Motors and Motion Sensors

07/10/2025
Dr. Jizhong Xiao

MAYFLOWER
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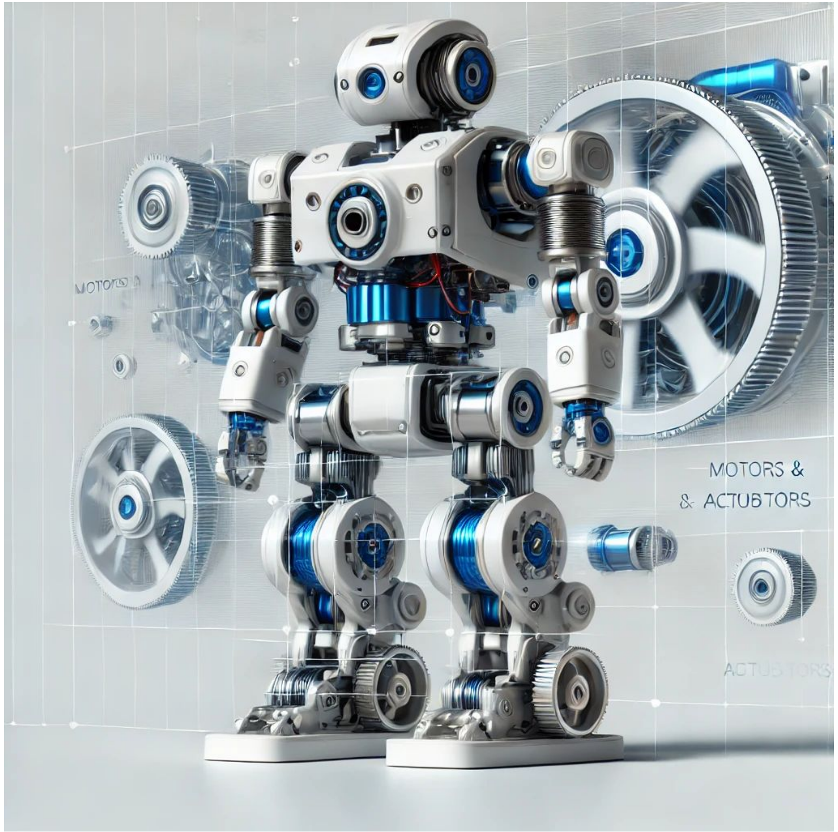
ACADEMY



Outline

1. Robot Actuators
    - Stepper Motor
    - DC Motor
    - Servo Motor
2. Motor Feedback Sensors
    - Rotary Encoder
    - Hall Effect Sensor
3. Motor Speed Control

1

Robot Actuators

Robot Actuators

Stepper motors

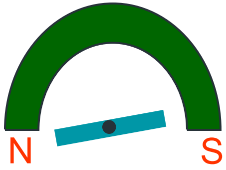
DC motors

Servo motors

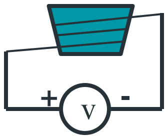
Physics review:

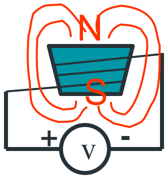
Nature is lazy.

Things seek lowest energy states.
- iron core vs. magnet
- magnetic fields tend to line up

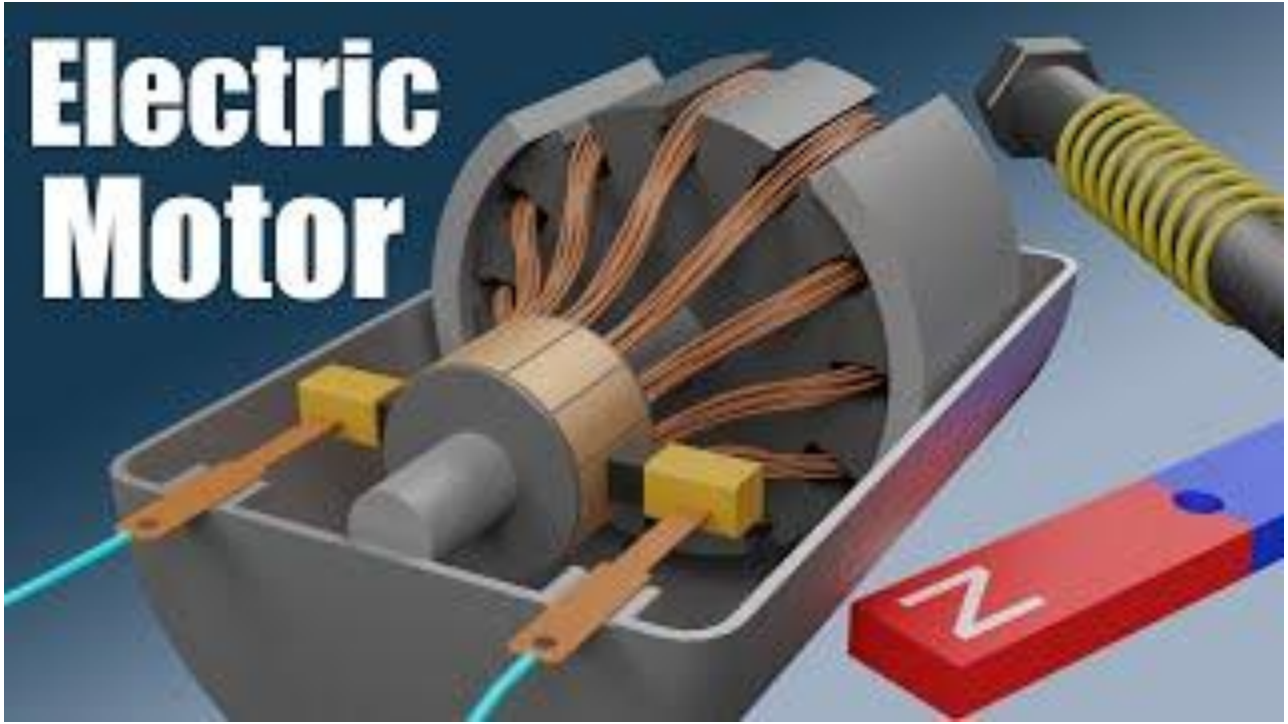


Electromagnetic fields and magnetic fields are the same thing.





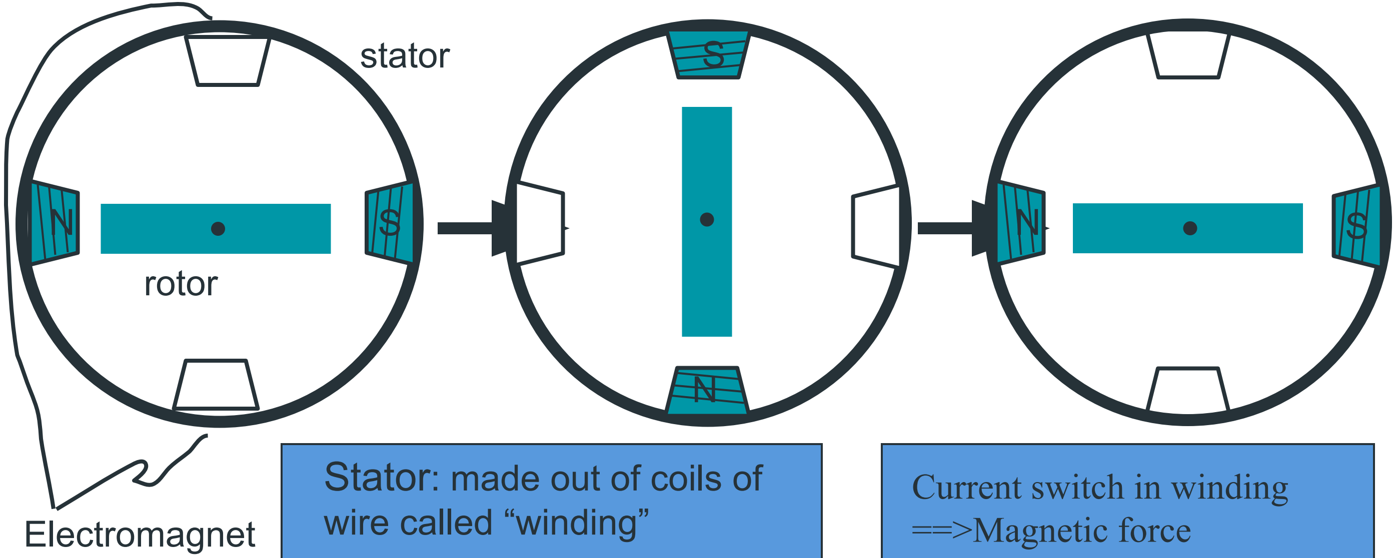
How Electric Motors Work?



1.1

Stepper Motors

Stepper Motor Basics



Stator: made out of coils of wire called "winding"

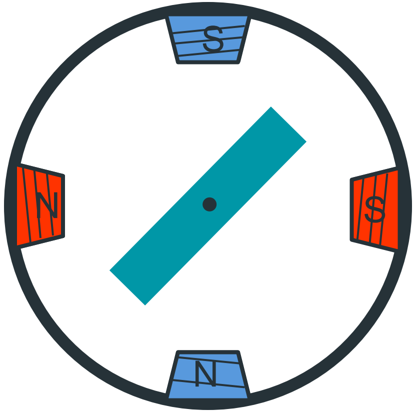
Rotor: magnet rotates on bearings inside the stator

Current switch in winding
==>Magnetic force

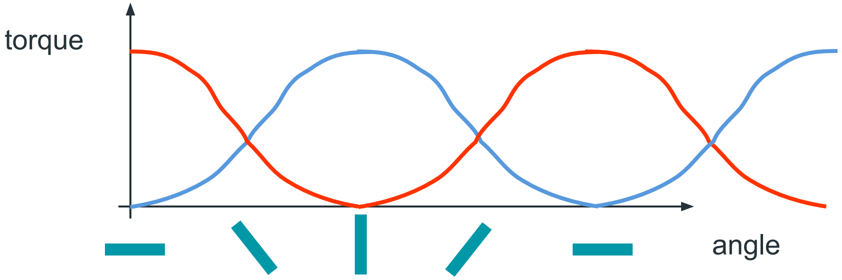
==>hold the rotor in a position

- Direct control of rotor position (no sensing needed) → printers
  computer disk drives
- Low resolution

