Lecture 14

DC Motors and driving them

Agenda

00. Review Lab 4: Mobility

01. MOSFETS/BJT recap

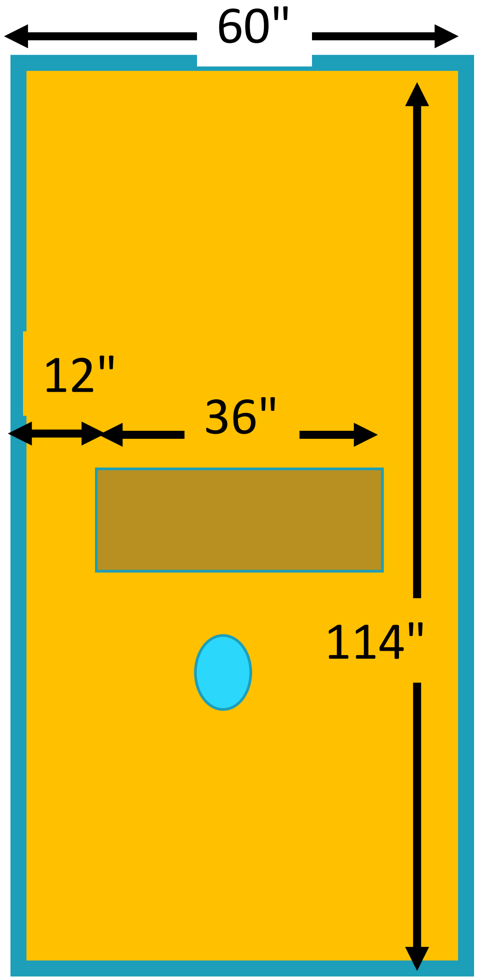
02. DC Motors + Solenoids

03. Driving DC motors

Lab 4

- Circle the center wall 3 times.
- 1st trial remote controlled from home through the internet
  - There will be lag in control
- 2nd trial autonomous mode

- Drop off your mobile base at GM lab.
  - Your TA/coach is your pit crew.



Lab 4 Constraints

- You may use Teensy or ESP32 for controlling vehicle
- You must use ESP32 for WiFi interface. (note using one processor is easier than two).
- Your vehicle can be up to 12" x 12" x 12"

- You may use any motor or servo you wish.
- You are encouraged to purchase items for this lab from your allocation

Purchasing Allocation

- Each student may purchase upto $75 worth of items from the following:

- Digikey.com: Electronics
- Mcmaster.com: Mechanical
- Adafruit: DIY electronics
- Sparkfun: DIY electronics
- Polulu: Motors, hubs
- Amazon.com: Everything

Purchasing Allocation

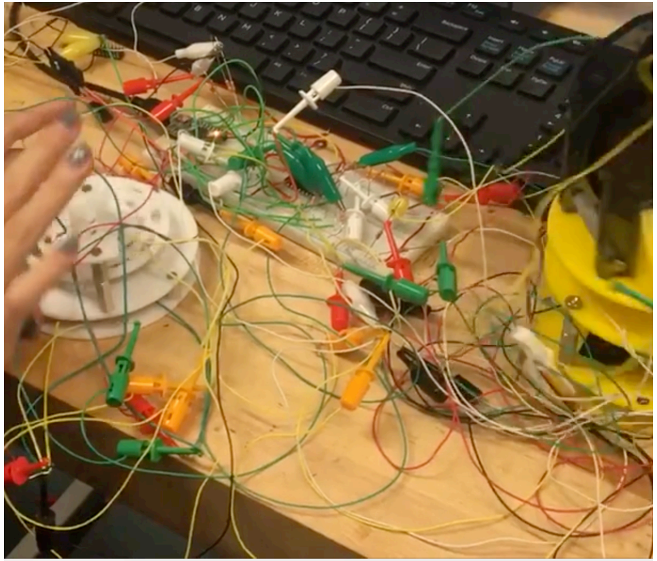
- You can have items shipped to your home.
- Track the costs of things you purchase (you will submit your purchases in the final report)
  - Include cost of item
  - Ignore shipping costs in your cost estimation
- Details in *Purchasing for MEAM510.pdf* on Canvas files
  - Fill out purchase request form… Include you phone# etc…
  - Send purchase request to yim@seas.upenn.edu
- Receiving parts may take 1 to 2 weeks (sometimes longer).
  - Purchase takes 3 business days to place order (currently)
  - Shipping takes 2-5 days to deliver.

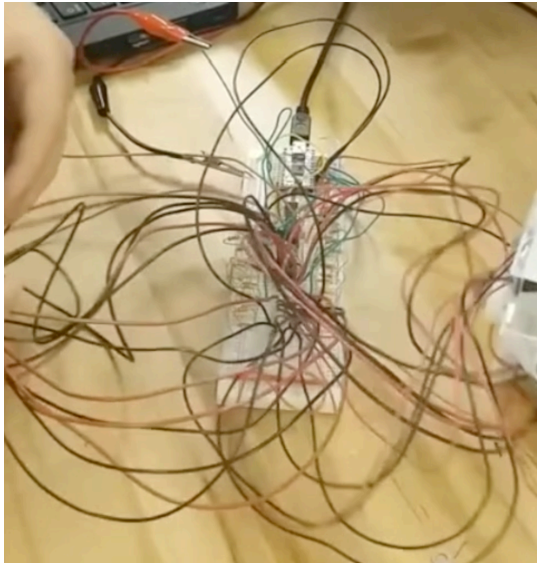
Tentative Lab 4 Schedule

	Sun	Mon	Tues	Wed	Thurs	Fri	Sat
March	7	**Today** Motor Control	[4.1 motor drivers]	Spring break	Spring break	**Lecture** ESP32	
	14	Lab 4.1 due Design Review Parts submitted	[4.2 wifi connectivity with ESP32]	Parts returned (start)		Parts returned (latest)	
	21	[4.2a Integration and assembly]		Lab 4.2 due WIfi Demo	[RACES]	[RACES]	
	28	[4.3a Integration and assembly]		Lab 4.3 due Auto Control	[AUTO RACES]	[AUTO RACES]	

Wiring robustness…

- Did you experience moving a device and have it stop working?
- What can we do about this?



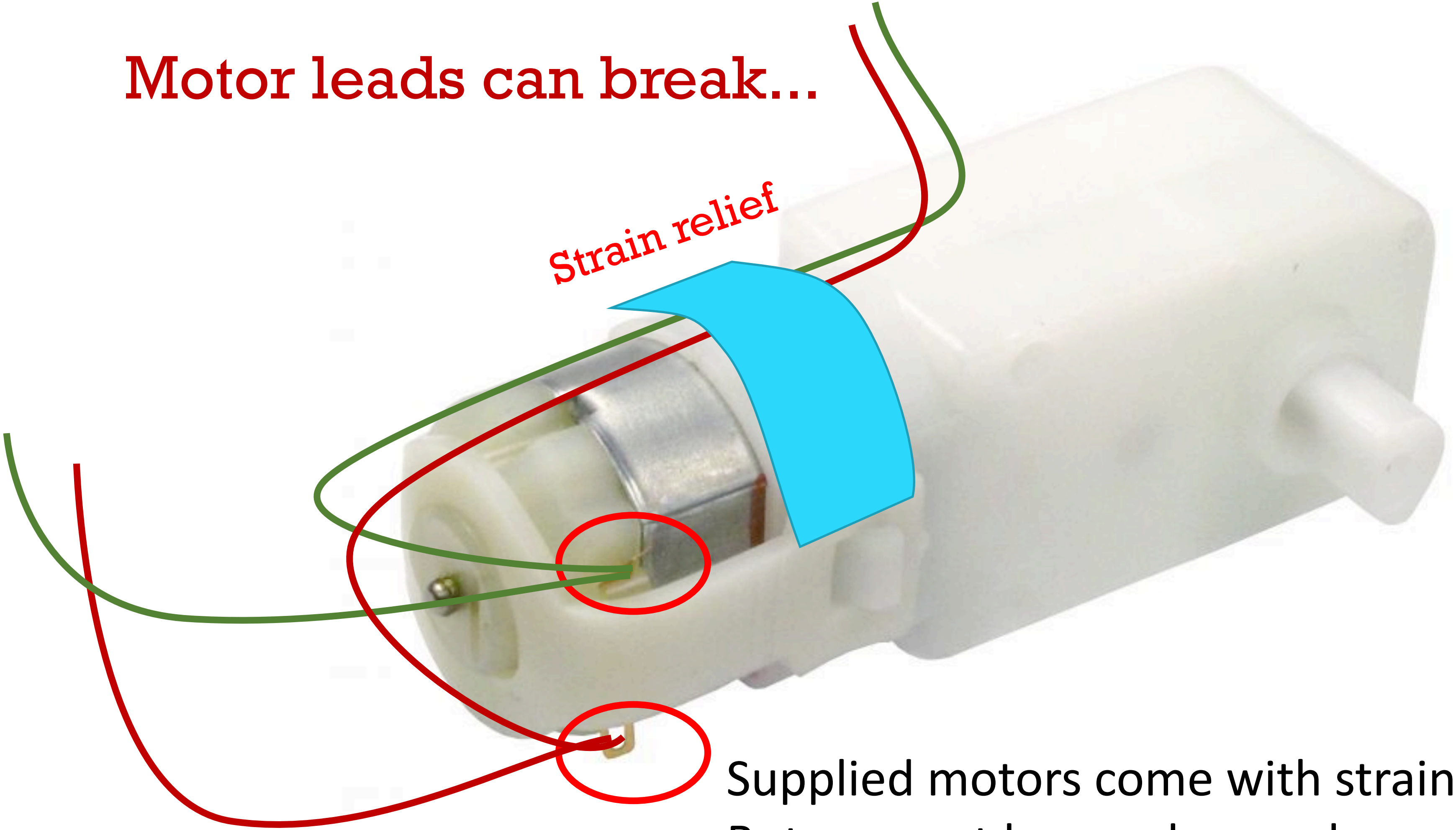


Connectors and cabling

- Most electromechanical failures occur at connections/connectors.
- If you need to have long wires, what can we do?



Motor leads can break...

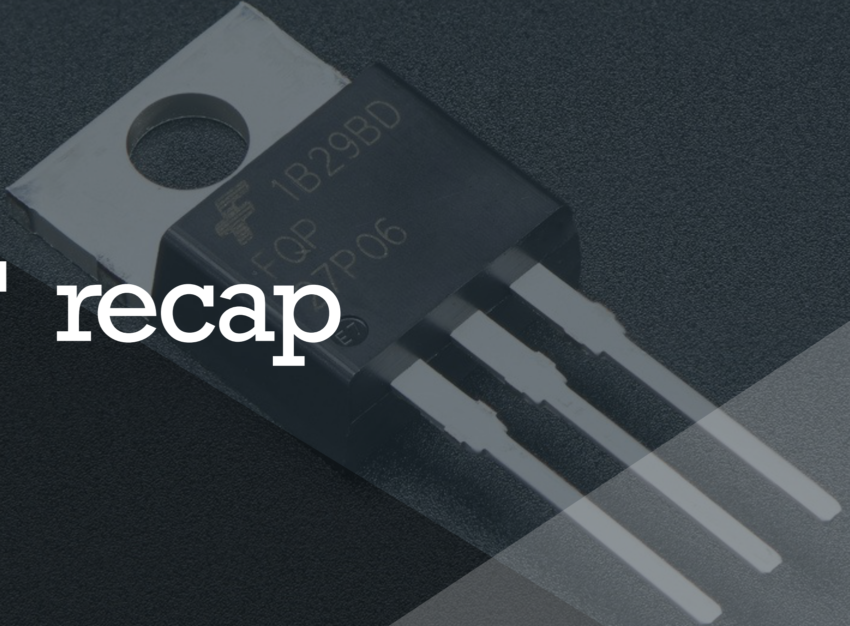


Supplied motors come with strain relief

But may not be good enough

01

MOSFET/BJT recap



Choosing MOSFET drivers (for this class)

Output Specifications

- $R_{DS(ON)}$ sets current capability (assuming you can heatsink device)
  - Look at continuous drain current

Driving Specifications

- V_{GS} Voltage required to turn on.
  - Older power MOSFETS require voltages larger than micro's normally supply $> 5V$ (not compatible)
- Q_G Total Gate Charge, - in general – not for this class.

BJT vs MOSFET

Driving

- BJT's are driven by current in base
- BJT's require Vbe ~0.7V to start conducting

- MOSFETS require $V_{GS(th)}$ to start (varies: 1-8V)
- MOSFETS are driven by voltage, Vgs

Outputs

- BJT limited by Vce

- MOSFETS limited by Rds_on
- MOSFETS can combine in parallel

Costs

- BJT's are cheaper for switching small currents e.g. I_C ~200mA

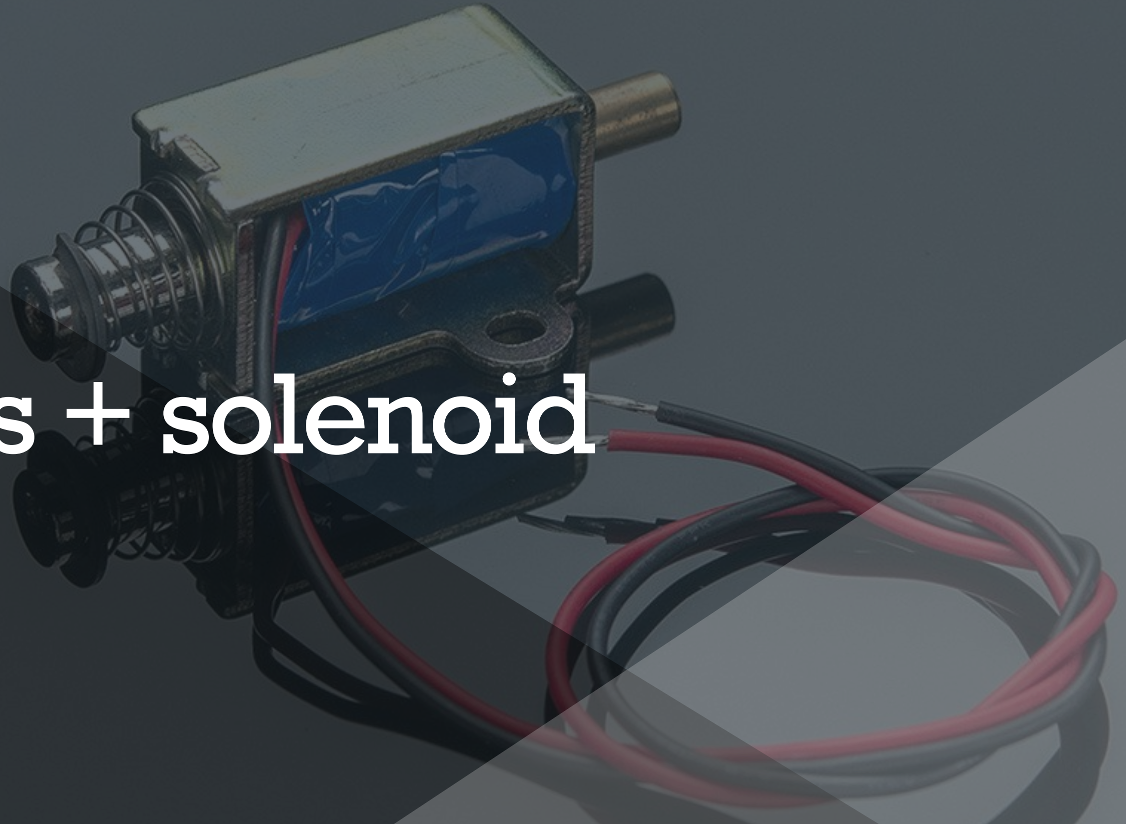
- MOSFETS are smaller and cheaper more efficient for switching larger currents e.g. I_D>~5A

