

• Servo Timing Signal

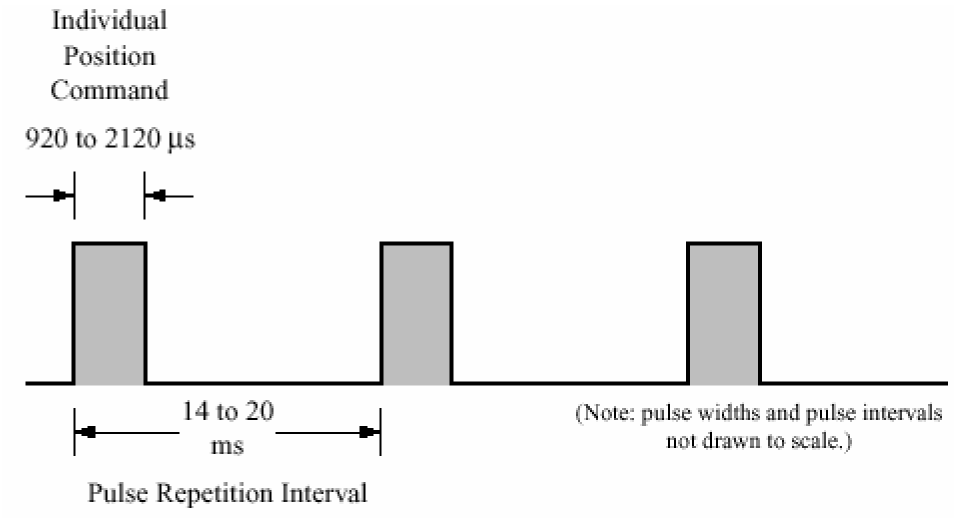
  – Pulse width must be accurate in μs; otherwise servo exhibits **jitter**

  – Interval between pulses may vary 14 - 20 ms; successive pulses need not be exactly same distance apart

• Limits mechanical first, then electrical

  – Electronics will try to drive output shaft to a point beyond mechanical limits

• **Do not plug servo motor in backwards!**



To get the servo motor to continually attempt to reach the desired position, the timing pulse must be repeated at a regular interval

Experiment: find range of motion of different servo motors

Servo Motor

Continuous Rotation - “Winch” Servo

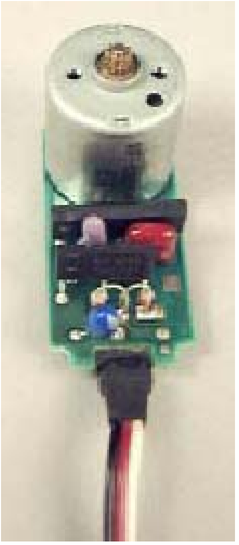
• Servo motor’s output shaft rotates back and forth with a sweep of travel of about 180 degrees

• ***Winch servo*** rotates continuously

– Control signal specifies the speed and direction of rotation, rather than the desired angular position

– Useful for wide variety of applications, including robot’s main drive motors

• Conversion:



– Feedback potentiometer is replaced by a pair of fixed resistors, which mimic the center position of the potentiometer; when the control signal deviates from center, the servo’s control electronics drive the motor one way or the other in a vain attempt to get the servo to move away from center

– Result is that the servo spins continuously with user-controllable speed and direction

• This methods allows both **speed and direction control**: the farther the control signal is away from the center position, the faster the motor turns