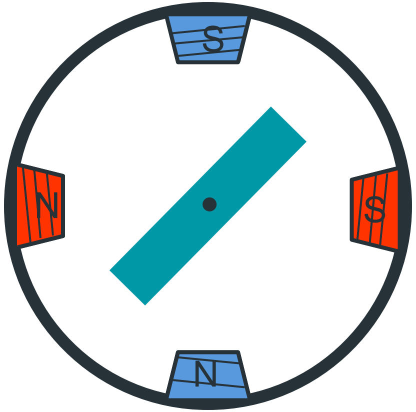
Increased Resolution



Half stepping

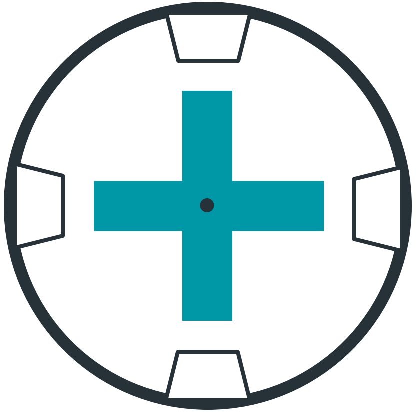


Increased Resolution

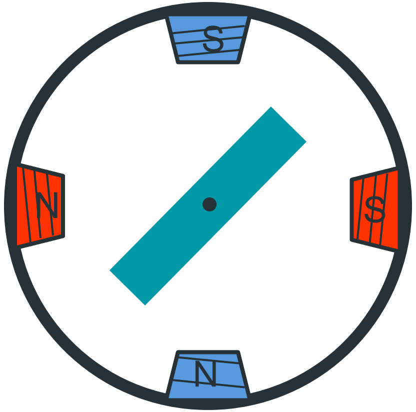


Half stepping

More teeth on rotor or stator

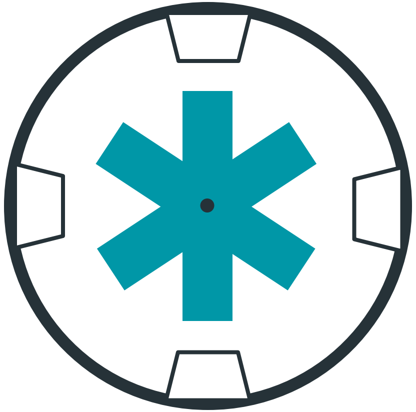


Increased Resolution

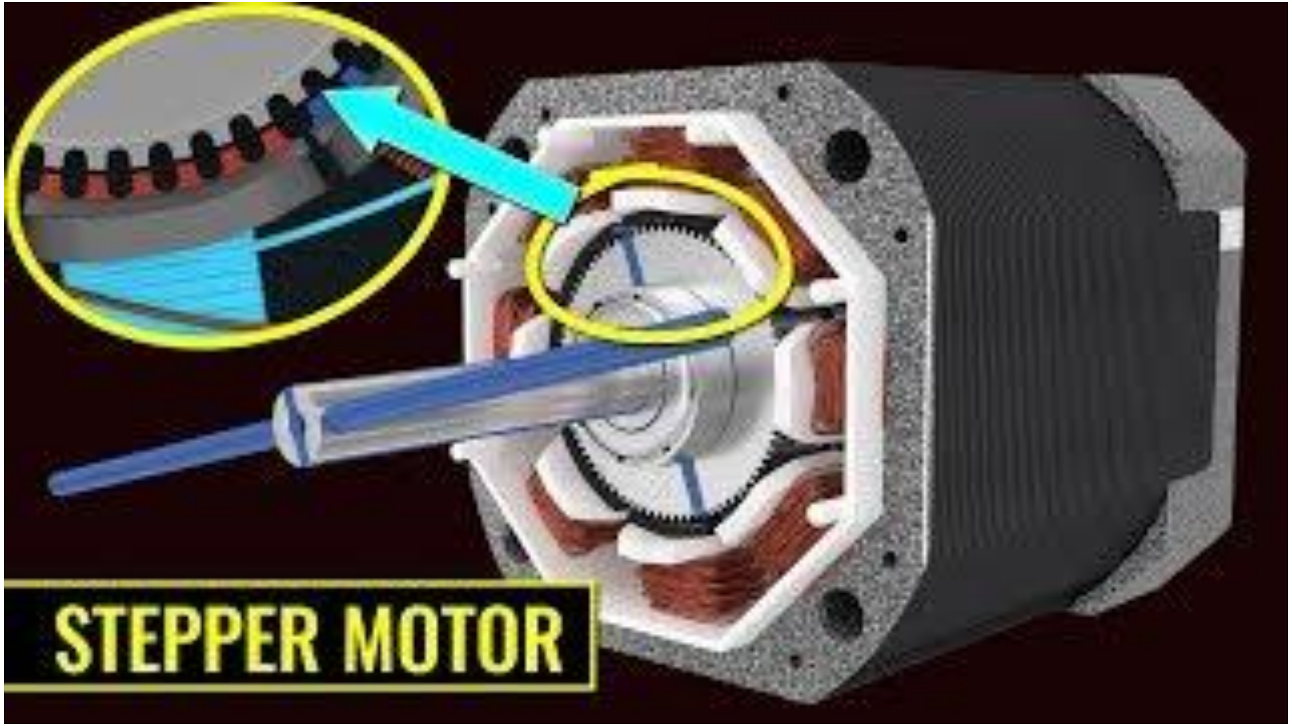


Half stepping

More teeth on rotor or stator



How Does a Stepper Motor Works?

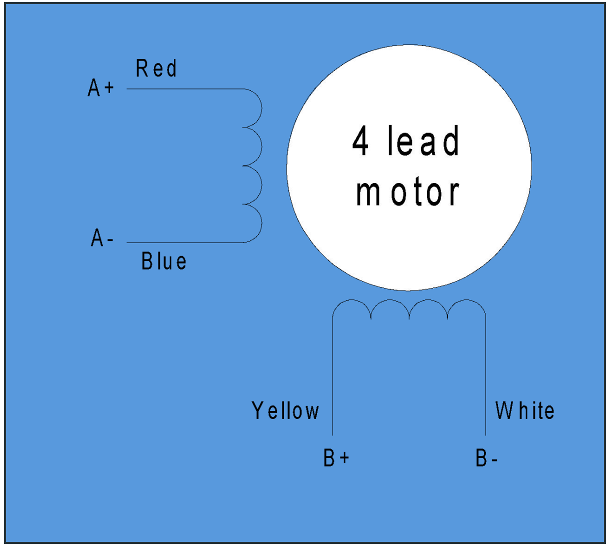


How to Control?

4 Lead Wire Configuration

Step Table				
Step	Red	Blue	Yellow	White
0	+	-	+	-
1	-	+	+	-
2	-	+	-	+
3	+	-	-	+
4	+	-	+	-

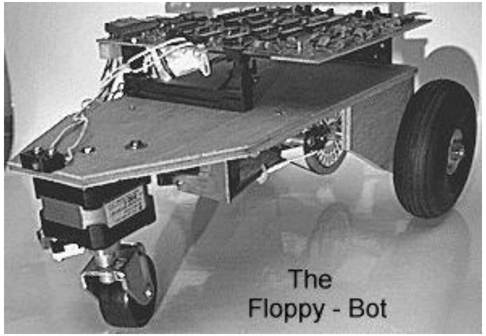
Clockwise Facing Mounting End



Each step, like the second hand of a clock => tick, tick

Increase the frequency of the steps => continuous motion

Motoring along...

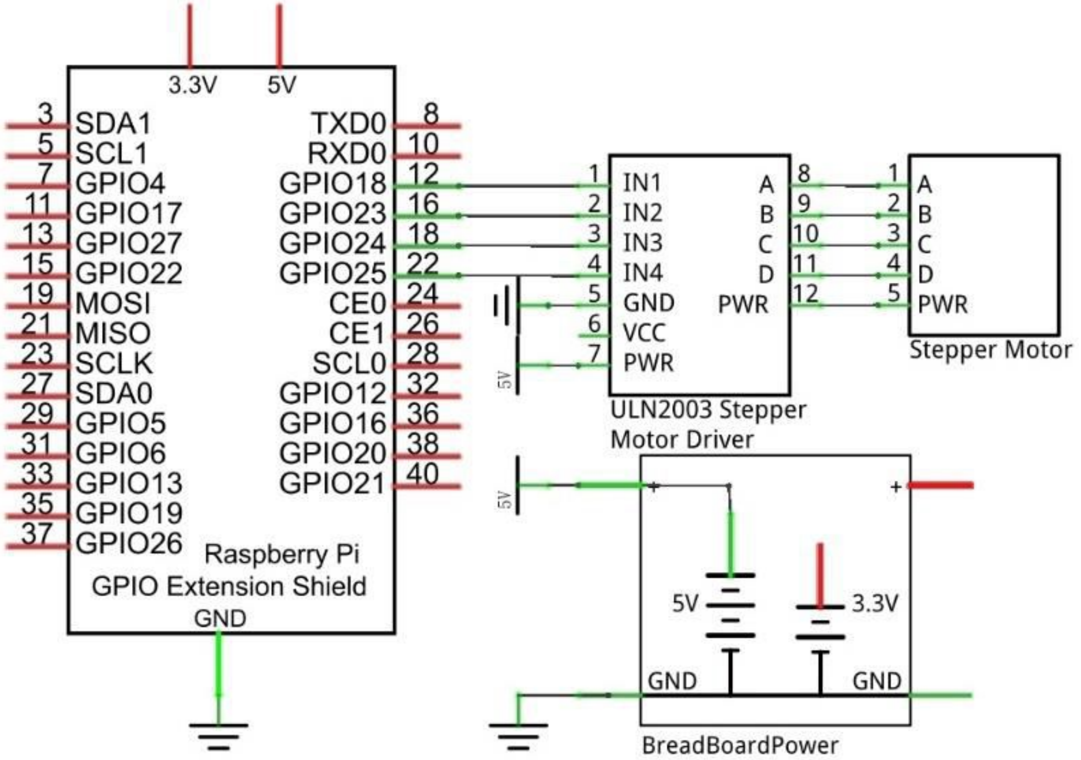


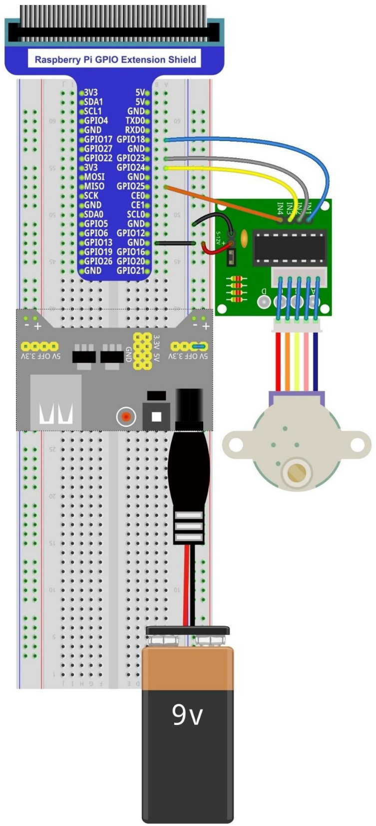
- direct control of position
- precise positioning (The amount of rotational movement per step depends on the construction of the motor)

- Easy to Control
- under-damping leads to oscillation at low speeds
- torque is lower at high speeds than the primary alternative…