Summary

- BJT are current controlled
- MOSFETs are voltage controlled
- MOSFETs are the trend for large current control
- Be sure to understand V_{GS} characterstics of MOSFETs for your application

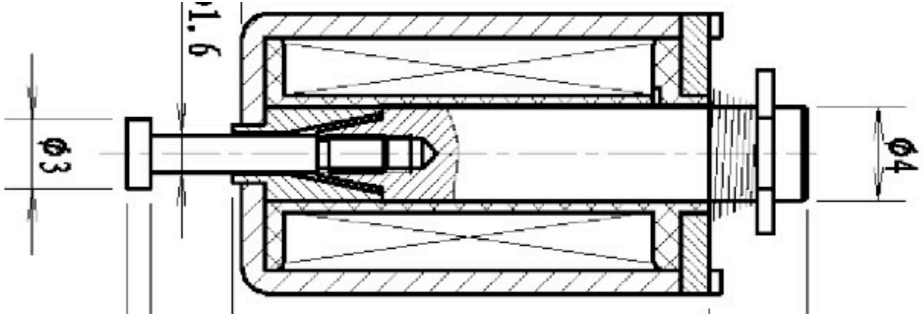
02

DC Motors + solenoid

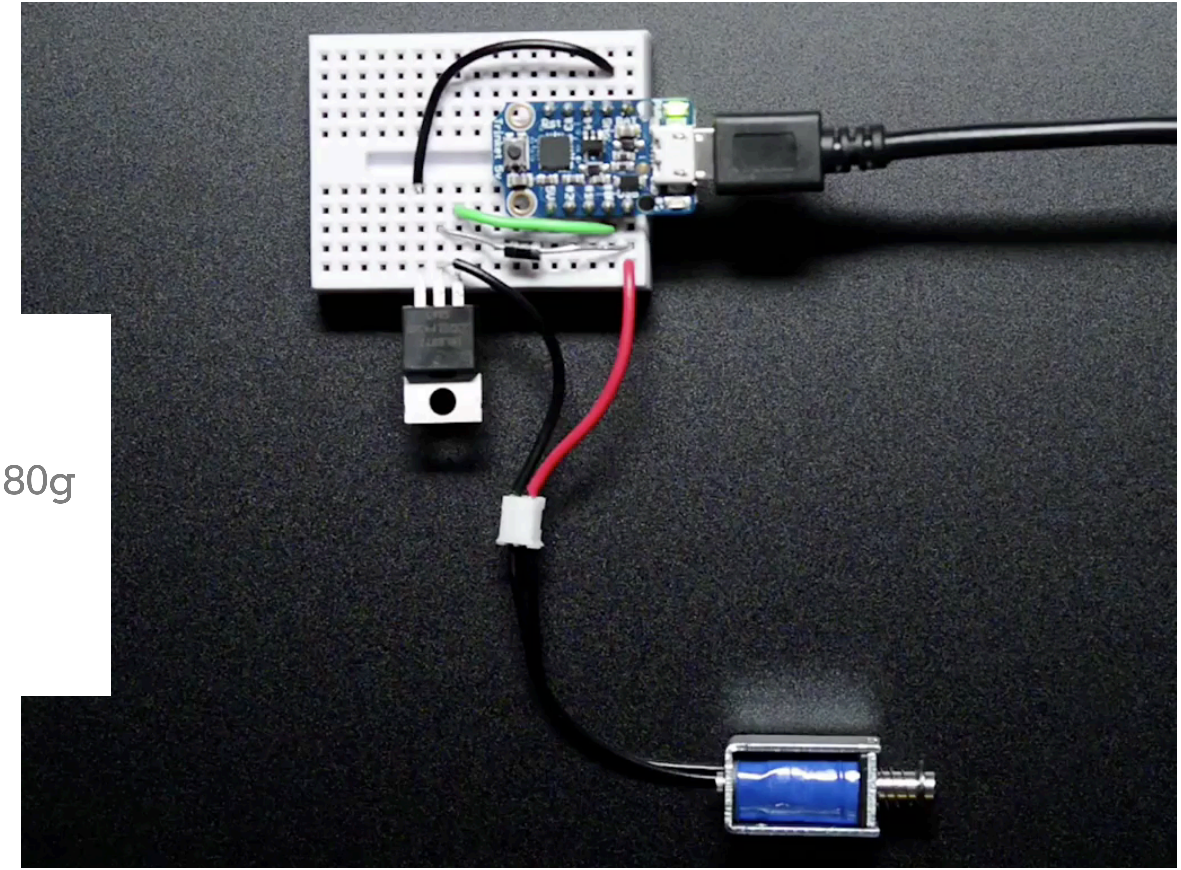


What is a solenoid?

- Magnetic plunger surrounded by a coil
- The plunger can move in or out to push against something.
- Moves quickly



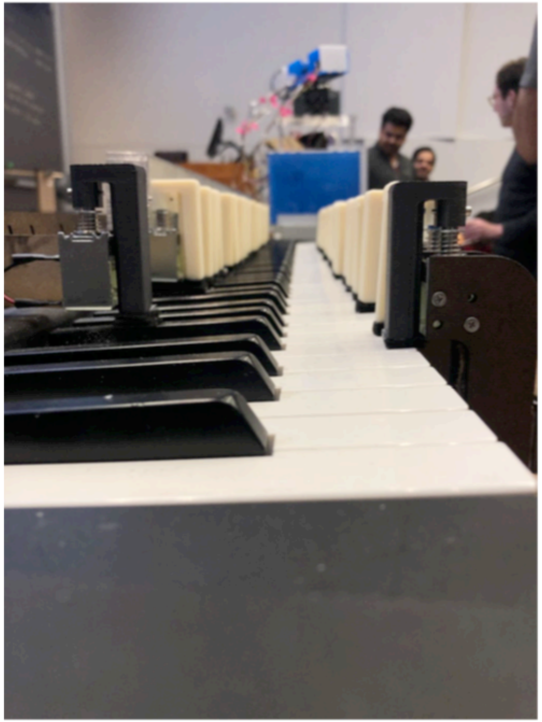
Mini Push-Pull Solenoid (in GM lab)



- Rated Voltage: 5V
- Current (at DC 5V): 1.1A
- Throw (at DC 5V): 3mm / 80g

MEAM516 2019 – Solenoid driven music

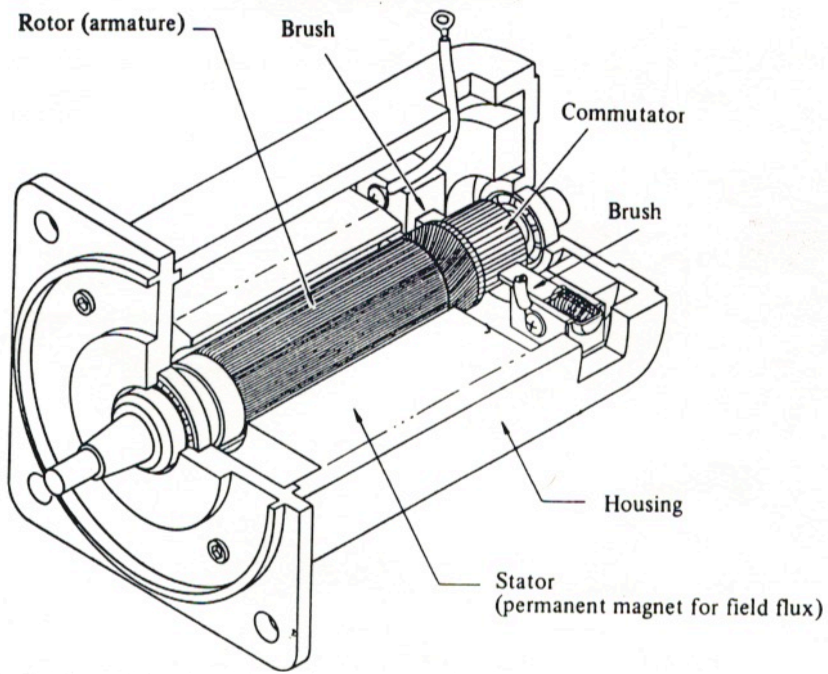
Andrew and his team

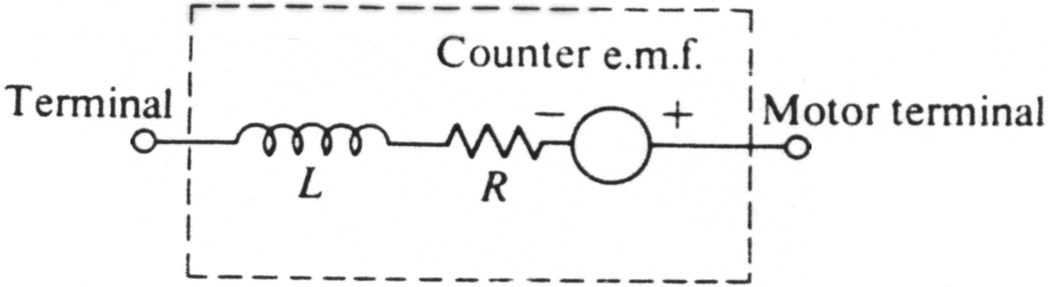


Shaun, Allie and their team

https://www.youtube.com/watch?v=jNhjGteu8xc&feature=youtu.be

Ideal Electrical Model of a DC motor

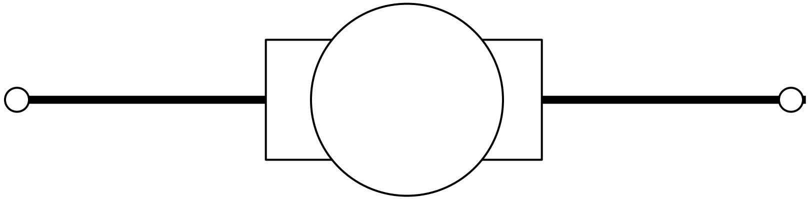




Actuators: Important properties?

Inputs:
- Voltage
- Current

Outputs:
- Speed
- Force/Torque
- Range of motion



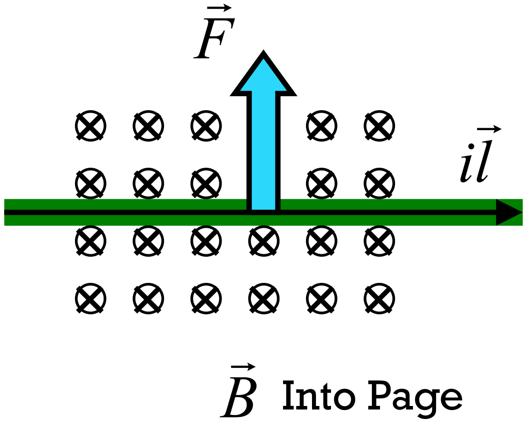
Motor

Solenoid (coil)

Basic Physics: Lorenz Force

$$\vec{F} = i\vec{l} \times \vec{B}$$

Force on a Wire Carrying Current
Through a Magnetic Field



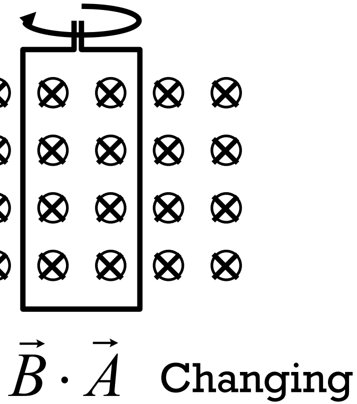
$$\boxed{\tau = K_T i}$$

For some motor with torque constant K_T

Basic Physics: Faraday's Law

$$\varepsilon = -\frac{d}{dt}\int_A \vec{B} \cdot d\vec{A}$$

Electromotive Force (Voltage)
Generated by Rate of Change of
Magnetic Flux Enclosed by a Coil

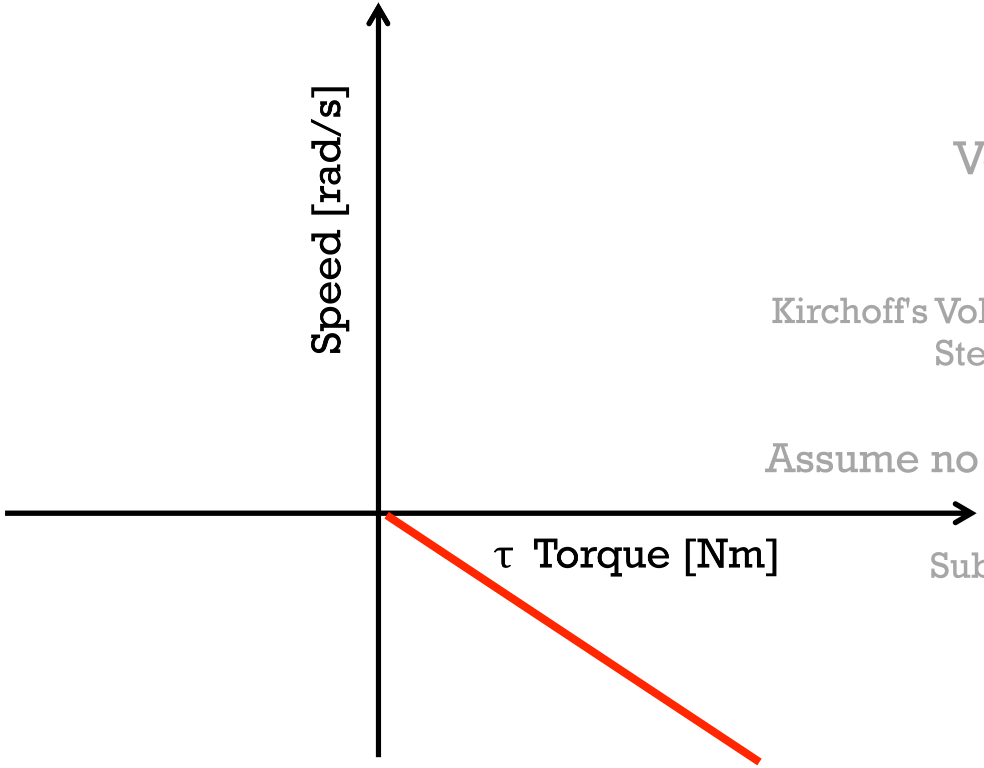


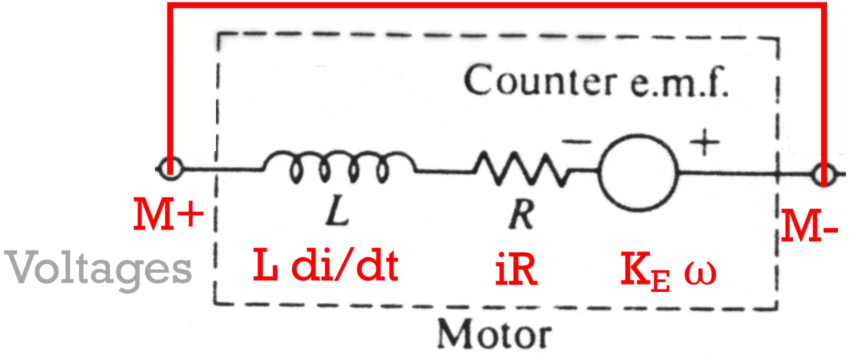
$$\boxed{V = K_E \omega}$$

For some motor with speed constant K_E

Ideal Electrical Model of a DC motor (alone)

Q1: Plot Speed vs Torque





Kirchoff's Voltage Law $0 = L\,di/dt + iR + K_E\,\omega$

Steady state $0 = 0 + iR + K_E\,\omega$

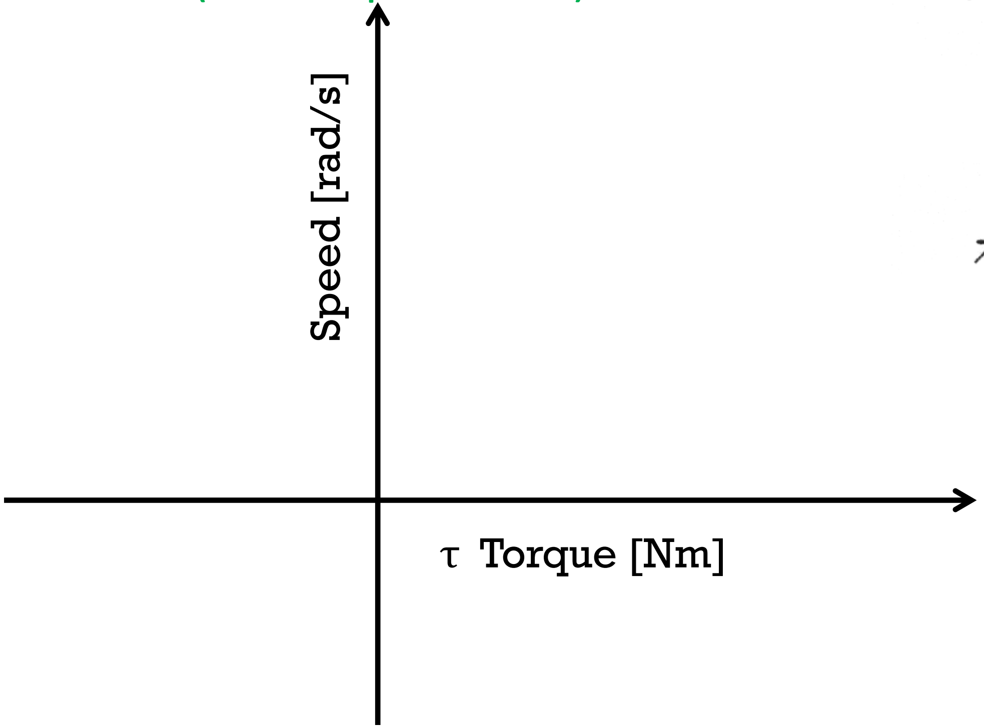
Assume no friction $\tau = K_T i$

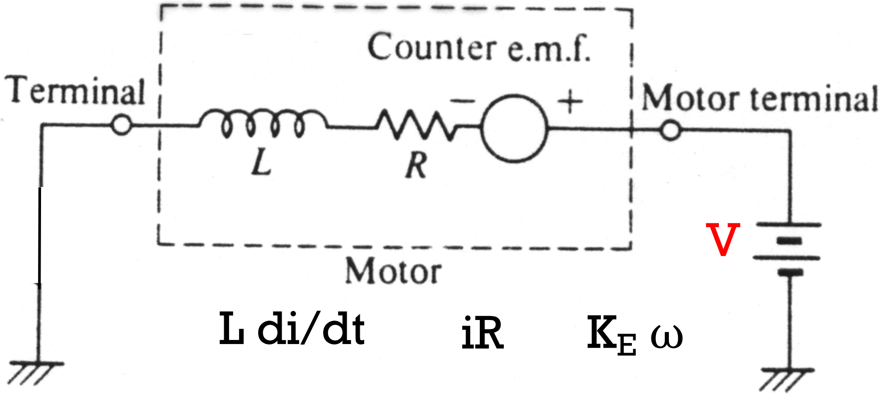
Substitution $0 = 0 + \tau R/K_T + K_E\,\omega$

Algebra $\omega = -\tau \underbrace{R/(K_T K_E)}_{\text{Motor Constants}}$

Ideal Electrical Model of a DC motor w/battery

Q2: Plot Speed vs Torque
(which quadrant?)





$$V = L\,di/dt + iR + K_E\,\omega$$

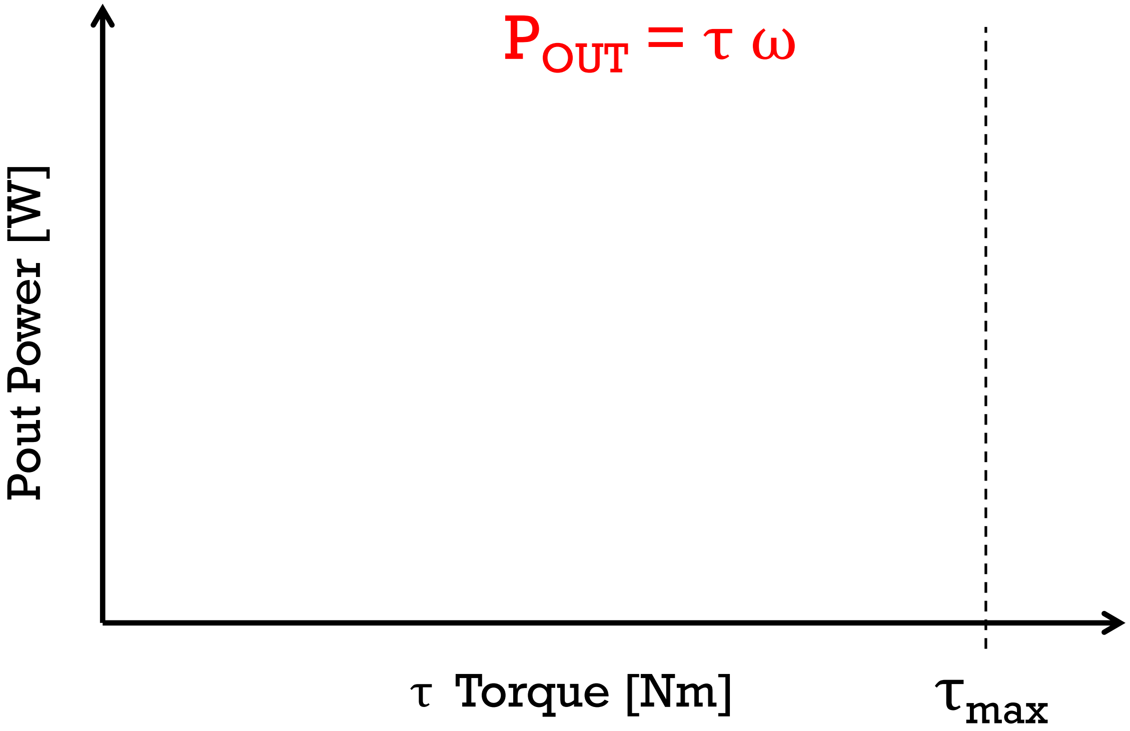
$$V = 0 + iR + K_E\,\omega$$

$$\tau = K_T i$$

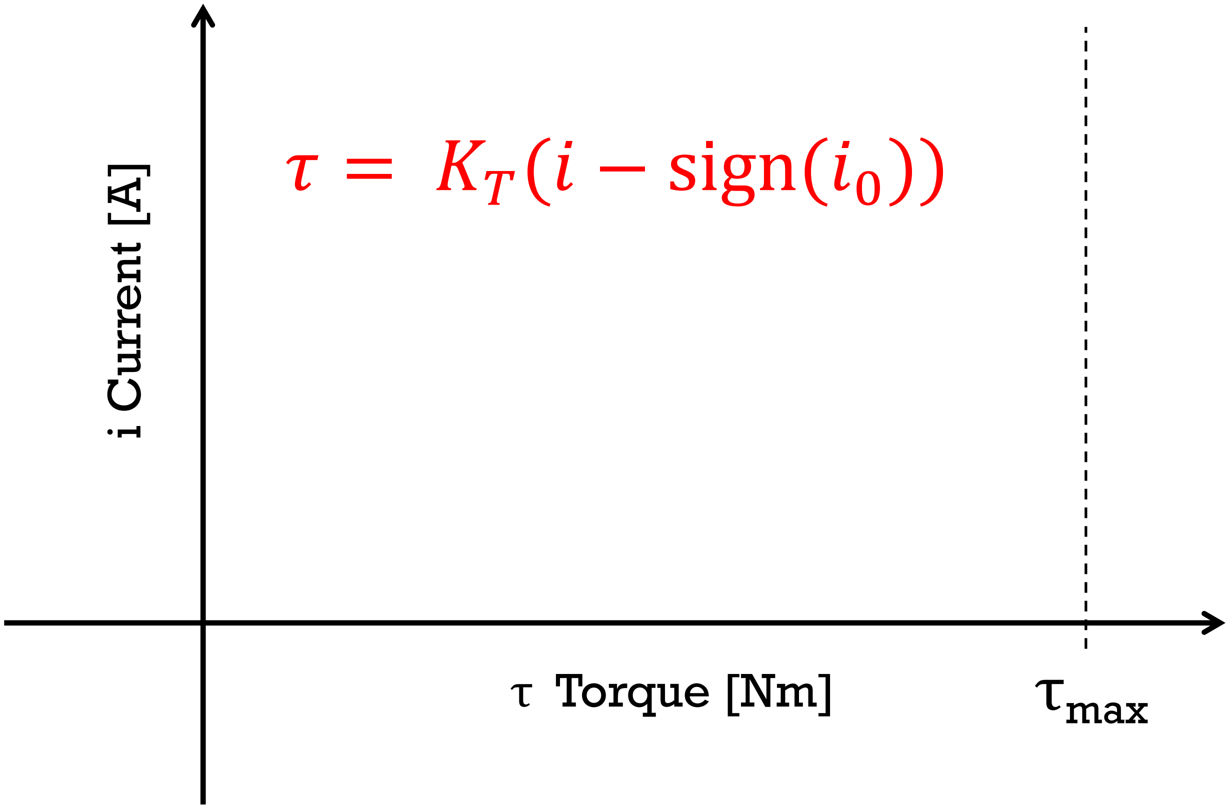
$$V = 0 + \tau R/K_T + K_E\,\omega$$

$$\omega = -\tau \underbrace{R/(K_T K_E)}_{\text{Motor Constant}} + V/K_E$$

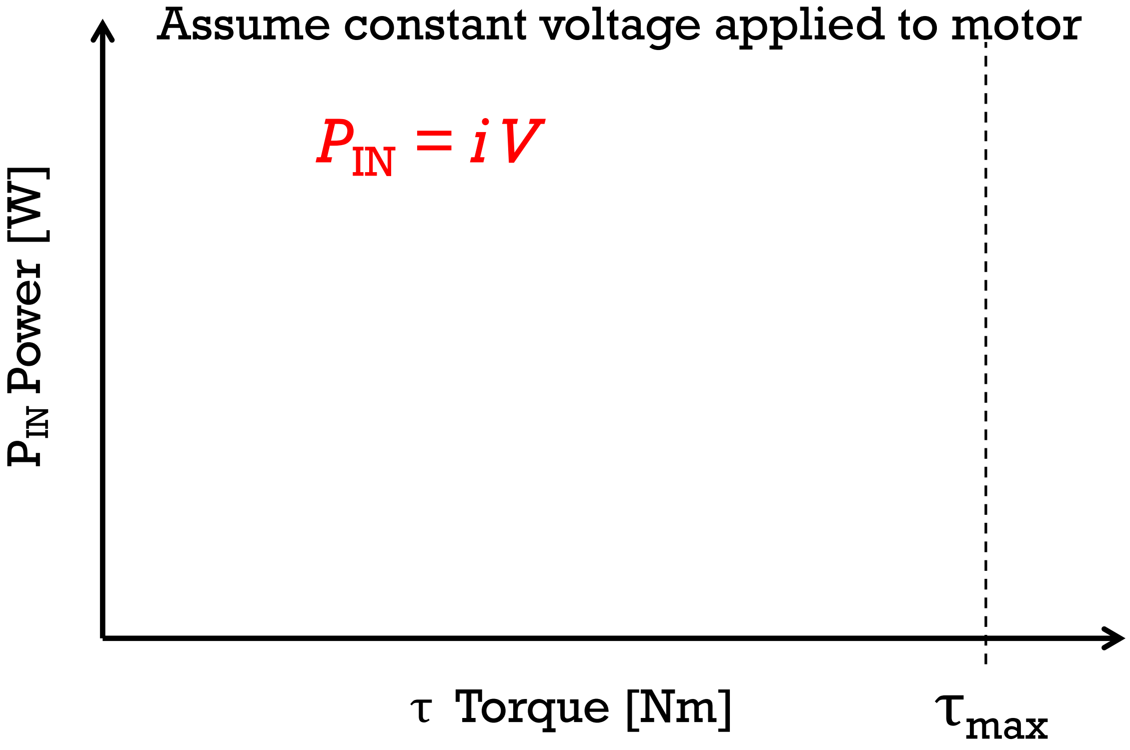
Q3: Plot (Mechanical) Output Power vs Torque (Does the curve hit the origin?)