Stepper Motors Explained

Project 16: Stepper Motor Experiment

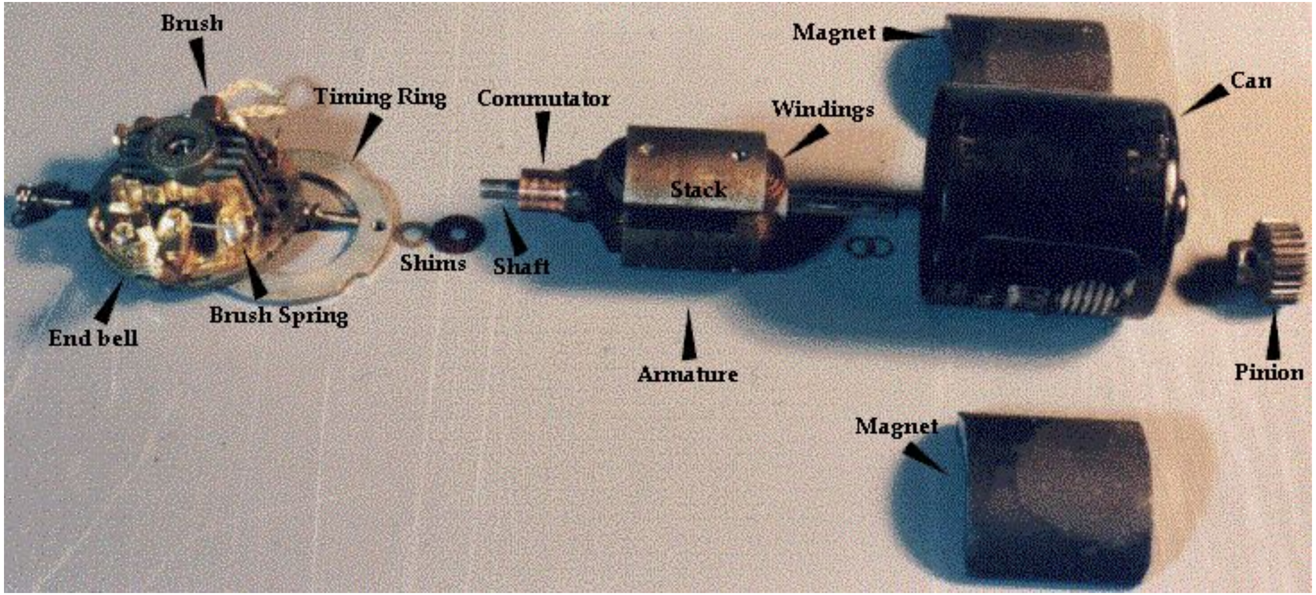




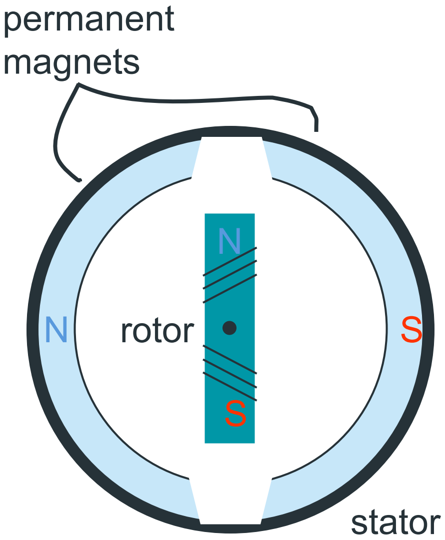
1.2

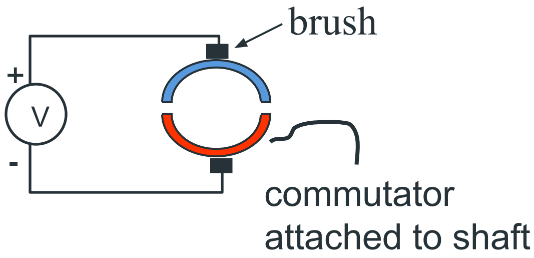
DC Motors

DC motors -- exposed !