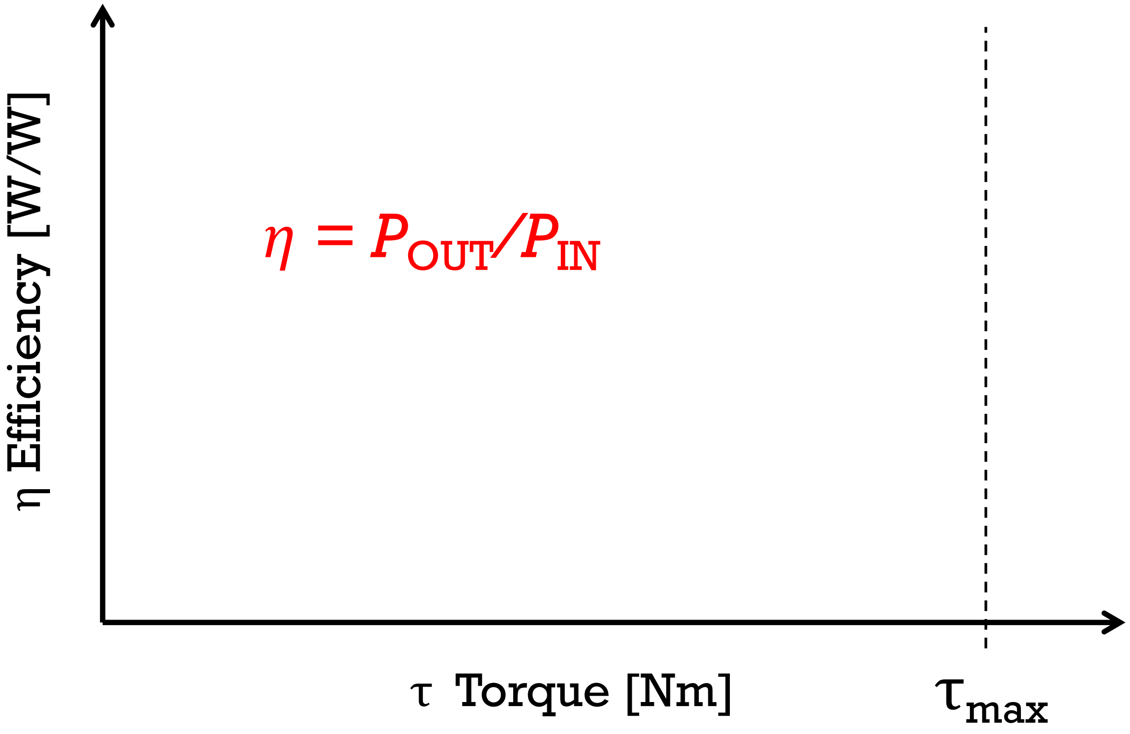
Q4: Plot Current vs Torque
(Does the curve hit the origin?)



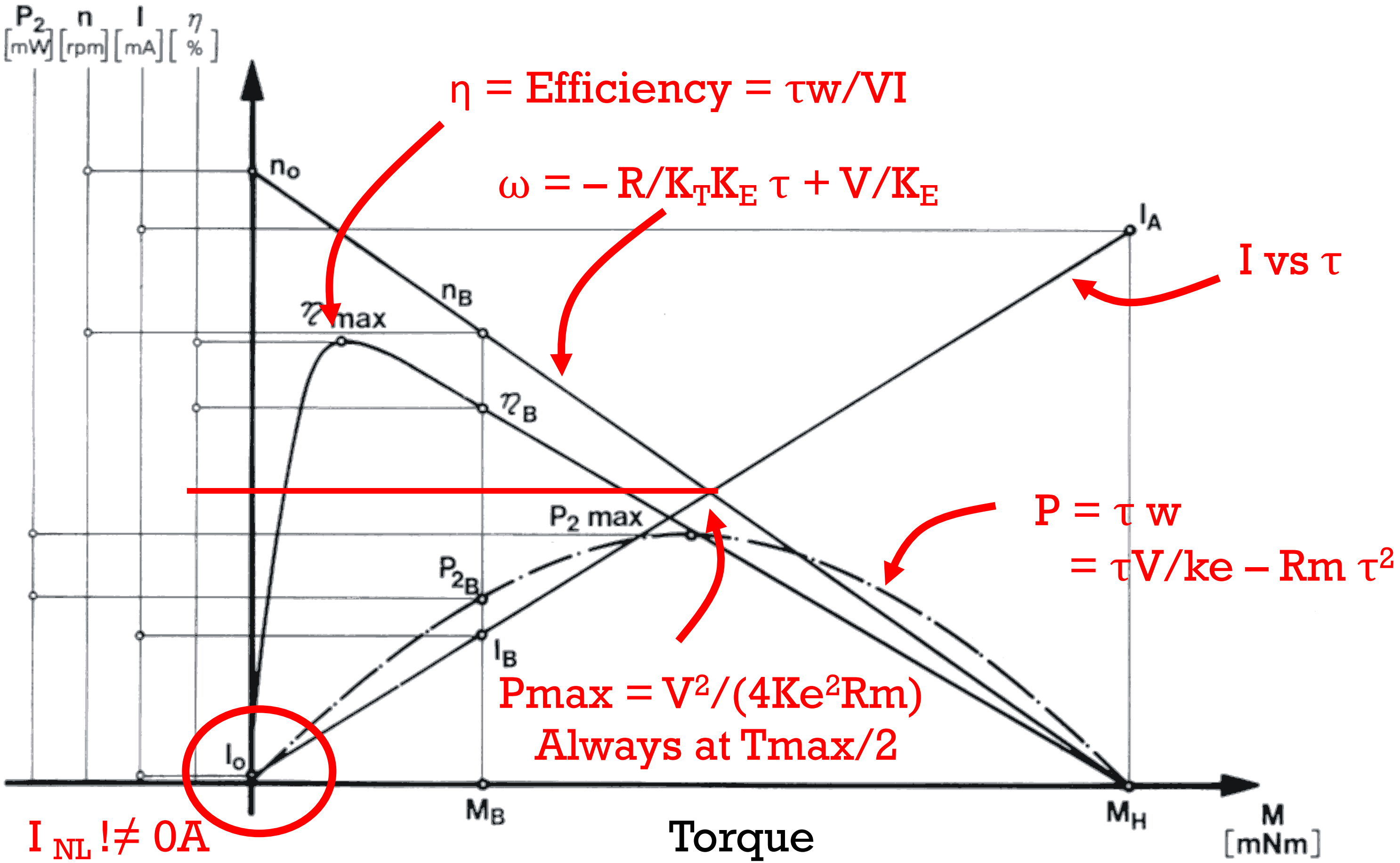
Q5: Plot (Electrical) Input Power vs Torque (Does the curve hit the origin?)



Q6: Plot Power Efficiency vs Torque (where is the peak efficiency?)



Torque vs Everything (for given V)



Choosing a motor

- Voltage specifications
  - indicates maximum voltage
  - doesn't say anything about motor capability
- Wattage
  - indicates maximum power
- Motor constants
  - indicate slope of torque/speed curve
- Stall torque
- Stall current
- No load speed

Pololu part #
1516
1124
2368
2367
2365
2364
992

Some terms and symbols

- K_T Torque constant [Nm/A], apply A get τ
- K_V Velocity constant [rad/s /V], apply V get ω
- $K_B = K_E$ Back EMF constant [V /Rad/s], apply ω get V

Note:

$K_T = K_E = 1/K_V$ when using SI units Nm/A : V / rad/s

$$\omega = -\tau R/K_T K_E + V/K_E$$

DC Motor Specs
(Maxon Motor catalog)

Labeled by power rating

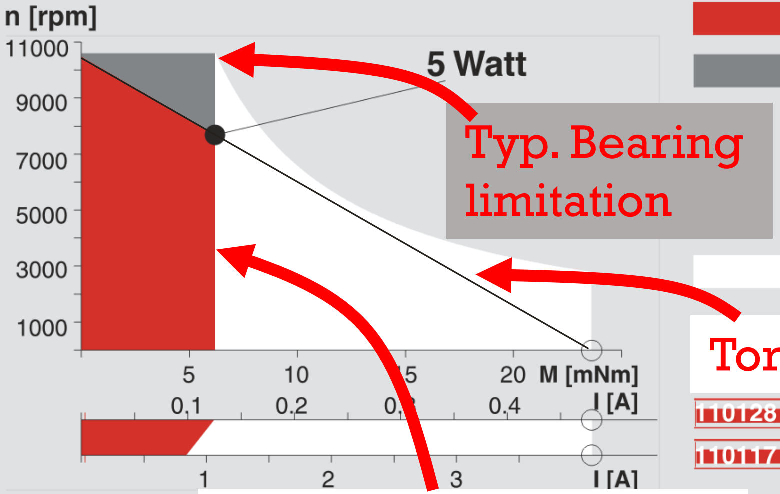
Stall current?

Bearing limitation

	Winding number		930	933	934	94[illegible]	[illegible]	[illegible]	[illegible]7	938	945
Motor Data											
1	Assigned power rating	W	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
2	Nominal voltage	Volt	3.0	7.2	9.0	12.0	12.0	12.0	15.0	18.0	18.0
3	No load speed	rpm	5080	9270	9460	10700	[illegible]	7770	8460	8240	8010
4	Stall torque	mNm	20.9	42.5	45.7	51.7	[illegible]	35.1	44.4	43.0	38.0
5	Speed/torque gradient	rpm/mNm	260	225	213	211	194	227	194	195	215
6	No load current	mA	114	101	83	73	50	47	42	34	33
7	Starting current	mA	3960	5910	[illegible]	4920	3090	2440	2680	2100	1810
8	Terminal resistance	Ohm	0.757	1.22	1.74	2.44	3.88	4.92	5.60	8.56	9.96
9	Max. permissible speed	rpm	11000	11000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	11000
10	Max. continuous current	mA	1500	1500	1440	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	609
11	Max. continuous torque	mNm	7.92	10.8	12.7	12.8	13.4	12.4	13.4	13.4	12.8
12	Max. power output at nominal voltage	mW	2460	9620	10800	13900	8770	6920	9590	9070	7780
13	Max. efficiency	%	64	73	75	76	75	74	76	76	75
14	Torque constant	mNm/A	5.28	7.19	8.85	10.5	13.8	14.4	16.6	20.5	21.0
15	Speed constant	rpm/V	1810	1330	1080	909	691	664	576	467	455
16	Mechanical time constant	ms	29	22	20	19	18	18	18	18	18
17	Rotor inertia	gcm^2	10.8	9.23	9.07	8.68	9.07	7.76	8.84	8.63	7.87
18	Terminal inductance	mH	0.07	0.12	0.18	0.26	0.45	0.48	0.64	0.98	1.03
19	Thermal resistance housing-ambient	K/W	17	17	17	17	17	17	17	17	17
20	Thermal resistance rotor-housing	K/W	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4
21	Thermal time constant winding	s	7	6	6	6	6	5	6	6	5

Motor Spec Sheet

Operating Ranges	Comments	Example from page 113



Recommended operating range

Continuous operation
In observation of above listed thermal resistances (lines 19 and 20) the maximum permissible rotor temperature will be reached during continuous operation at 25°C ambient.
= Thermal limit

Short term operation
The motor may be briefly overloaded (recurring).

110128 Motor with high resistance winding (Line 8)

110117 Motor with low resistance winding (Line 8)

Speed (n), torque (M), current (I):
The outer edges of the values depicted represent limits for continuous and short term motor operation. Values listed in the tables (lines 3, 4, 6, 7, 12 and 13) are valid for operation at nominal voltage (line 2). These are therefore values which are only reached when operating the motor at higher voltages

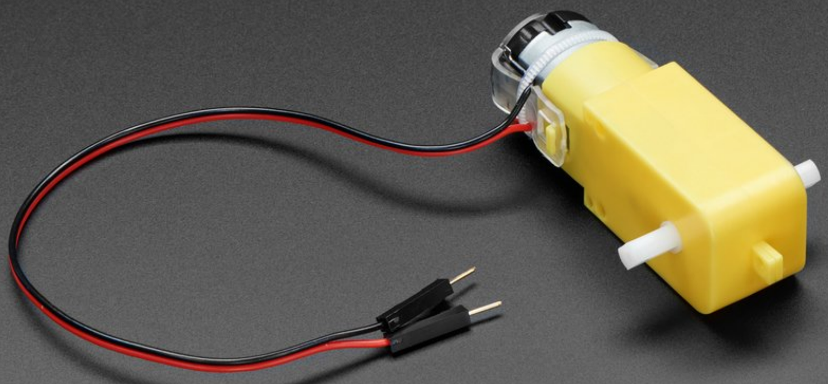
● Assigned Power Rating P_{2T} (W) (Line 1)
○ Starting current I_A at nominal voltage (Line 7) as well as related stall torque

M_H (mNm) (Line 4) $I_A = \frac{U}{R} \cdot 10^3$ (mA)

110128 Winding number with the related current curve at the appropriate torque.

Motor in your kit

- https://www.adafruit.com/product/3777



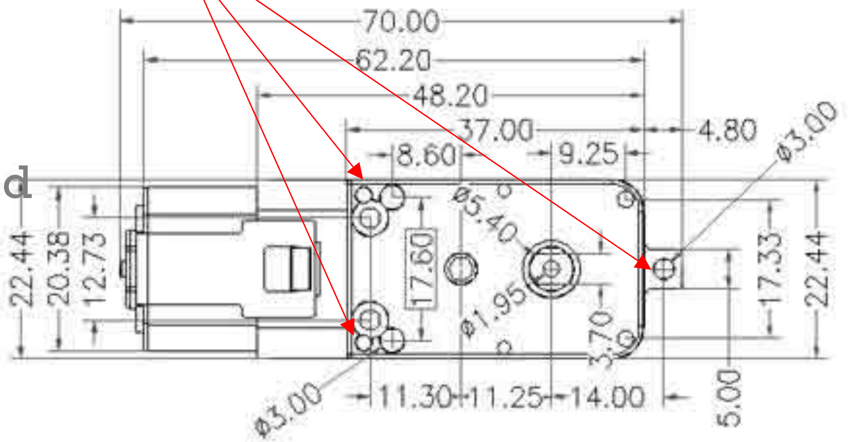
- Rated Voltage: 3~6V
- Continuous No-Load Current: 150mA
- Min. Operating Speed (3V): 90 RPM
- Min. Operating Speed (6V): 200 RPM
- Stall Torque (3V): 0.4kg.cm
- Stall Torque (6V): 0.8kg.cm