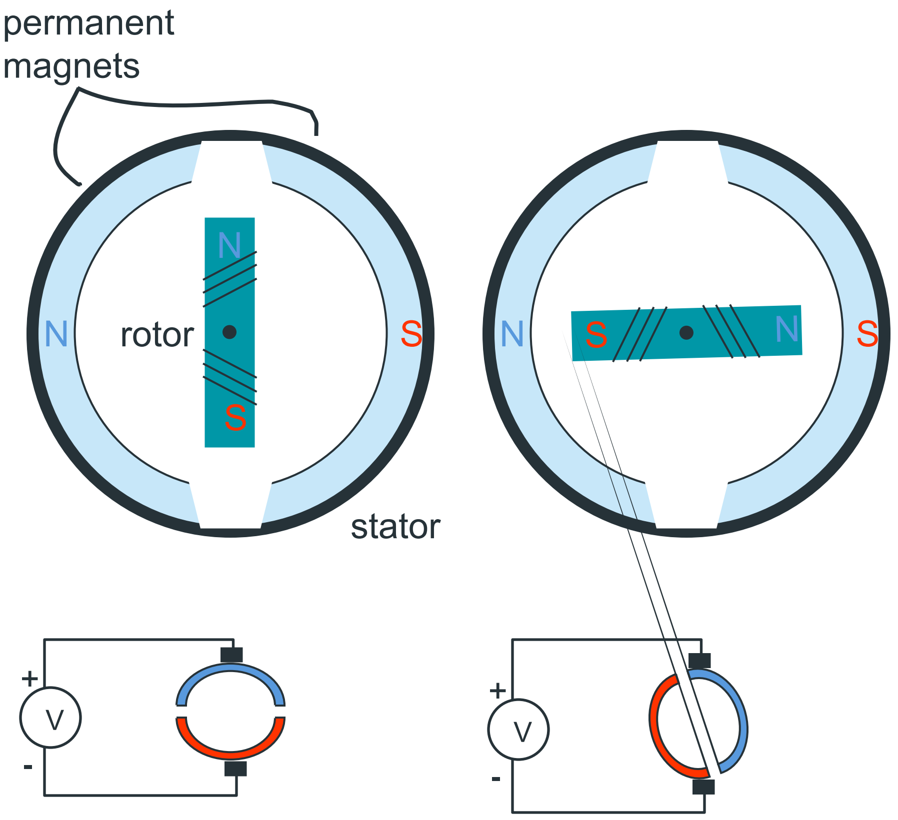


DC motor basics

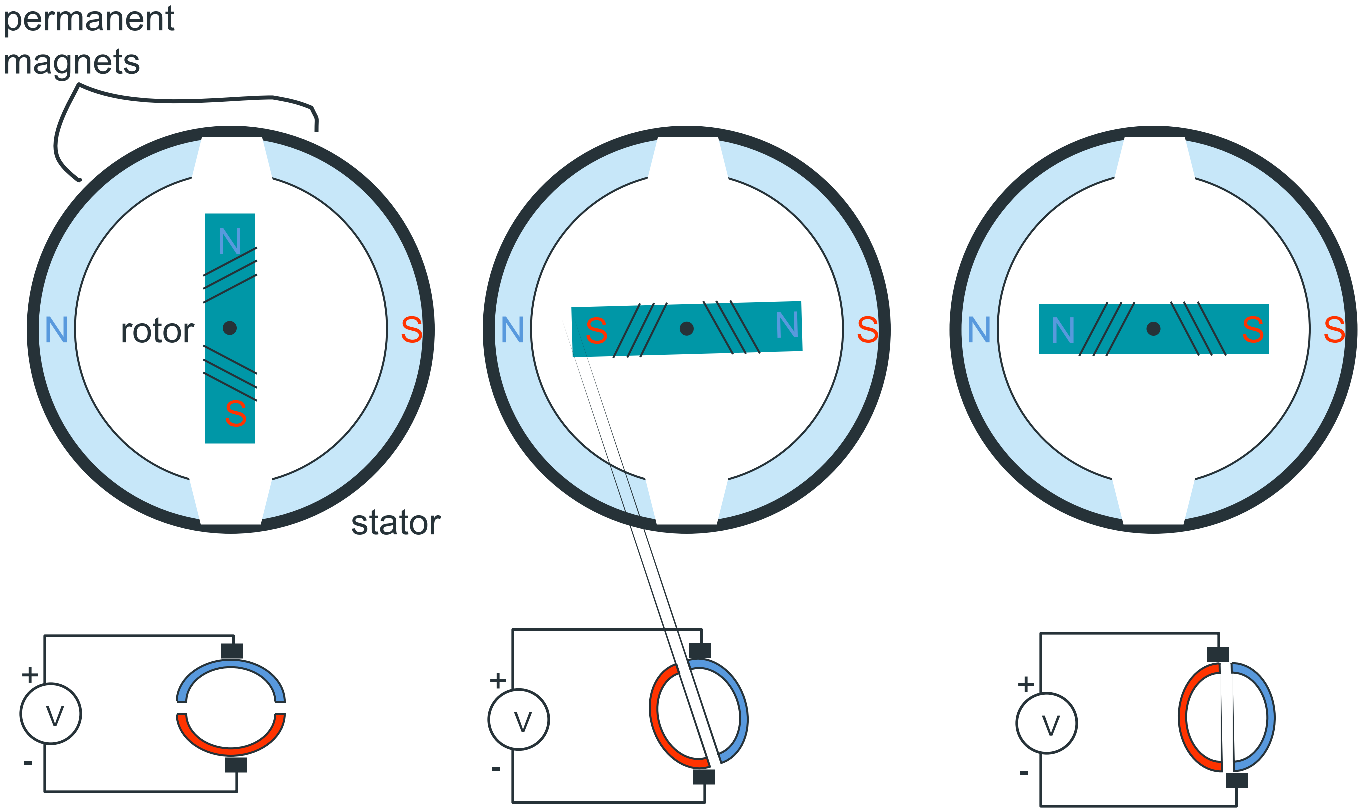




DC motor basics

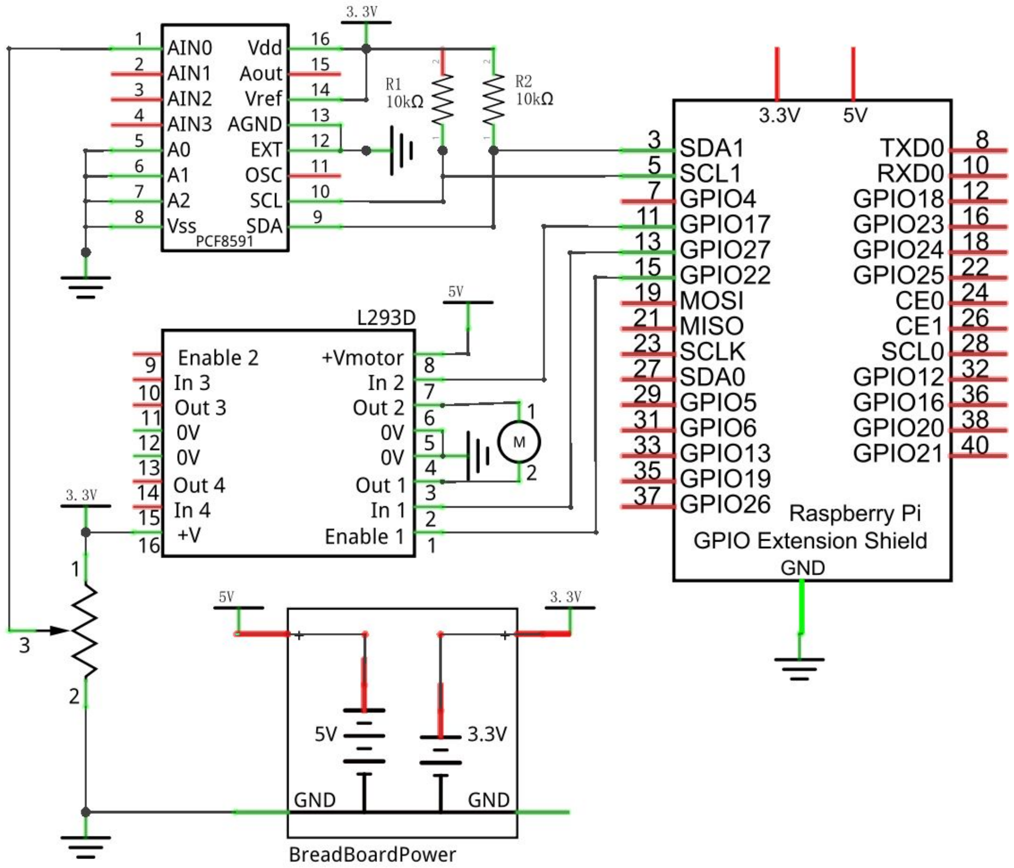


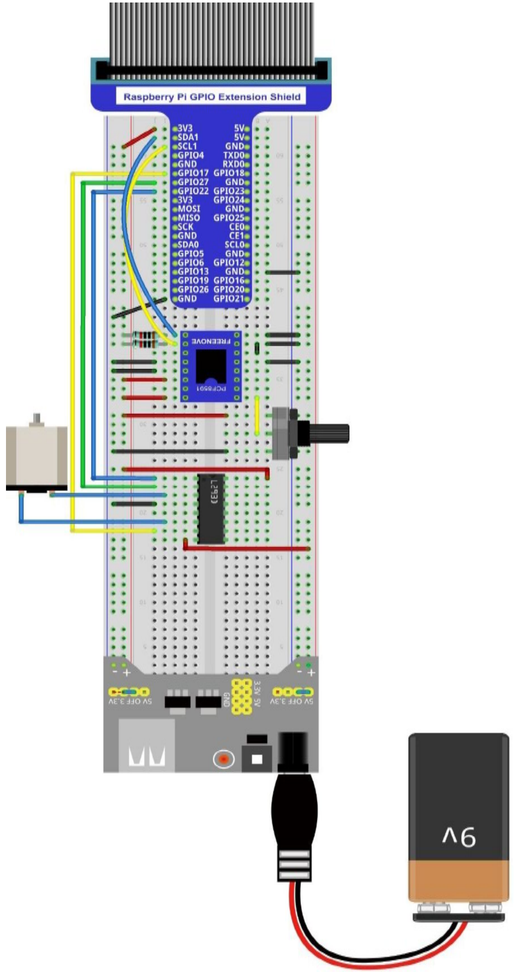
DC motor basics



DC Motors Explained

Project 13: DC Motor and Driver



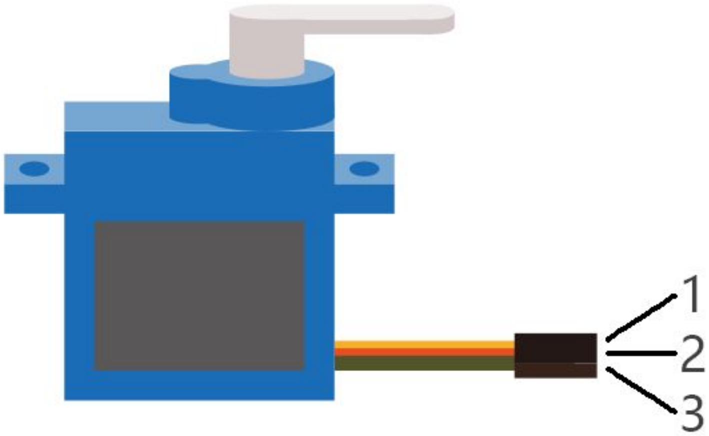


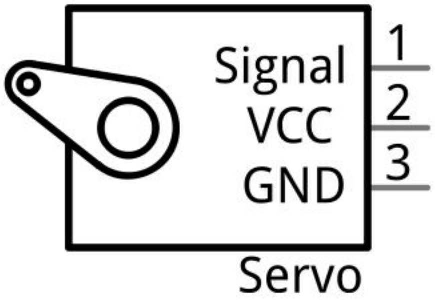
1.3

Servo Motors

Servo motor

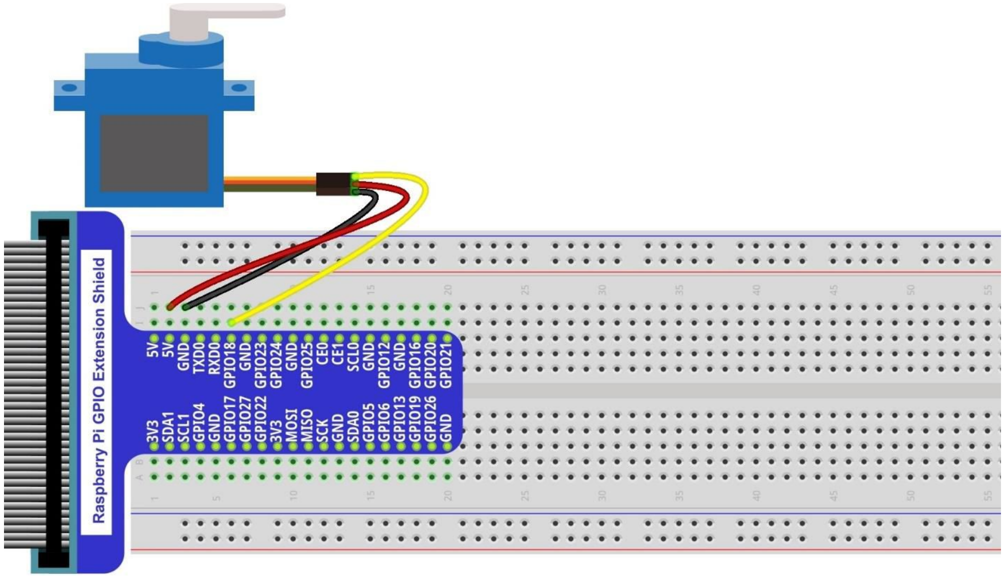
- Compact package which consists of a DC Motor, a set of reduction gears to provide torque, a sensor for position feedback (potentiometer or encoder), and a closed-loop controller that uses position feedback to control its motion and final position.
- Servos can output higher torque than a simple DC Motor alone and they are widely used to control motion in toys, robots, etc.
- Servos have three wire leads, VCC, GND and servomotor signal
- Use a PWM signal with a duty cycle in a certain range to drive the Servo to the designated angle

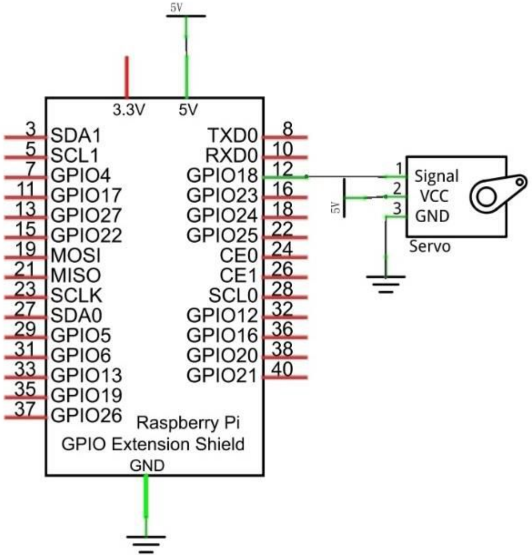




Servo Motors Explained

Project 15: Servo Motor Experiment





2

Motor Feedback Sensors

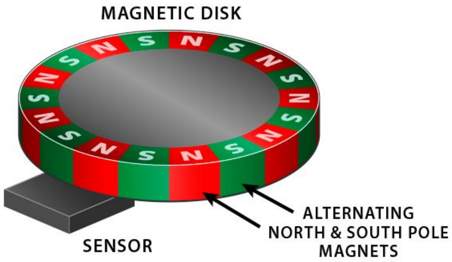
Encoders

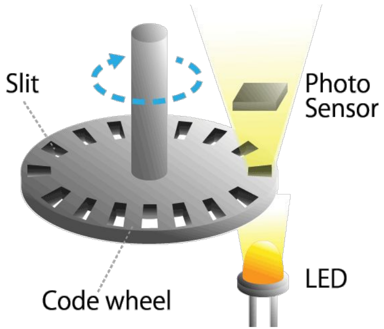
Encoders continually measure the rotation of the motor

Gives us a way to tell how **far** and **fast** we are traveling!

Magnetic vs Optical Encoders

- Hall Effect Sensors





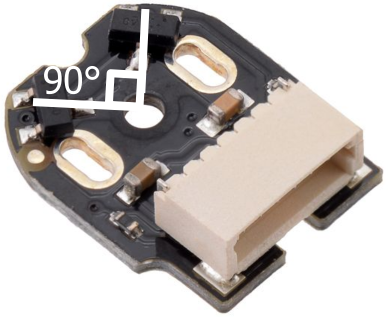
Magnetic Encoders

Senses change in rotational position as motor spins

6 pole magnetic disk (60° between each pole)

2 Hall Effect Sensors (90° between each sensor

- Detects the presence of a magnetic field



Hall Effect: Production of a voltage difference from a current and a magnetic field

Motor Position Sensors

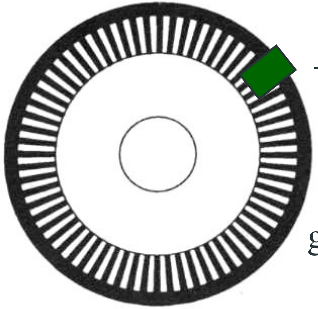
- Optical Encoders
  - Relative position
  - Absolute position
- Hall Effect Sensors

2.1
Incremental Encoder

Optical Encoders

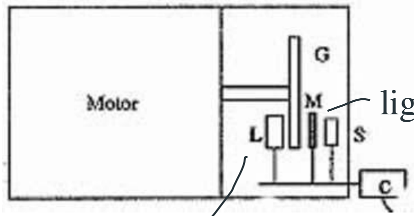
- Relative position

- direction
- resolution



grating

light emitter

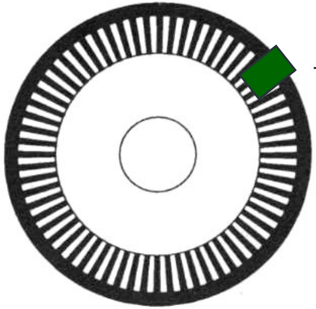


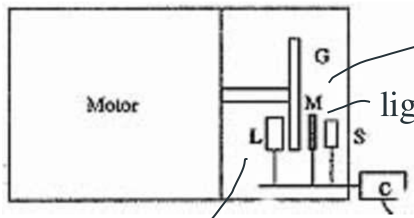
light sensor

decode circuitr y

Optical Encoders

- Relative position





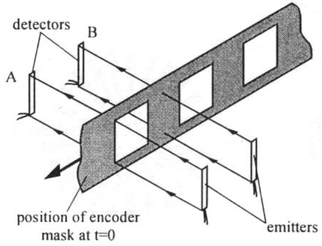
mask/diffuser

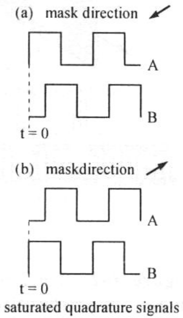
light sensor

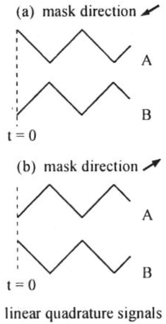
light emitter

decode circuitr y

grating







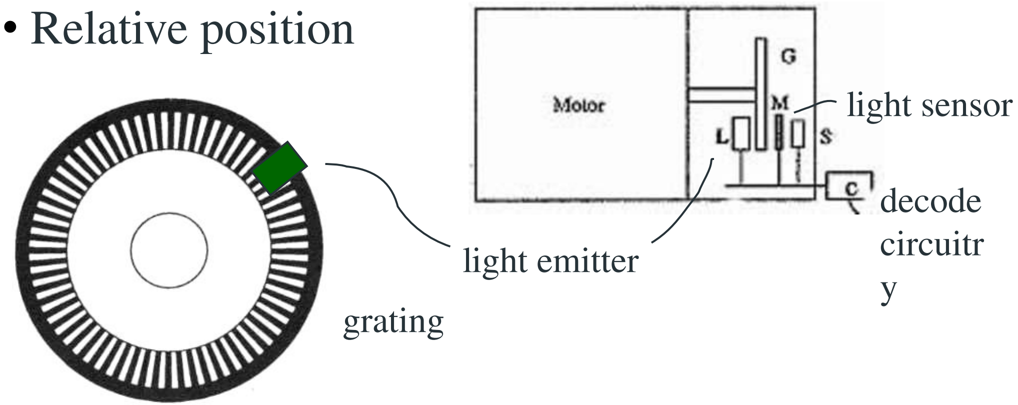
A diffuser tends to smooth these signals

Ideal

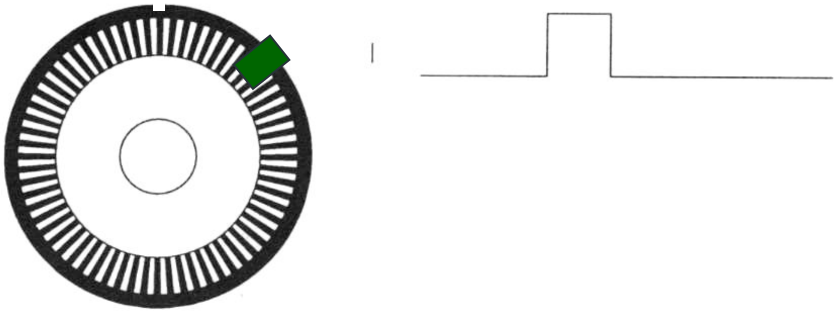
Real

Optical Encoders

- Relative position

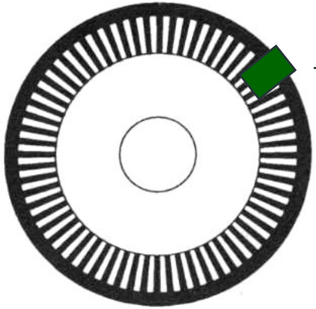


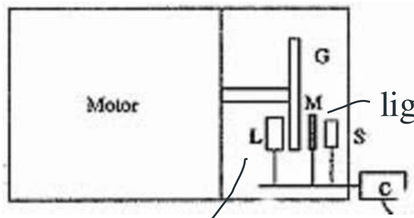
- direction
- resolution



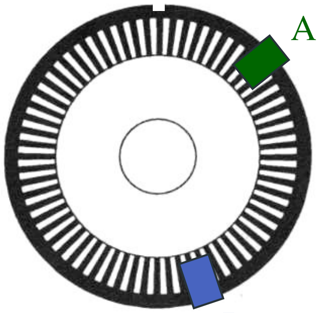
Optical Encoders

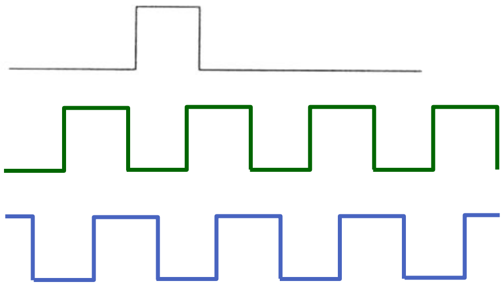
- Relative position





- direction
- resolution

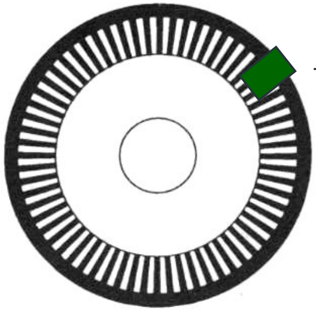




A lags B

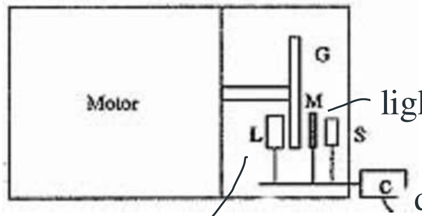
Optical Encoders

- Relative position



grating

light emitter

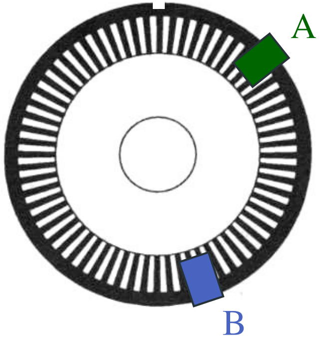


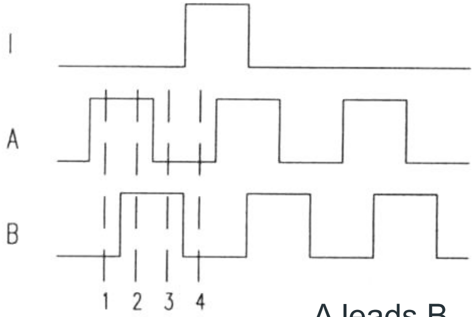
light sensor

decode circuitr
y

- direction
- resolution

Phase lag between A and B is 90 degree





State	Ch A	Ch B
S_1	High	Low
S_2	High	High
S_3	Low	High
S_4	Low	Low

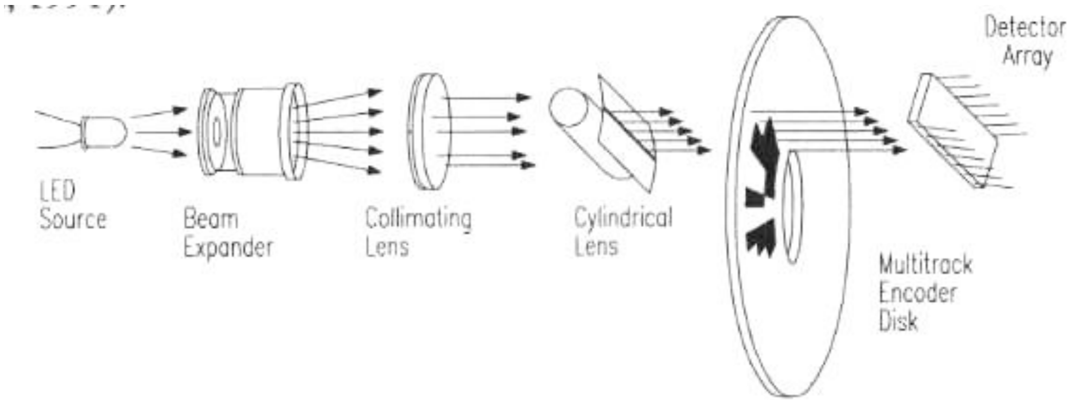
A leads B

Incremental Encoder

2.2 Absolute Encoder

Optical Encoders

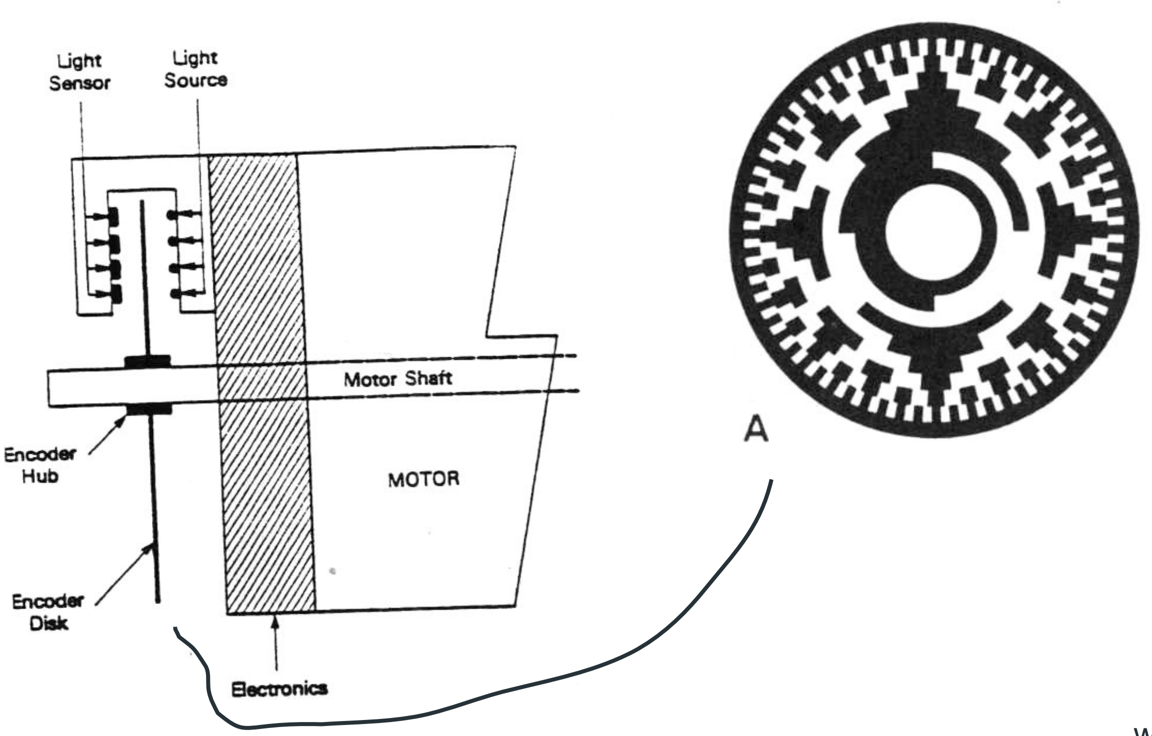
- Detecting absolute position



something simpler ?

Absolute Encoders

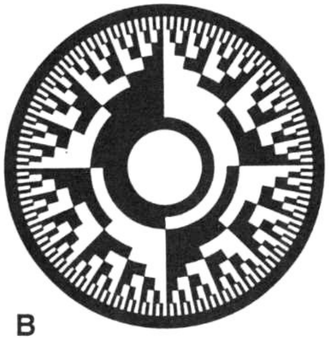
- Detecting absolute position

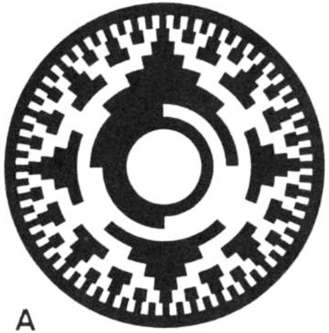


wires ?

Gray Code

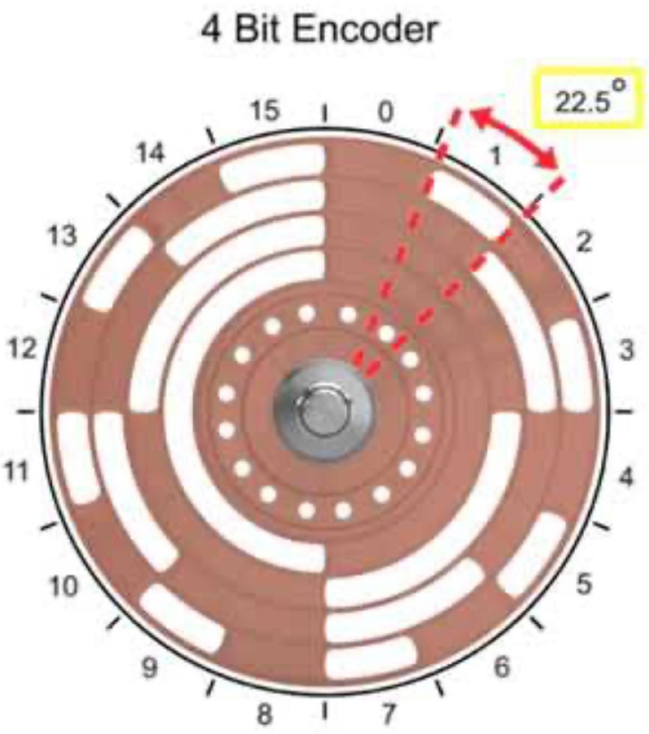
#	Binary	
0	0	000
1	1	001
2	10	011
3	11	010
4	100	110
5	101	111
6	110	101
7	111	100
8	1000	
9	1001	


B


A

among others...