Supplied DC Motor (x2)

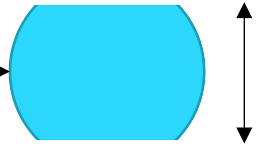
https://www.adafruit.com/product/3777

- Mounting
  - 3mm x3 mounting holes
  - Using these holes is encouraged
- Shaft mount – has 2 flats
  - Can laser cut this shape hole

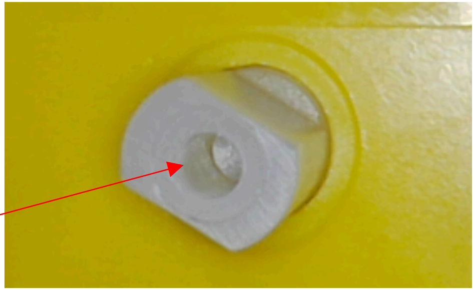
Mounting holes



5.4mm OD



3.7mm

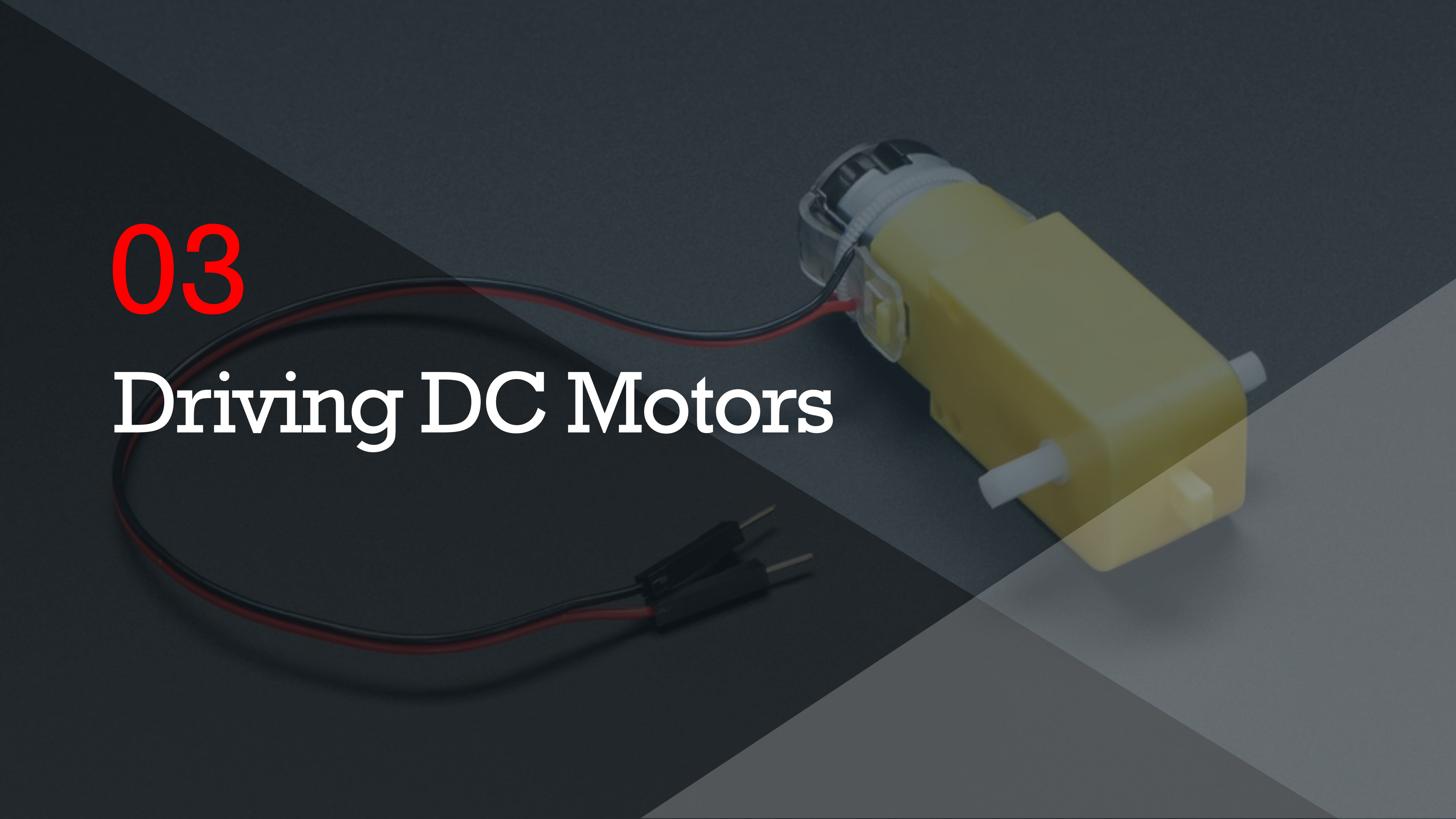


Smooth hole

Can use #2 or #3 wood screw

03

Driving DC Motors

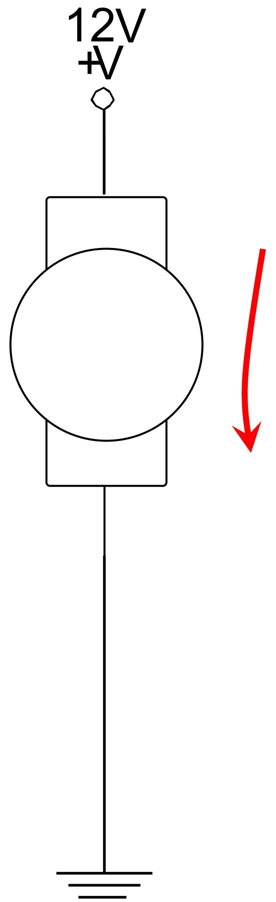


Driving a motor

Q7: To calculate how much current will flow:

- In general, what does it depend on?
- Worst case, what does it depend on?

- Can my driver (e.g. transistor) handle that much current?



Motors may require large currents

- The yellow motors in your kit ~1.5 Amps @ 5V stall
- Motors in typ. MEAM510: 1 to 6 Amps @ stall
- Motors in typ. quadrotor 5 to 30 Amps @ stall
- Motors in typ. electric car 100's of Amps

Pololu part #
1516
1124
2368
2367
2365
2364
992

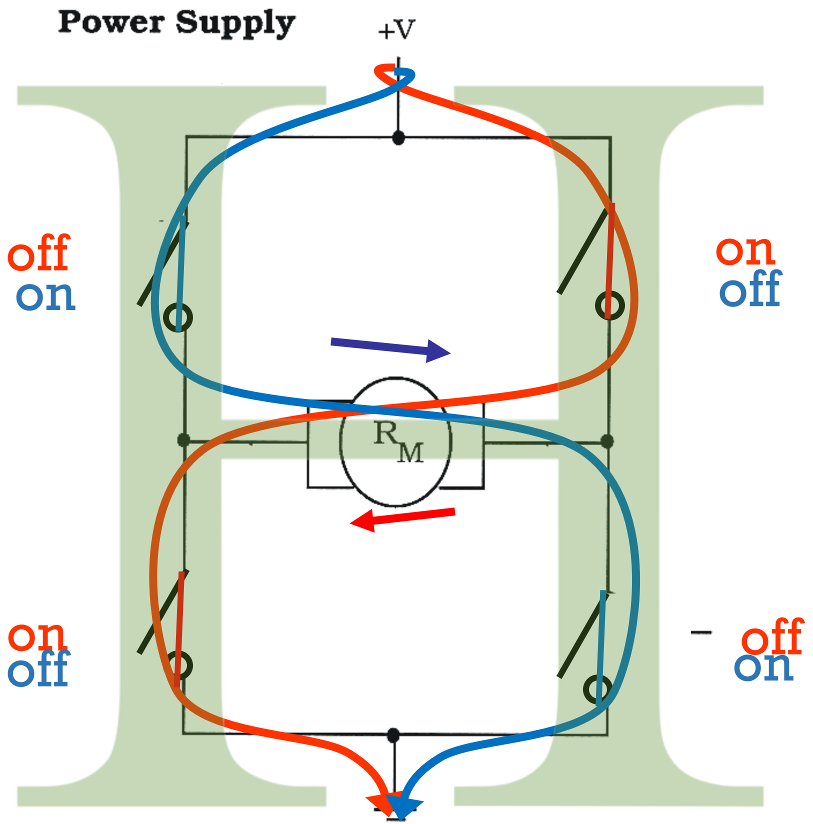
GM Lab Options for Driving Large Currents

- ULN2003 Seven Darlington Array ~0.5A
- TIP31C NPN Transistor 3A
- TIP102 NPN Darlington 8A

- IRLB8721 N-channel MOSFET 25A
- IRF9520 P-Channel MOSFET ~6.8A
- FQP8P10 P-Channel MOSFET 4A
- IRF630 N-Channel MOSFET 5.9A
- SN754410 H-bridge driver 1A

Switching directions

H-Bridge



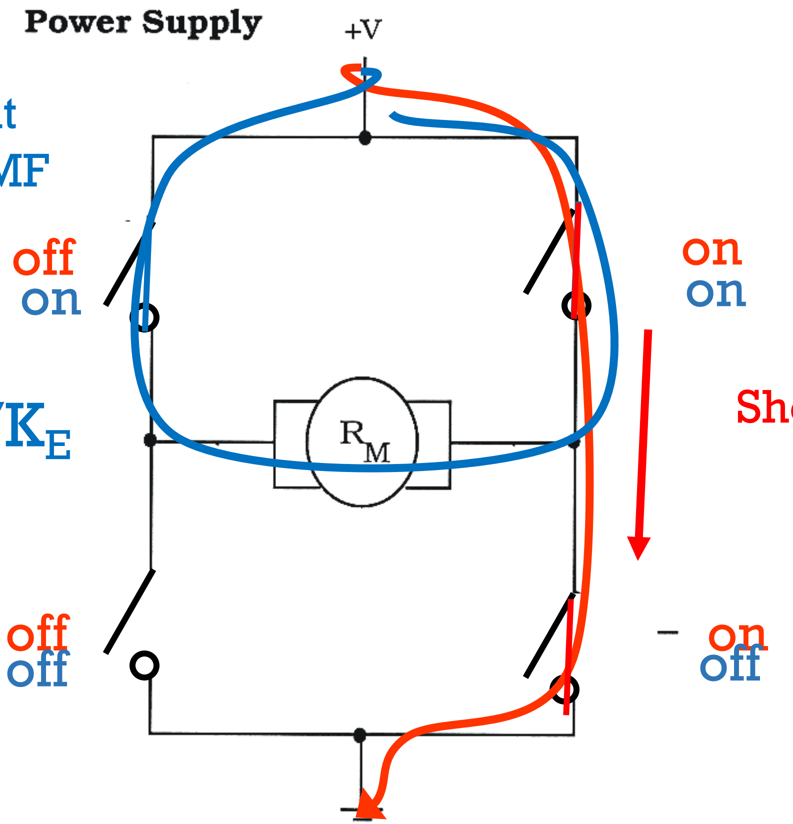
Change current in motor changes direction

Other Switch Options

No power from supply, but
Current flows from back EMF
Acts as a brake

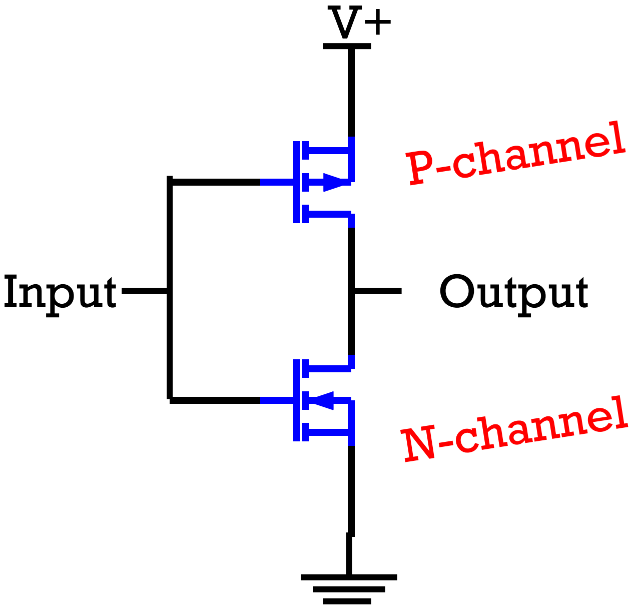
$$\omega = -R/K_T K_E \,\tau + V/K_E$$

$$\tau = -\omega\, K_T K_E / R$$

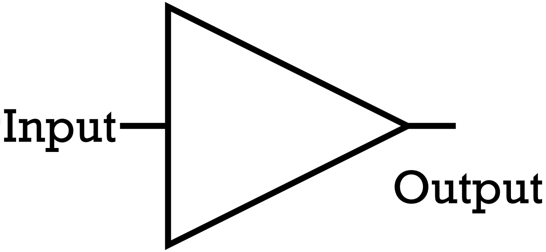


Short from V+ to GND
Very bad!