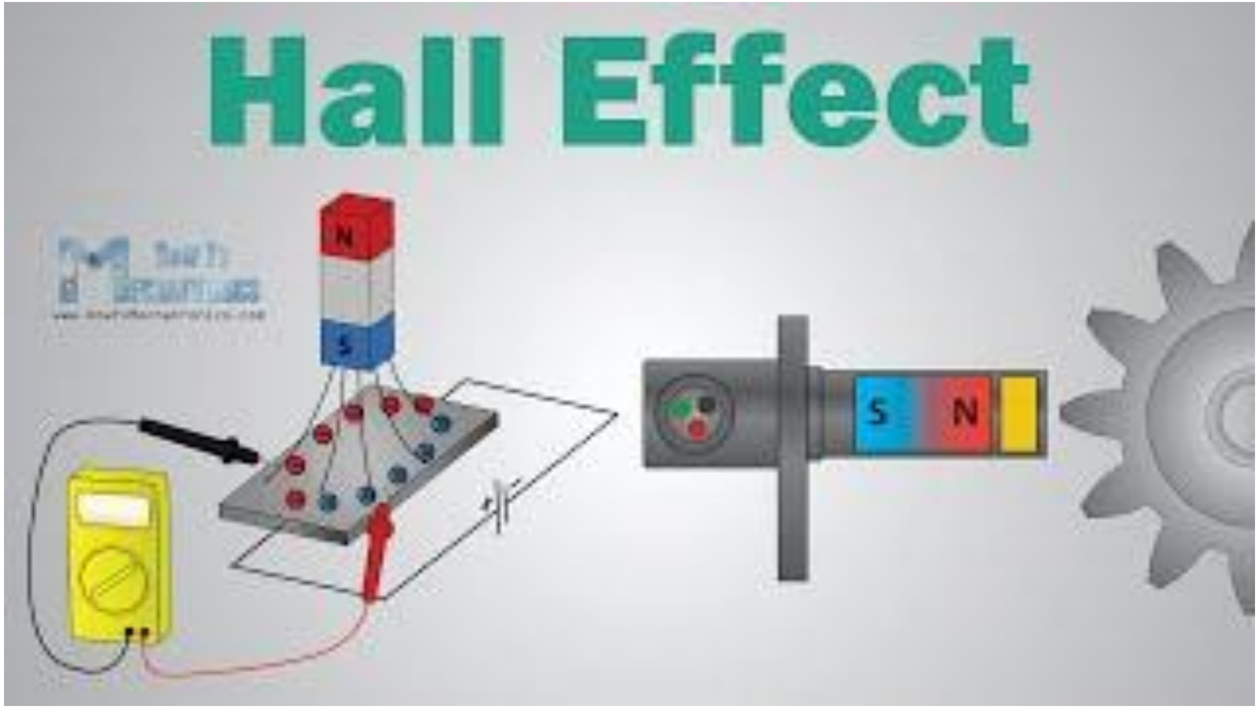
Absolute Encoder



Incremental v.s. Absolute Encoder

2.3
Hall Effect Sensors

Hall Effect and Hall Effect Sensors



3

Motor Control

Motor Control

Control: getting motors to do what you want them to

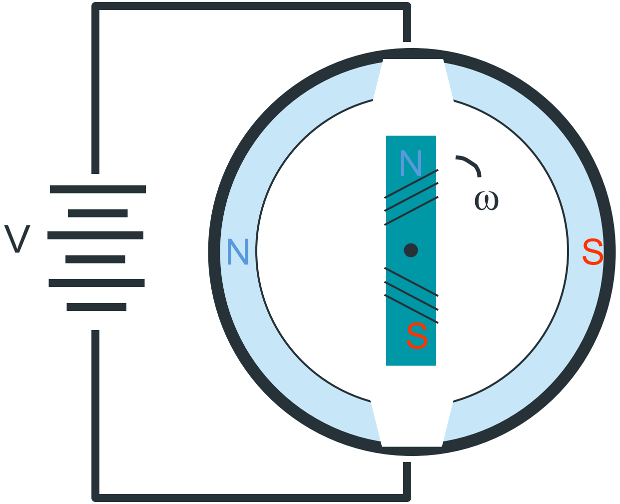
What you want to control $\neq$ what you can control

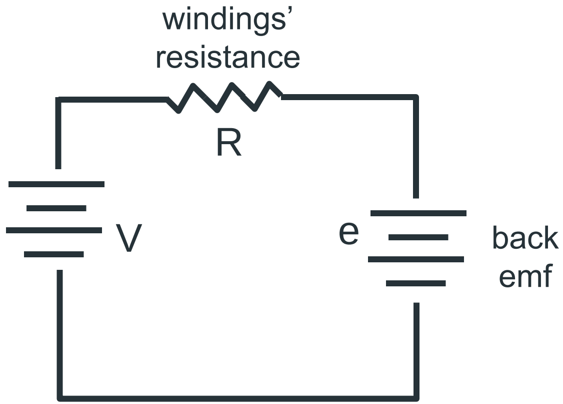
For DC motors:

speed

voltage

Equivalent Circuit □





e is a voltage generated by the rotor windings cutting the magnetic field

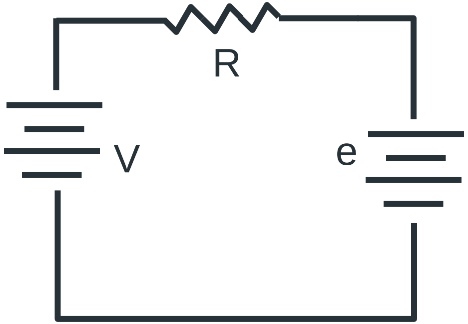
emf: electromagnetic force

Controlling speed with voltage

- The back emf depends only on the motor speed.
- The motor's torque depends only on the current, I.

$$e = k_e\ \omega$$

$$\tau = k_\tau\ I$$



DC motor model

Equivalent Circuit

Controlling speed with voltage

- The back emf depends only on the motor speed.

$$e = k_e\,\omega$$

- The motor's torque depends only on the current, I.

$$\tau = k_\tau\, I$$

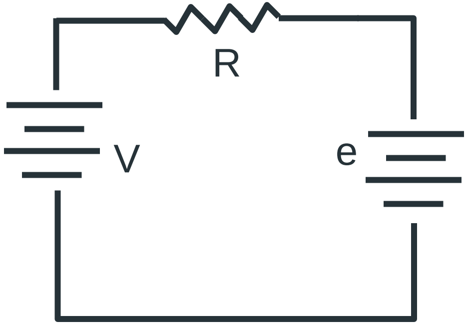
$I_{stall} = V/R$
current when motor is stalled

speed = 0
torque = max

- Consider this circuit's V:

$$V = IR + e$$

How is V related to ω ?



Equivalent Circuit

$$V = \frac{\tau R}{k_\tau} + k_e\,\omega$$

- or -

$$\omega = -\frac{R}{k_\tau k_e}\,\tau + \frac{V}{k_e}$$

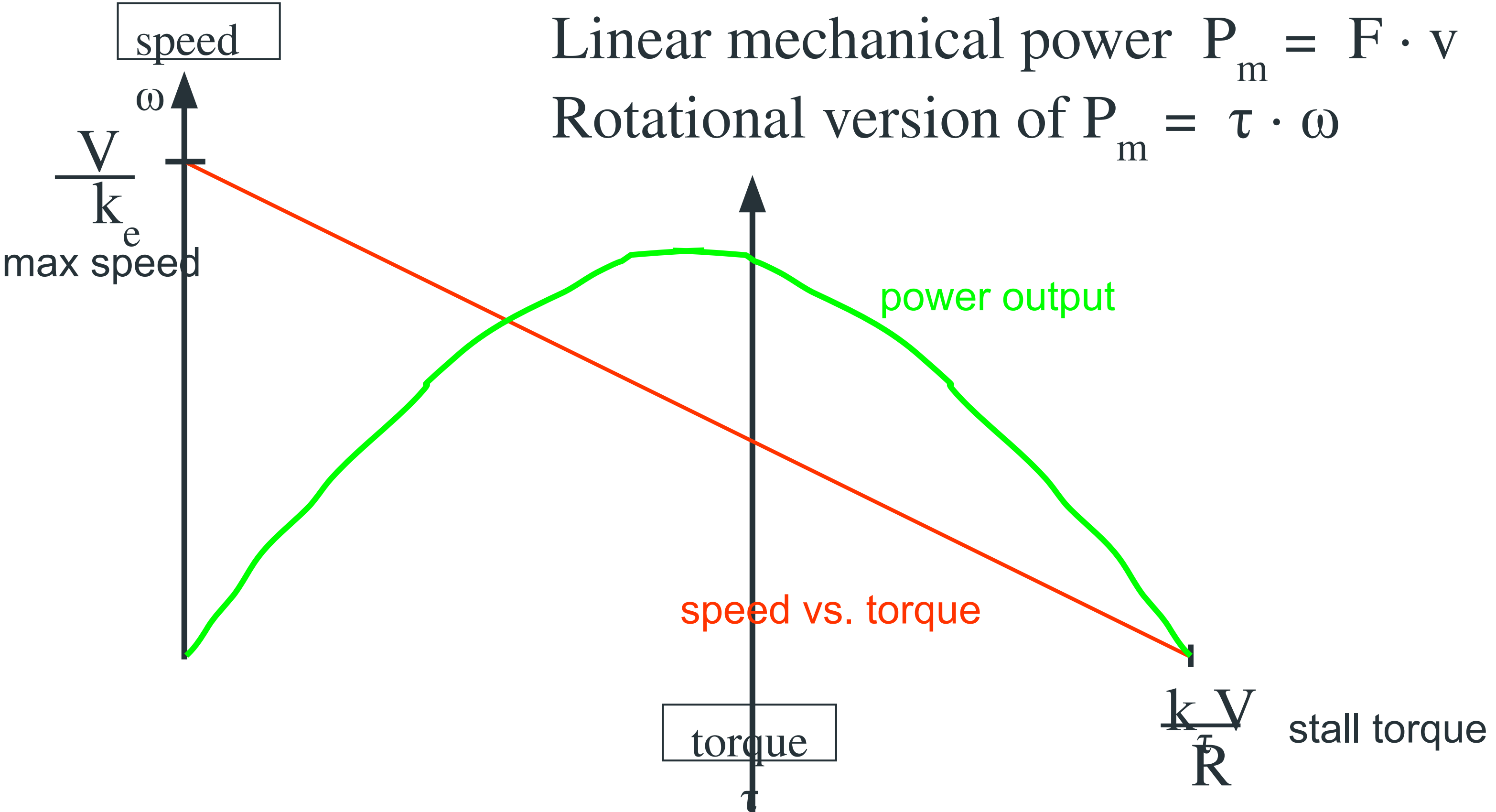
DC motor model

Speed is proportional to voltage.

speed vs. torque at a fixed voltage

Linear mechanical power $P_m = F \cdot v$

Rotational version of $P_m = \tau \cdot \omega$



Motor specs

FAULHABER
MicroMo Electronics, Inc.
About MicroMo
Products
Application Notes

Electrical Specifications (@22°C)

For motor type 1624		**003S**	**006S**	**012S**	**024**	
--------------------------	--------	--------	--------	---------		-------
nominal supply voltage	(Volts)	3	6	12	24	
armature resistance	(Ohms)	1.6	8.6	24	75	
maximum power output	(Watts)	1.41	1.05	1.50	1.92	
maximum efficiency	(%)	76	72	74	74	
no-load speed (rpm)	12,000	10,600	13,000	14,400		
no-load current (mA)	30	16	10	6		
friction torque (oz-in)	.010	.011	.013	.013		
stall torque	(oz-in)	.613	.510	.600	.694	
velocity constant (rpm/v)	4065	1808	1105	611		
back EMF constant	(mV/rpm)		.246	.553	.905	1.635
torque constant (oz-in/A)	.333	.748	1.223	2.212		
armature inductance	(mH)	.085	.200	.750	3.00	

k_e

k_τ

Back to control

Basic input / output relationship:

$$V = \frac{\tau R}{k_\tau} + k_e \omega$$

We can control the voltage applied V.