Half H-Bridge



Rough schematic

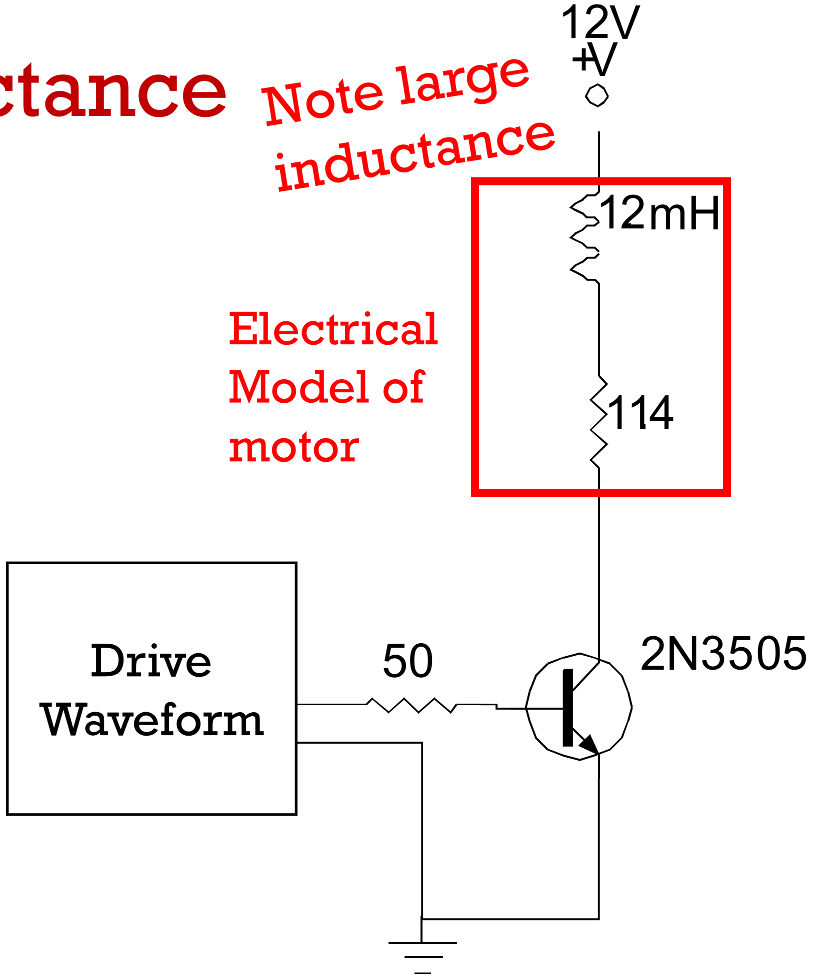


Symbol

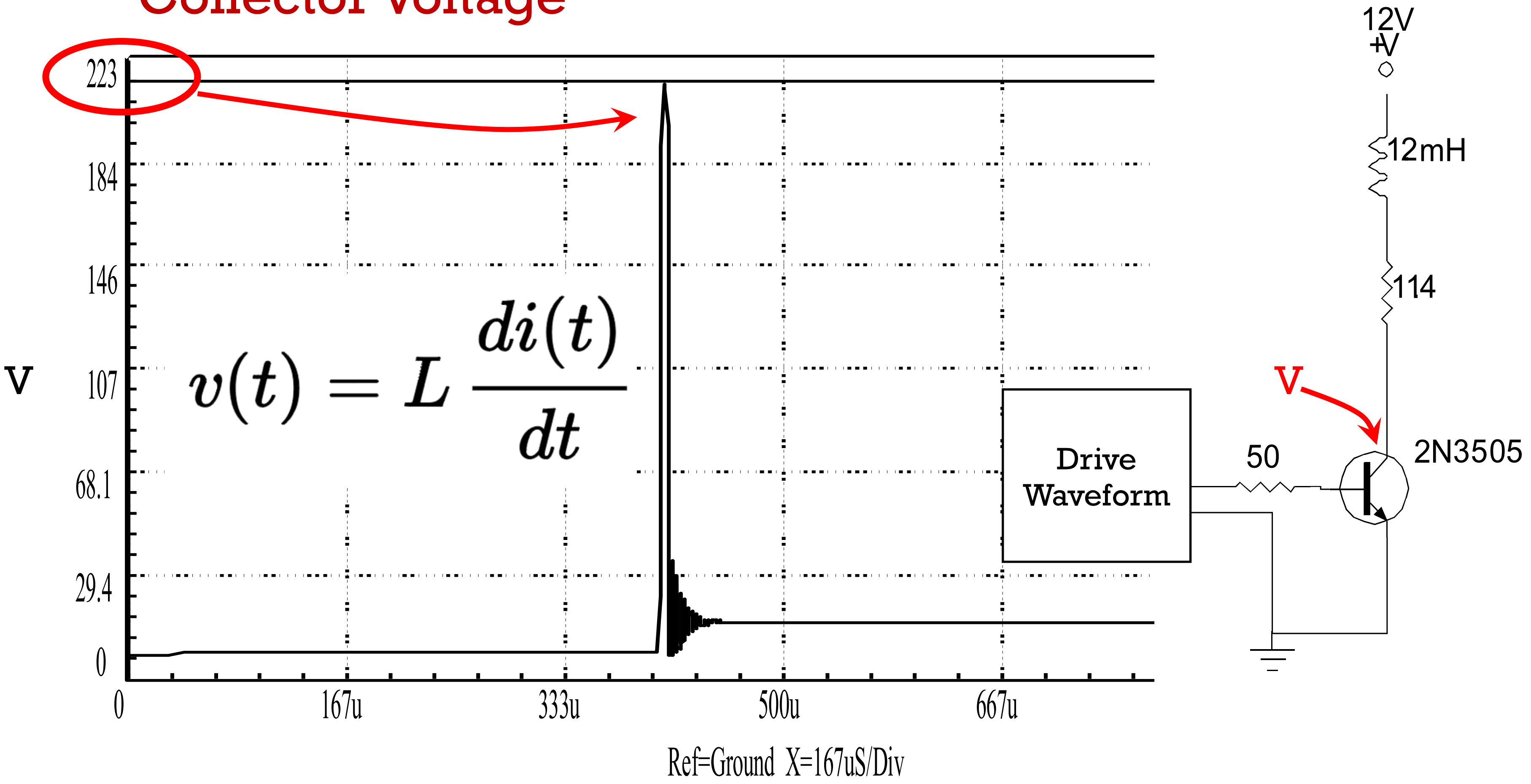
Recall
Effect of Large Inductance

Circuit simulation package

$$v(t) = L\frac{di(t)}{dt}$$



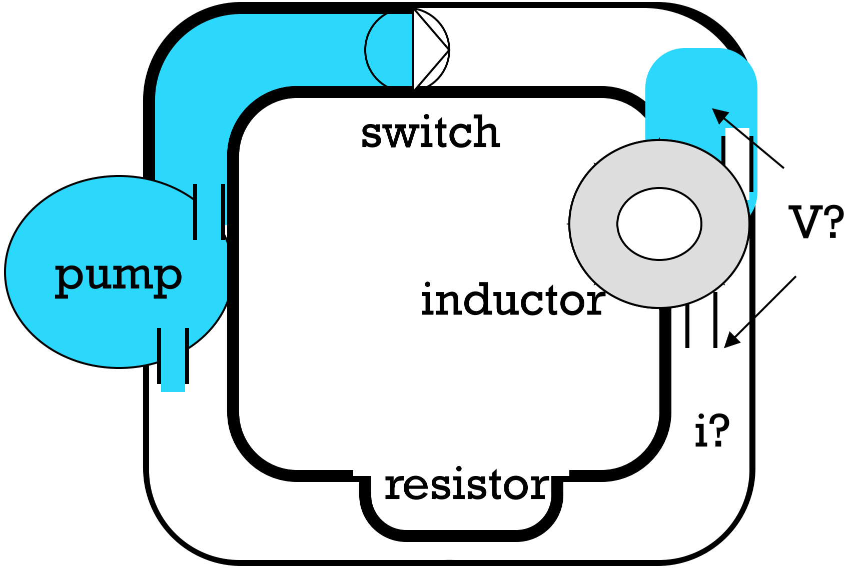
Collector Voltage



$$v(t) = L\frac{di(t)}{dt}$$

Circuit simulator (from Prof. Ed Carryer @ Stanford)

Recall Large inductance



L i similar to mv, momentum

Initial state, switch is off
no voltage across inductor
no current in inductor

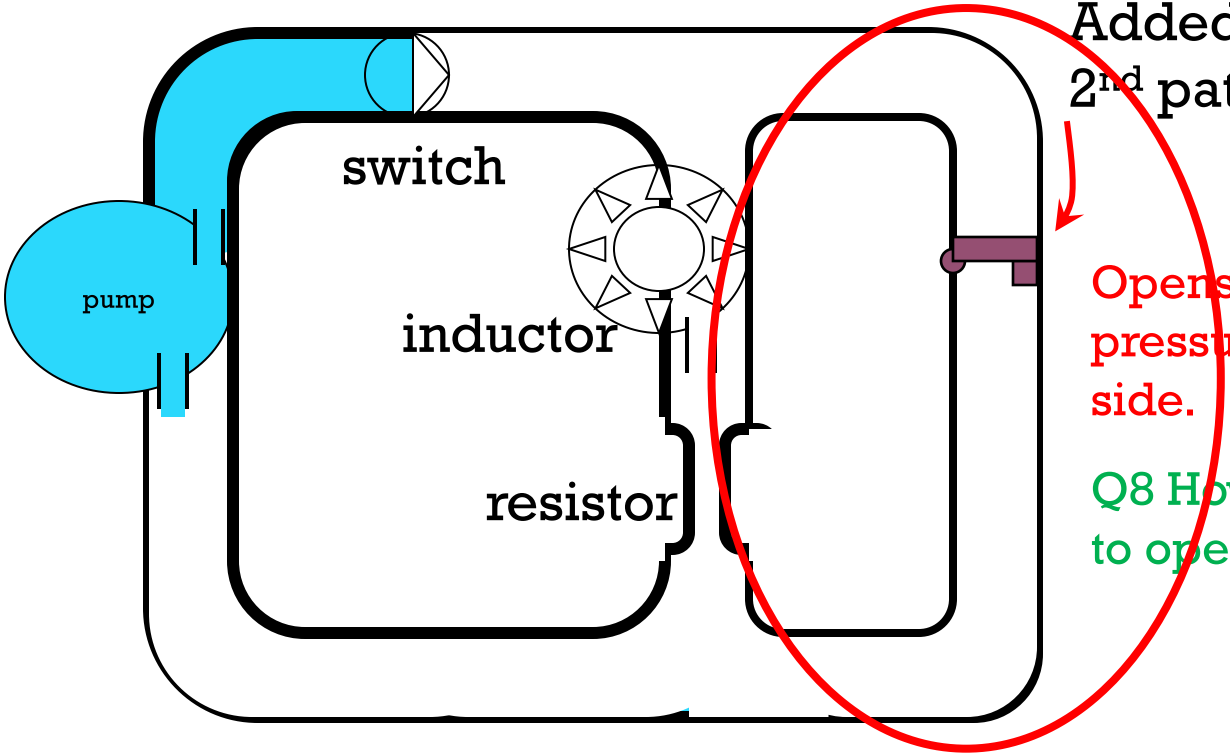
Switch turns on
hi voltage seen on one side
no current in inductor

Steady state
voltage equal on both sides
current in inductor

Switch turns off
hi voltage on other side
no current in inductor

Steady state
voltage equal on both (0)
no current in inductor

Large inductance with clamping diode



Added diode and 2nd pathway

Opens with larger pressure on bottom side.

Q8 How much voltage to open?

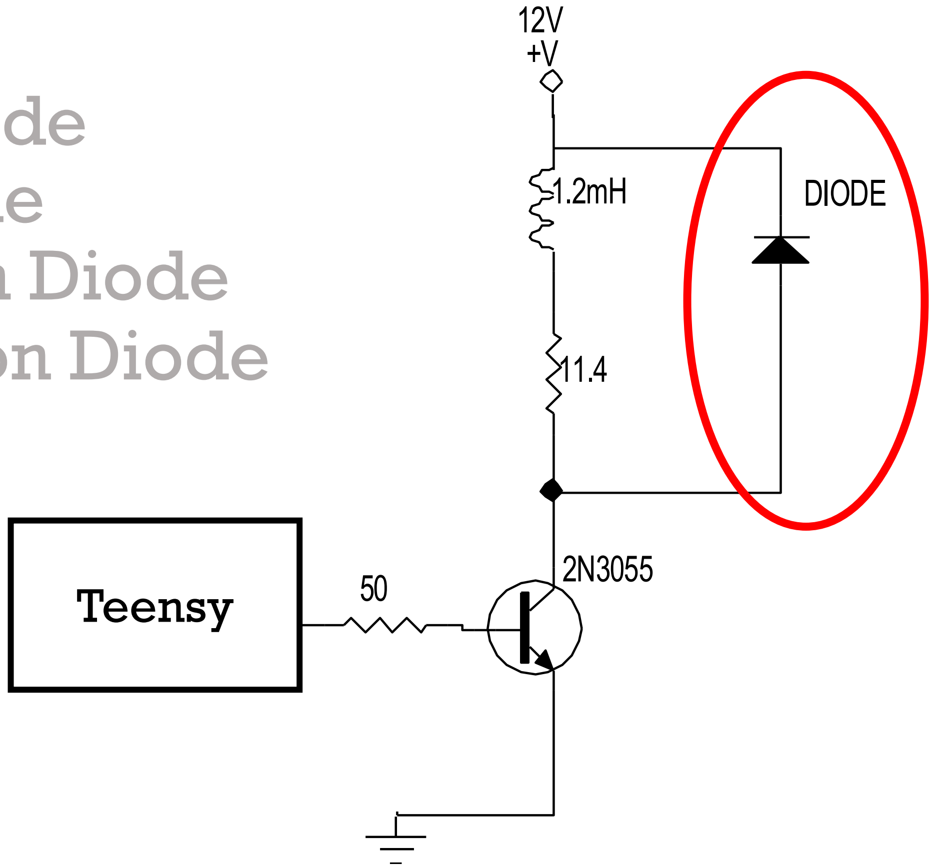
Snubber Diode

AKA Flyback Diode

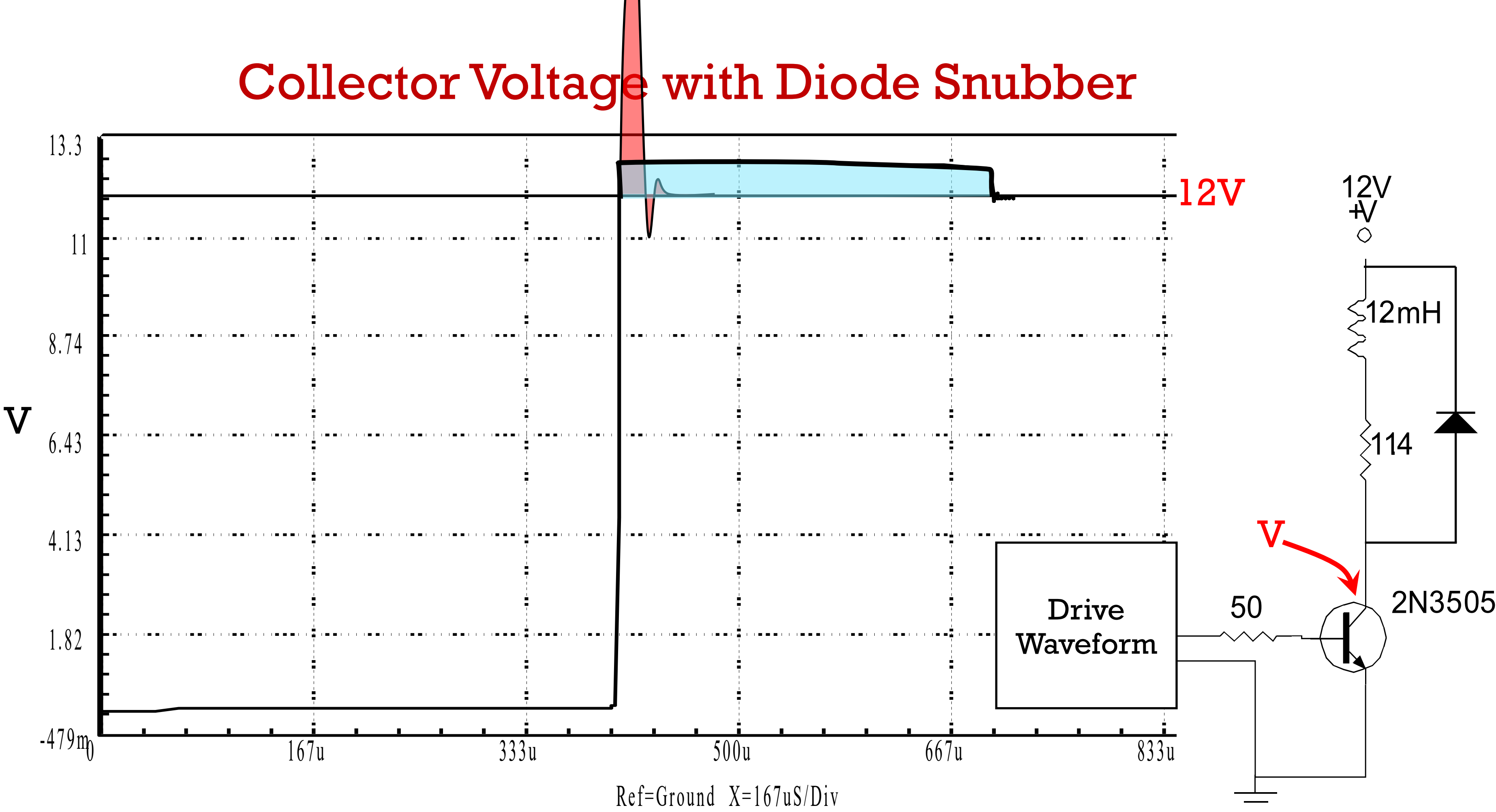
AKA Clamp Diode

AKA Suppression Diode

AKA Commutation Diode

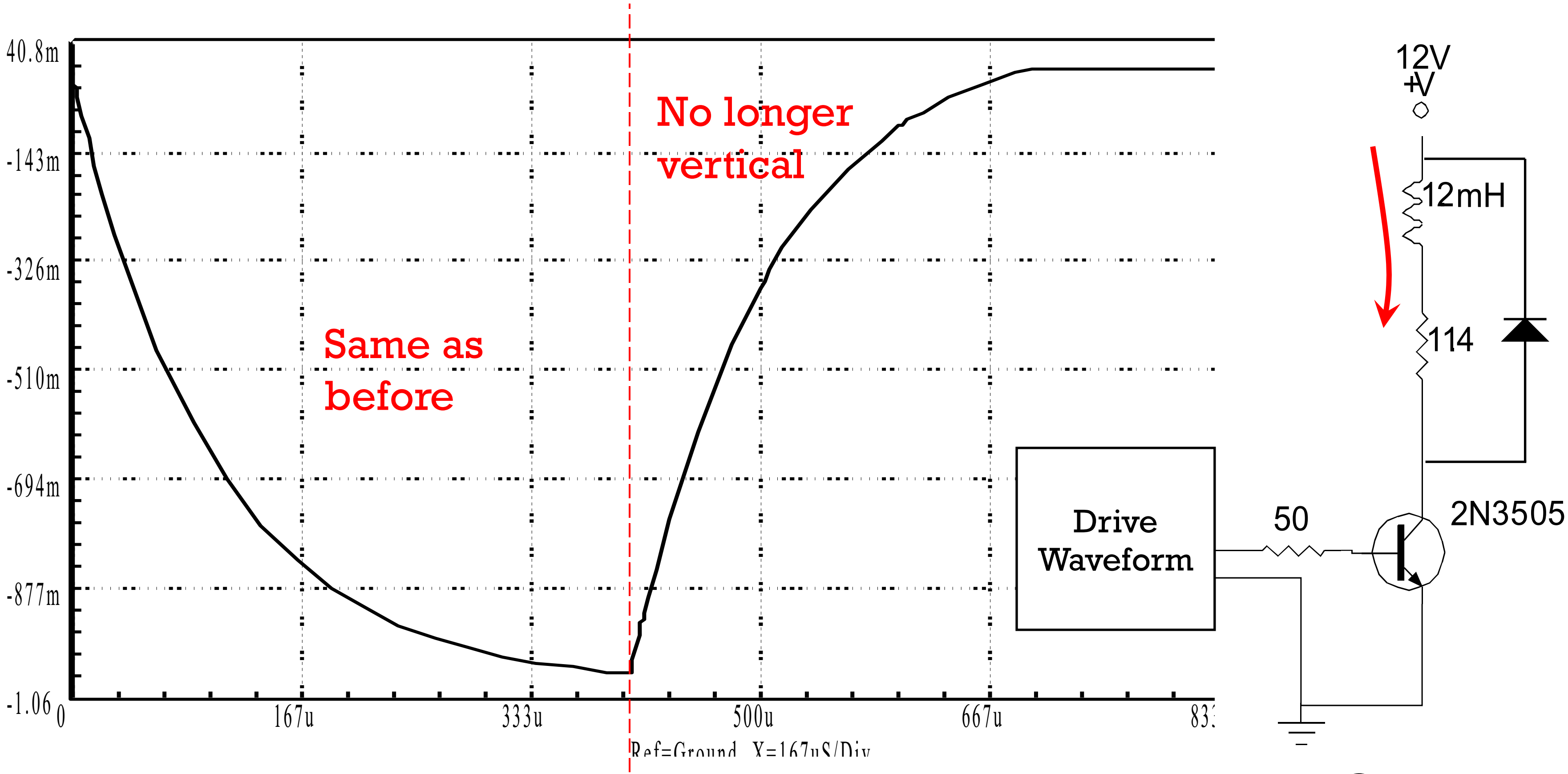


Collector Voltage with Diode Snubber



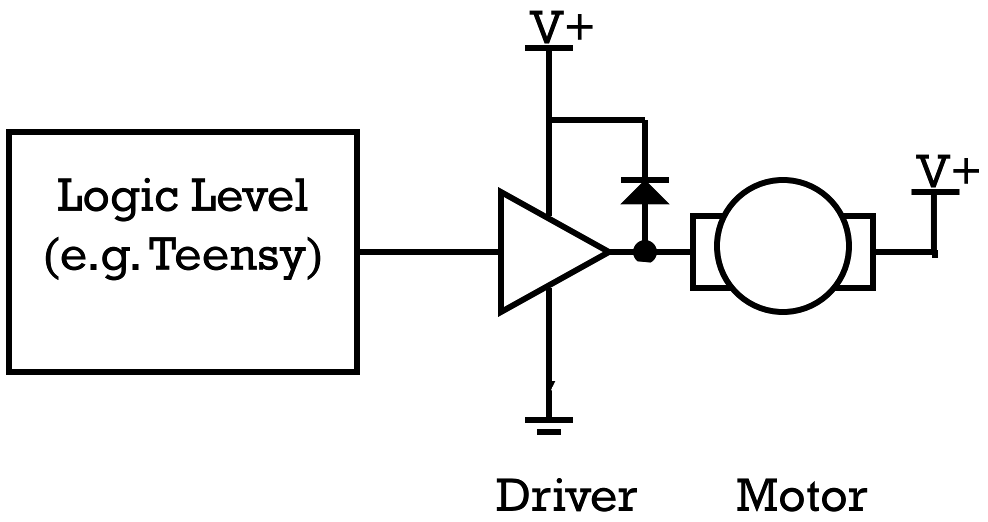
Circuit simulator (from Prof. Ed Carryer @ Stanford)

Inductor Current with Diode Snubber



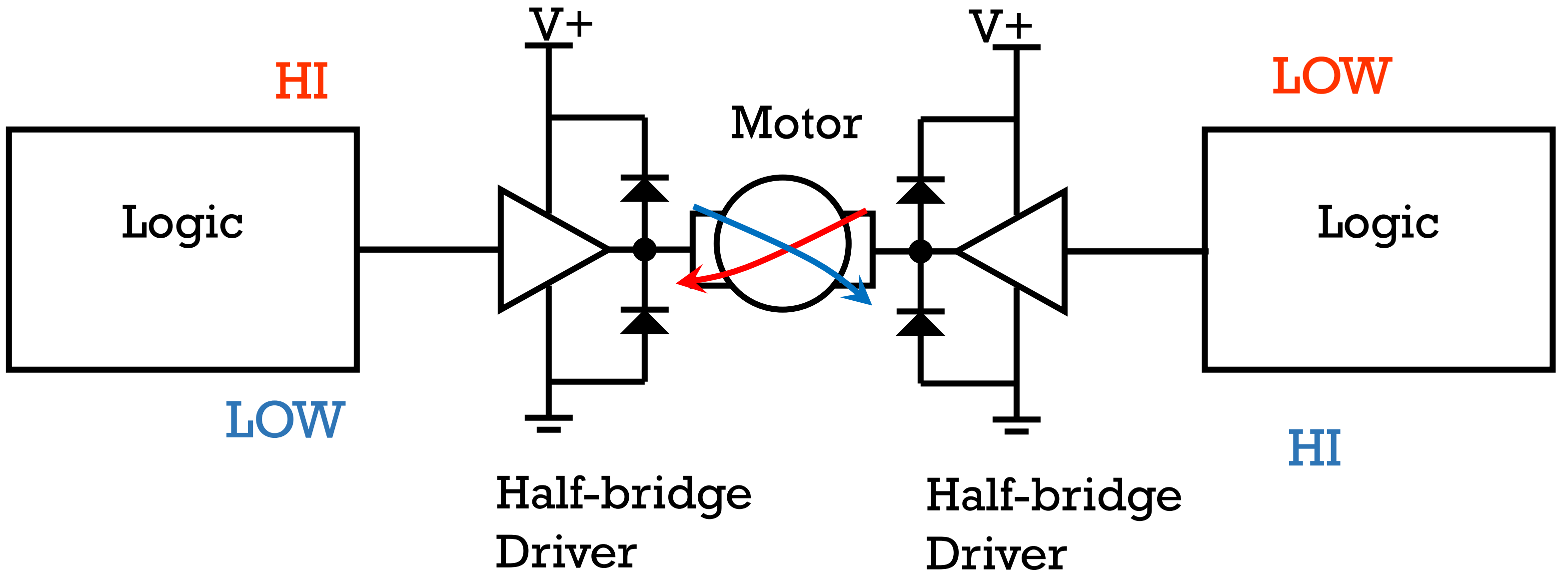
Circuit simulator (from Prof. Ed Carryer @ Stanford)

So how do we drive a motor with Logic output?



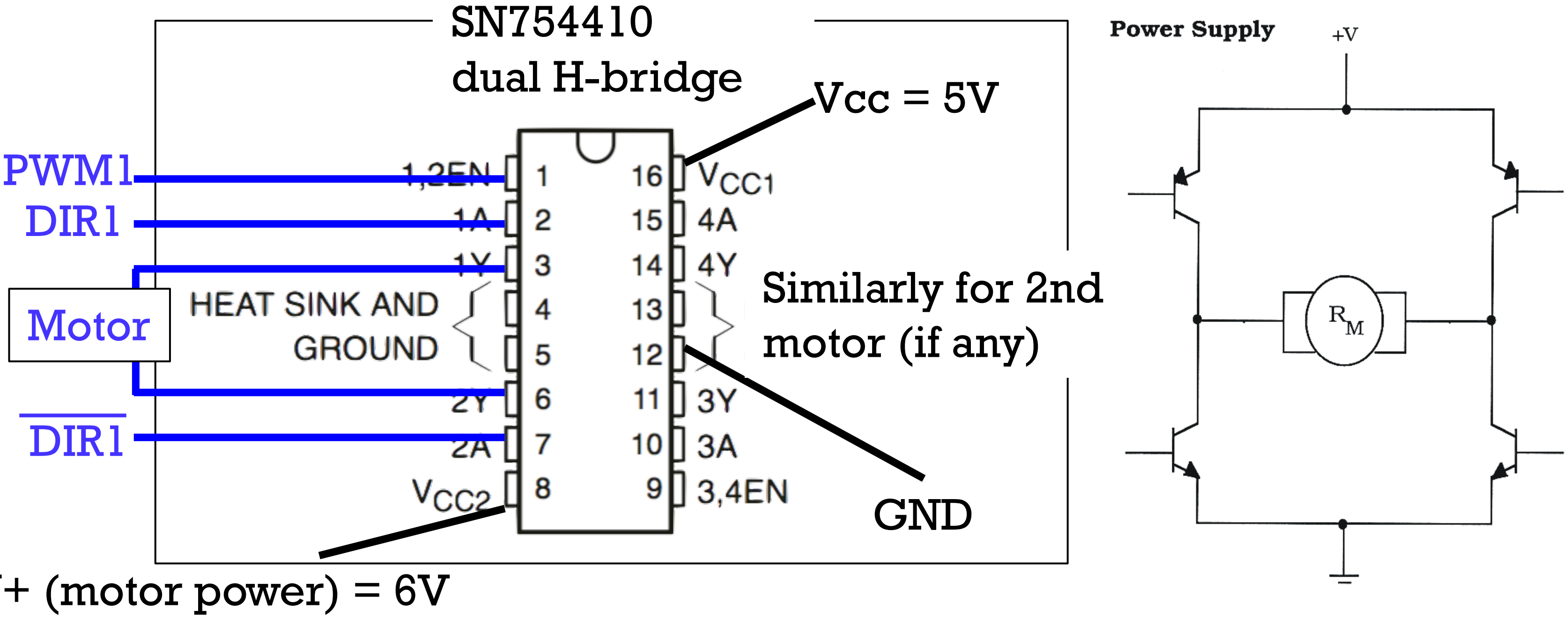
Q9: Draw a snubber diode for the protecting against a negative spike

Two half-bridges w/clamping diodes

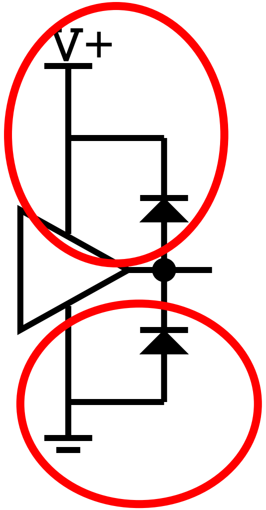


H-Bridge in your kit SN754410

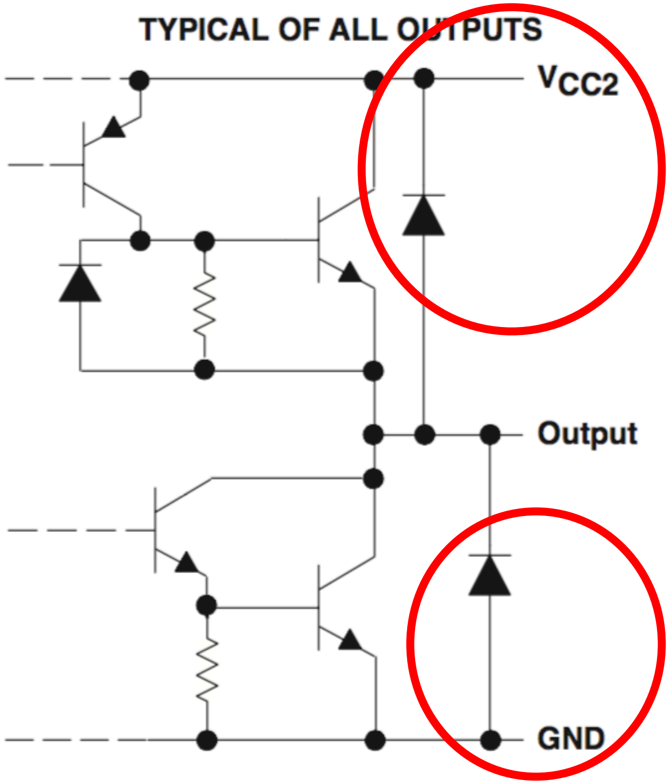
- When using the h-bridge to switch directions on a motor in the circuit below, it will be equivalent to swapping 6V and ground across the motor.