We want a particular motor speed ω .

How to change the voltage?

V is usually controlled via PWM -- “pulse width modulation”

3

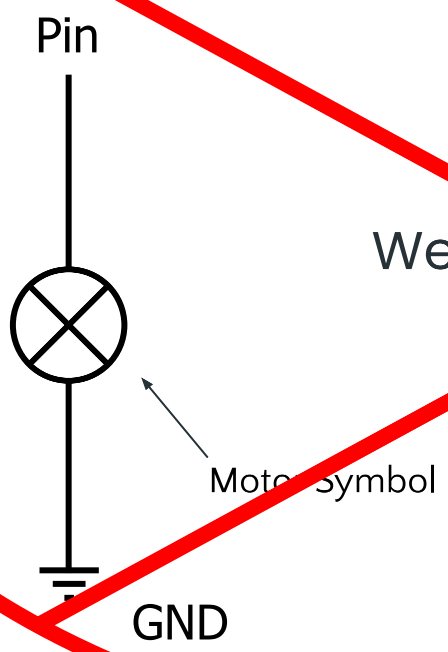
DC Motor Control

Turning the motors on and off, controlling
the motor’s direction and speed

Checklist for Motor Control

- ❑ Motor On/Off State
- ❑ Motor Direction
- ❑ Motor Speed

Motor On/Off State



We can connect the motors directly to the output pins on the microcontroller

Motor On/Off State

We can't power the motor directly from the MCU!!

Why? Not enough voltage or current from the MCU

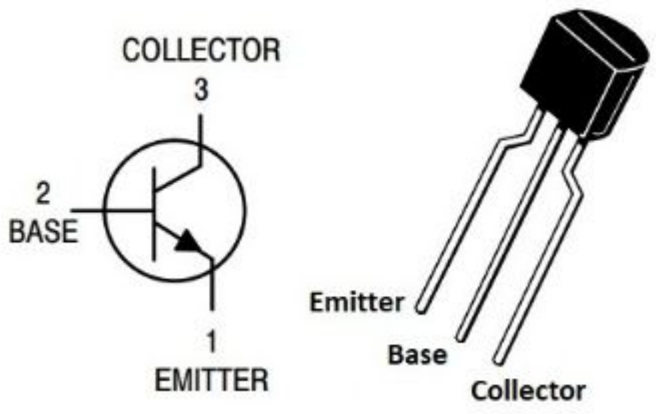
Big boi battery power

MCU power

Motors require at least 6V and can draw up to 0.67A

MCU can only supply 3.3V and relatively little current

(Part of) The Solution: Transistors



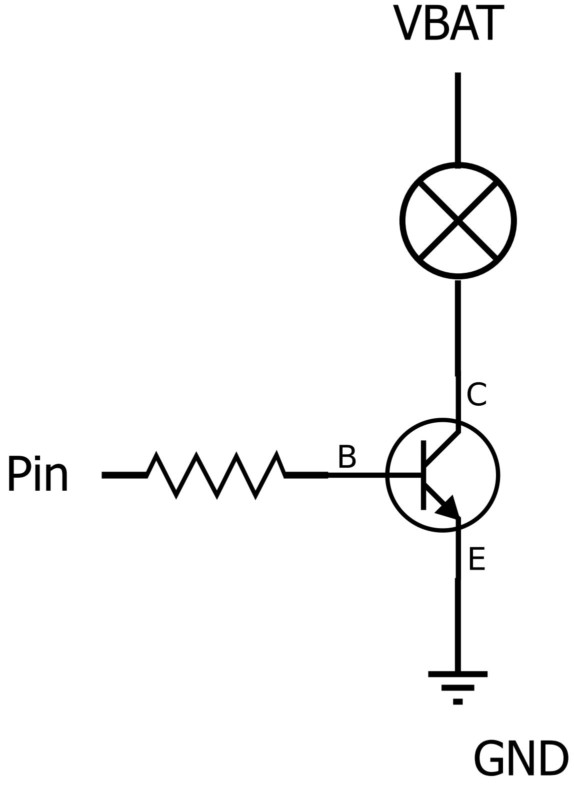
When voltage is applied to the base, current is allowed to flow between the collector and the emitter.

The NPN transistor acts as a normally open switch

Similar to relays, except faster and better suited for smaller applications

(Part of) The Solution: Transistors

We can control the on and off state of the motor from the MCU using an NPN transistor!

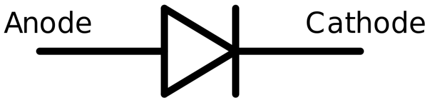


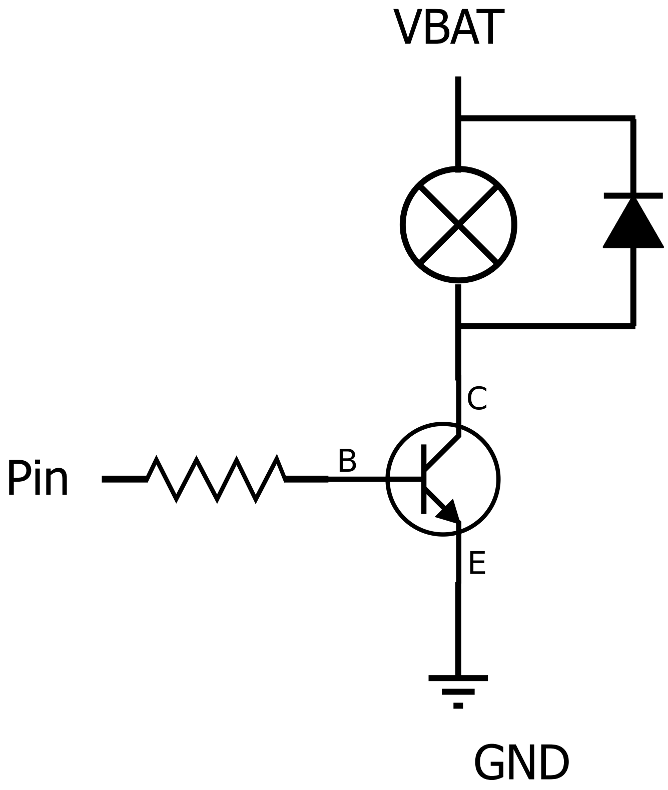
Flyback Diode

Recall that motors involve creating magnetic fields… Inductance!

Turning motors off results in a temporary voltage spike to maintain current (back emf)

Diode: allows current to flow in ONE direction



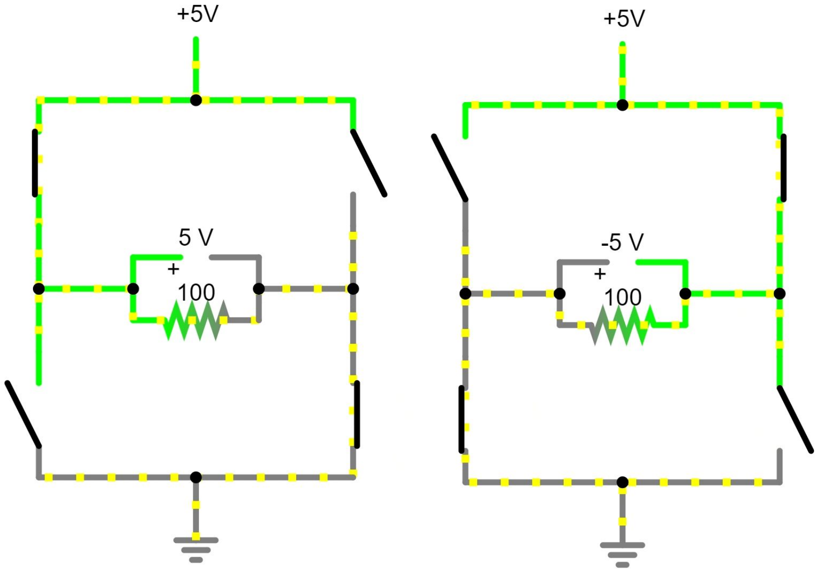


Checklist for Motor Control

- ✓ Motor On/Off State
- Motor Direction
- Motor Speed

We can take advantage of this fact to create a circuit called an H-Brid

https://tinyurl.com/yxn
yk4



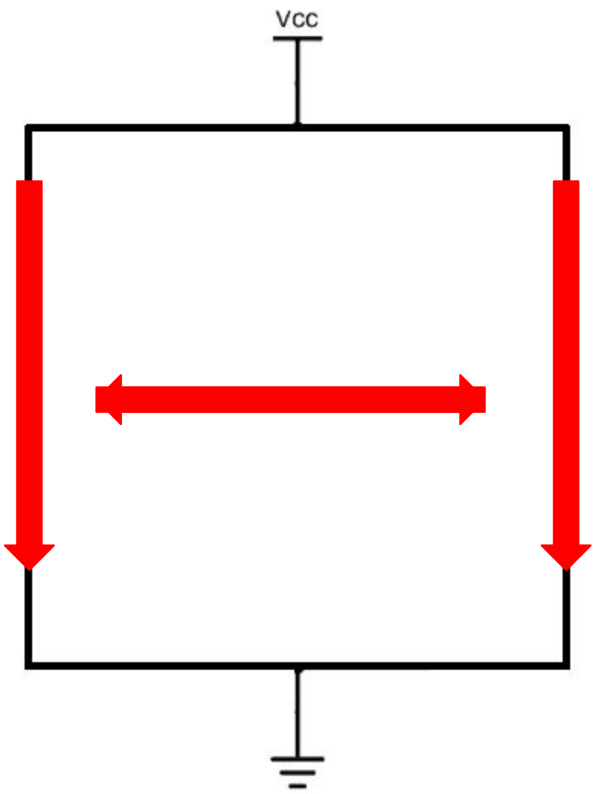
H-Bridge

Four Transistors, Four Flyback Diodes

Turning on Q1 and Q4 ⇒ current flows through the motor to the **right.**

Turning on Q2 and Q3 ⇒ current flows through the motor to the **left.**

Turning on all four transistors results in a short circuit - **Don't do it!**



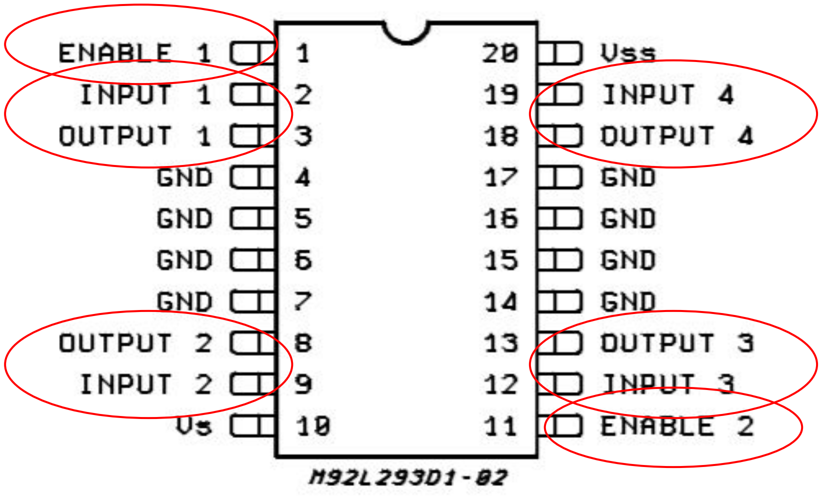
Dual H-Bridges

One IC to control two motors!