SN754410 output stage w/diode clamps

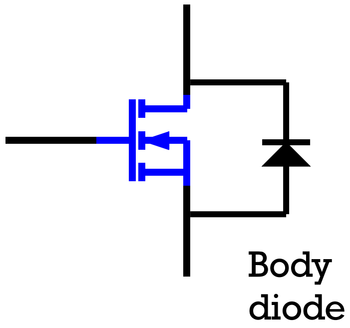


From SN754410 Datasheet:

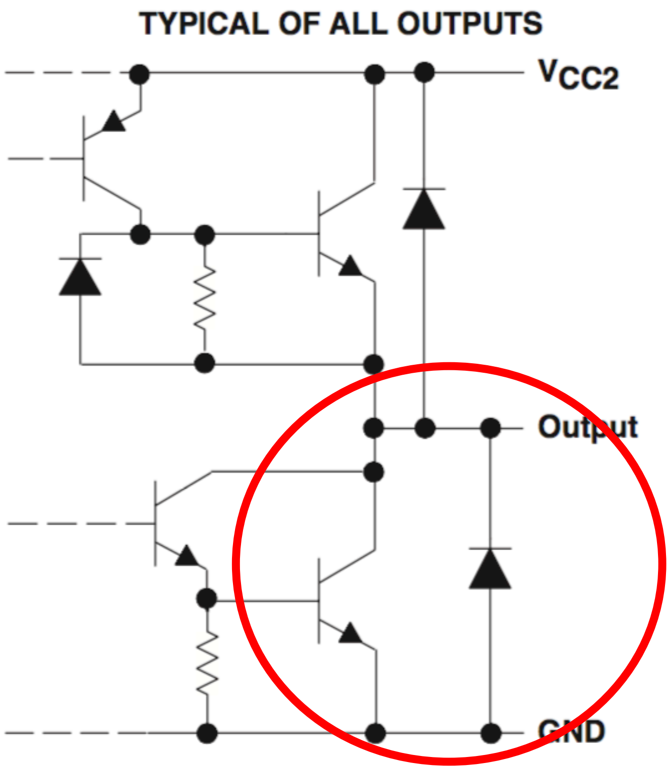


MOSFETs Body Diode

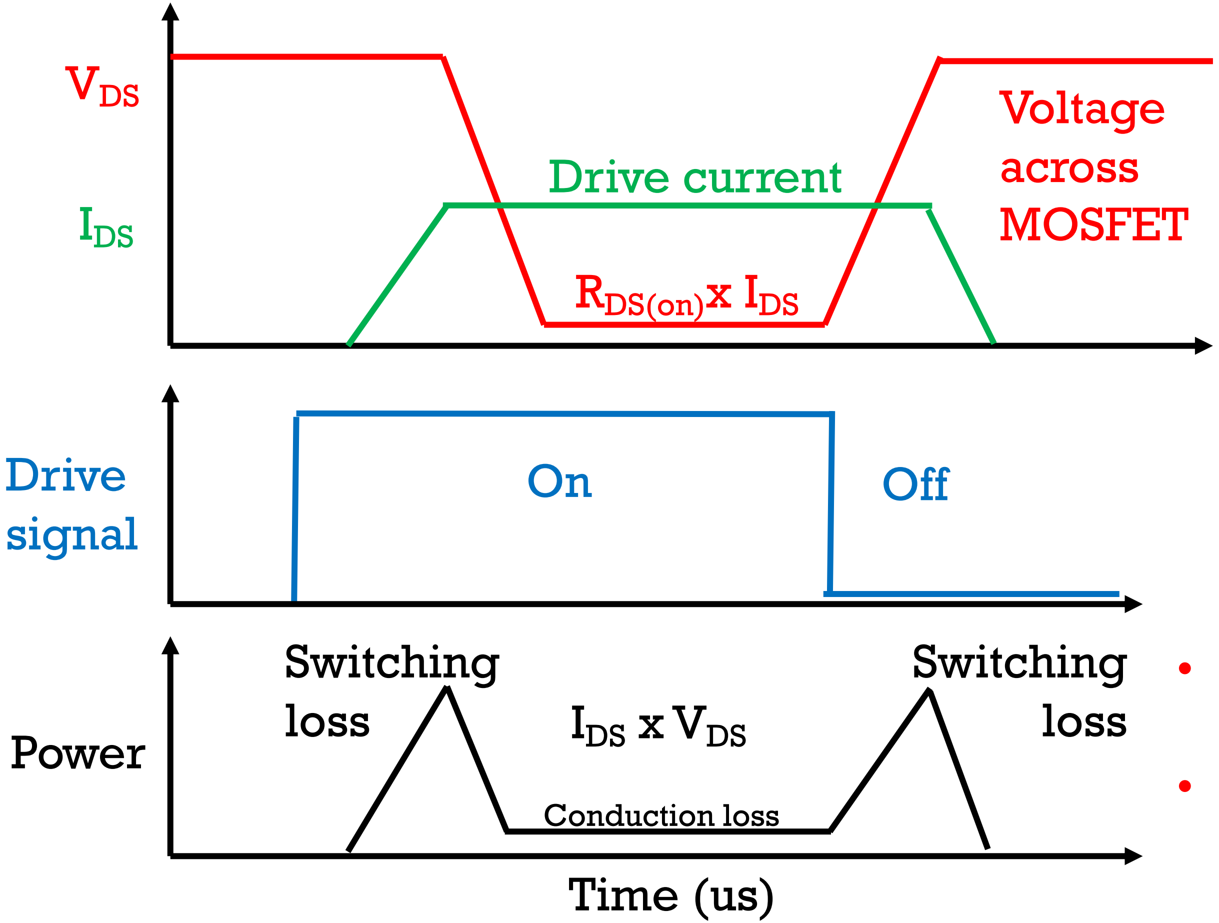
- Most FETS (MOSFETs) have an inherent diode called the *body diode*
- Turns out to be convenient for inductive protection.



From SN754410 Datasheet:



MOSFET caveat when driving Large Currents



- Power is consumed in the driver during switching
- This becomes **HEAT**.
- 2nd most common cause of "smoking" chips in this class.

- Need to drive gate quickly (minimize resistance)
- Don't use high freq. PWM

Caveat with SN754410

SN754410
QUADRUPLE HALF-H DRIVER

SLRS007B – NOVEMBER 1986 – REVISED NOVEMBER 1995

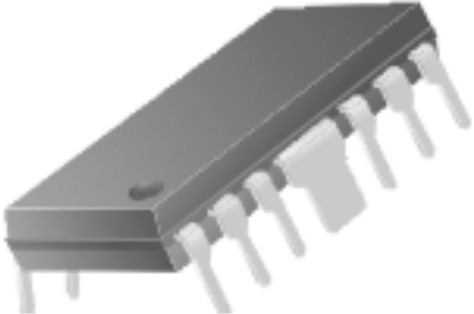
electrical characteristics over recommended ranges of supply voltage and free-air temperature (unless otherwise noted)

PARAMETER		TEST CONDITIONS	MIN	TYP†	MAX	UNIT
V_{IK}	Input clamp voltage	$I_I = -12$ mA		-0.9	-1.5	V
V_{OH}	High-level output voltage	$I_{OH} = -0.5$ A	$V_{CC2}-1.5$	$V_{CC2}-1.1$		V
		$I_{OH} = -1$ A	$V_{CC2}-2$			
		$I_{OH} = -1$ A, $T_J = 25°C$	$V_{CC2}-1.8$	$V_{CC2}-1.4$		
V_{OL}	Low-level output voltage	$I_{OL} = 0.5$ A		1	1.4	V
		$I_{OL} = 1$ A			2	
		$I_{OL} = 1$ A, $T_J = 25°C$		1.2	1.8	

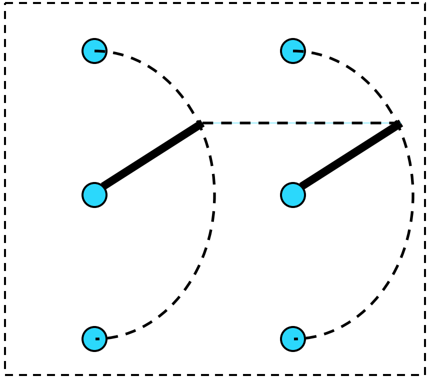
Q10: What if you were driving a motor with 5V, what is the worst case scenario for motor performance (i,e., smallest voltage across the motor?)

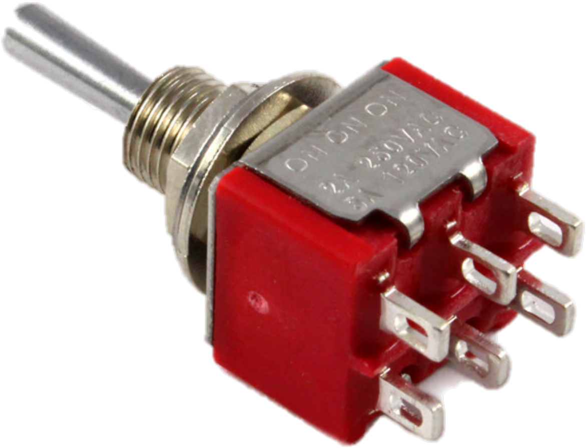
FAN8100

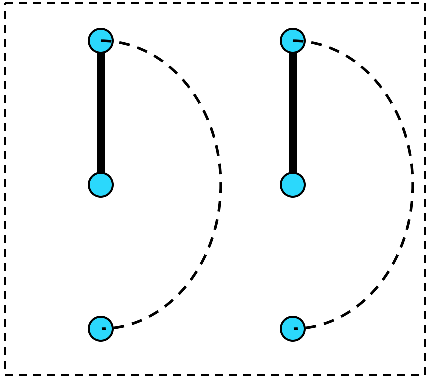
- Obsolete chip from Rochester Electronics LLC (sells large min qty obsolete stock for cheap...)
- Has better V_{OH}. Better current driving 1.5A ea channel
- Datasheet available on Canvas -> files-> Resources
- Caveat: double wide ground pins are used as heatsink fins (won't fit in protoboard)



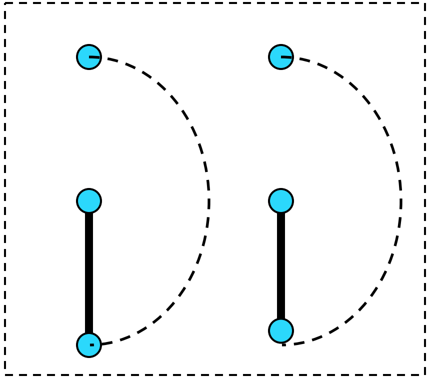
Double pole double throw switch





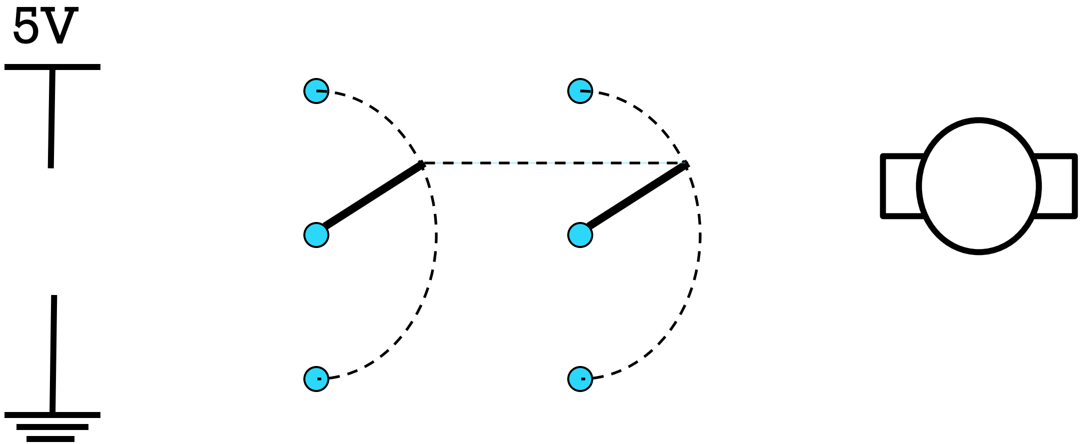


Switch up



Switch down

Double pole double throw switch as h-bridge



Q8: Connect power ground and motor leads to the 6 leads of a DPDT connections to form an h-bridge

Summary

- Motors are more energy efficient towards higher speeds
- Motors have maximum power at half max torque.
- Large currents require special drivers.
- Driving motors and solenoids can lead to large voltage spikes.
- Snubber diodes protect from these spikes.
- H-Bridges can be used to drive current bi-directionally.
- MOSFETs are the trend for drivers. BJT's are on the way out.

Answer in Chat

Answer how you feel about each topic below with:

1. I don't understand this topic at all
2. I don't know now, but know what to do to get by
3. I understand some, but expect to get the rest later
4. I understand completely already

A. Transistors (BJT / MOSFET)

B. Choosing Motors

C. Driving Motors with H-bridges