Four **Inputs**: each input is connected to two transistors (i.e input 1 turns on Q1 and Q4)

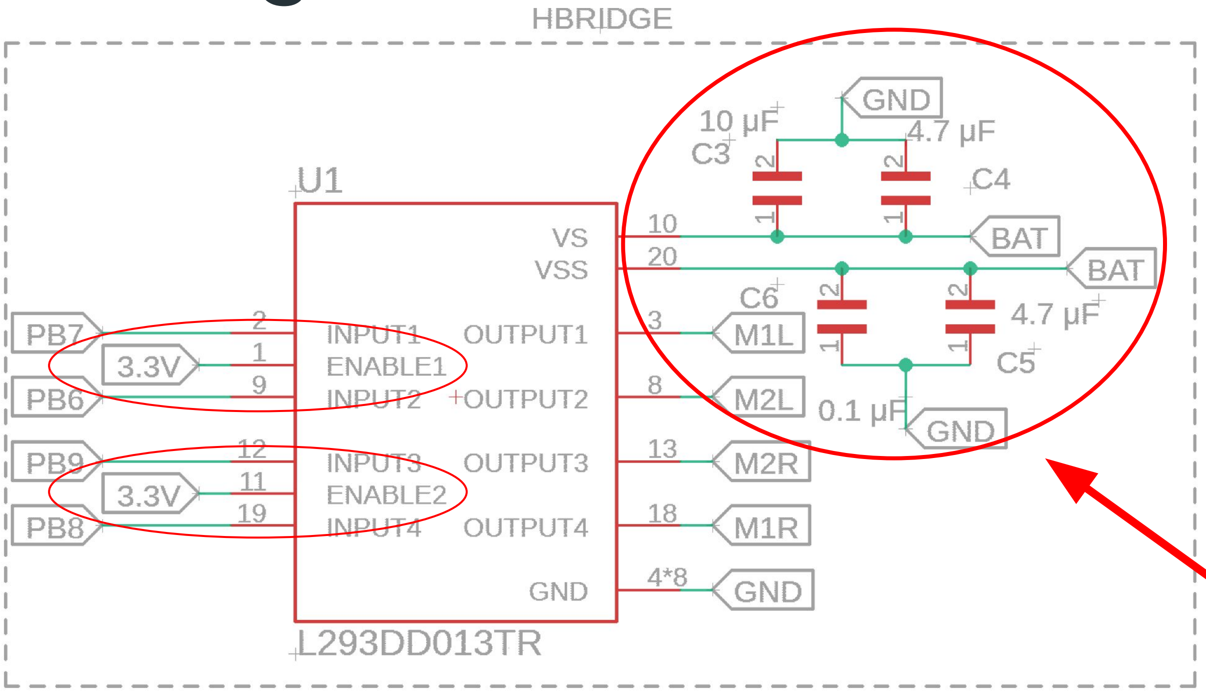
Four **Outputs**: two outputs to connect to each motor

Enable Pins: activate the H-Bridge and allow us to turn on the transistors



L293DD H-Bridge

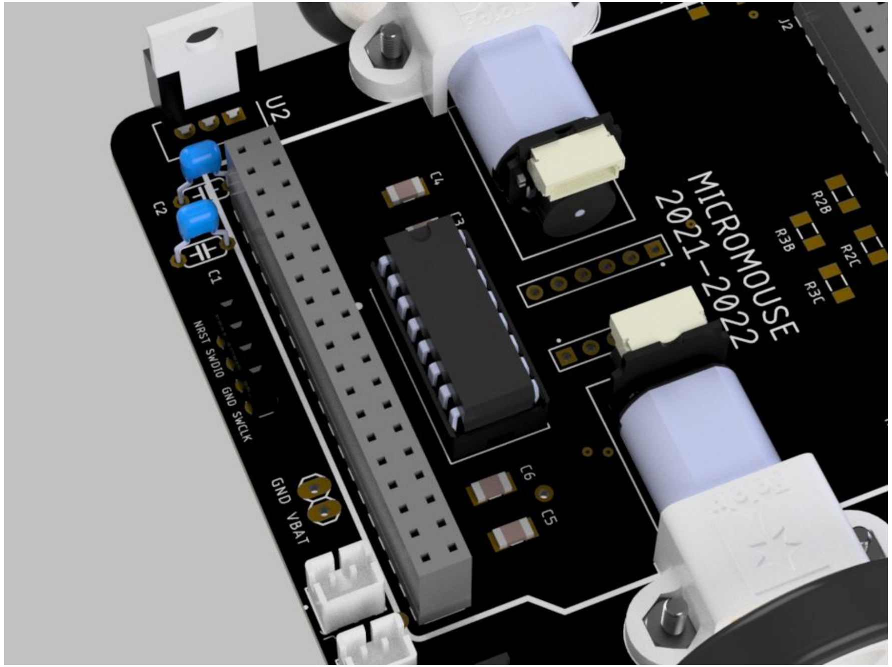
Dual H-Bridges



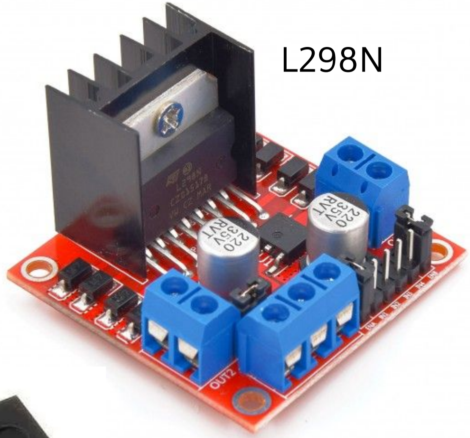
Decoupling Capacitors:

Low pass filter to remove noise

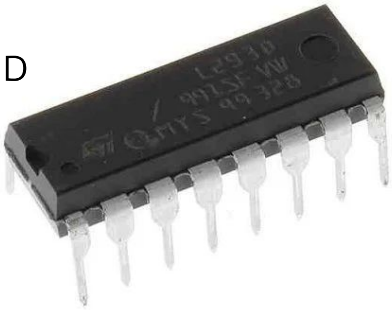
The Physical H-Bridge ICs



L298N



L293D



Checklist for Motor Control

- ✓ Motor On/Off State
- ✓ Motor Direction
- ☐ Motor Speed

The Problem: Motor Speed

Since we are directly connecting the motors to the battery voltage, we only have two speeds -> 0% and 100%

How do we tell the motors to go 50% speed? 75%?

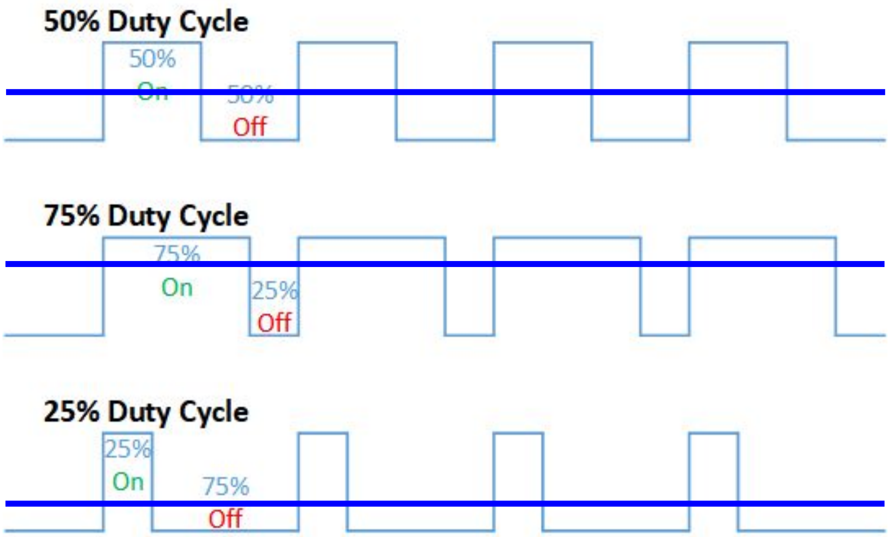
PWM

We can rapidly mix on and off inputs to create a range of voltages

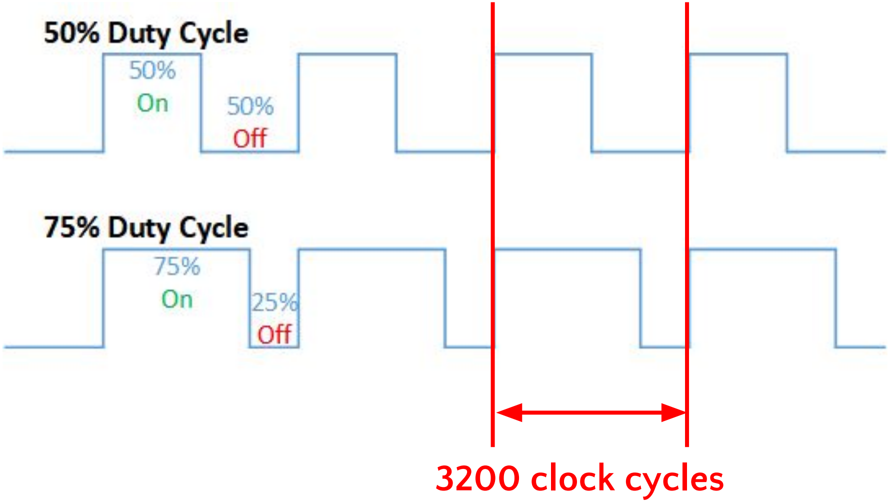
Motors have inertia, so they respond slowly to rapid voltage changes

Quick Vocab Terms:

- PWM: Pulse-Width Modulation
- Duty Cycle: % of time in the ON state
- Frequency: # of cycles per second



PWM on our MCU



Implemented using Timers!

MCU Clock Speed 16 MHz

H-Bridge Max Frequency 5 kHz

Counter Period: 16 MHz / 5 kHz = **3200 clock cycles**

Pulse Value: Clock cycles to stay on per period

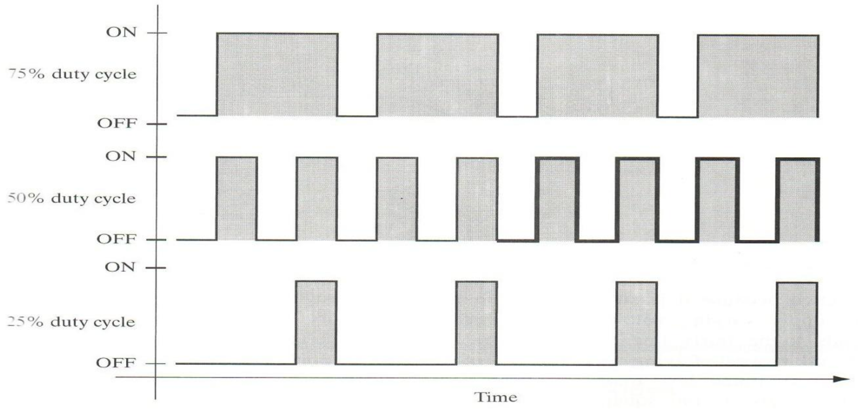
Ex. 75% duty cycle ⇒ 2400 clock cycles on, 800 off

Checklist for Motor Control

- ✓ Motor On/Off State
- ✓ Motor Direction
- ✓ Motor Speed

PWM

- PWM -- “pulse width modulation



- Duty cycle:
    - The ratio of the “On time” and the “Off time” in one cycle
    - Determines the fractional amount of full power delivered to the motor