Lecture 14

DC Motors and driving them

Stuff

COVID19 RED PASS

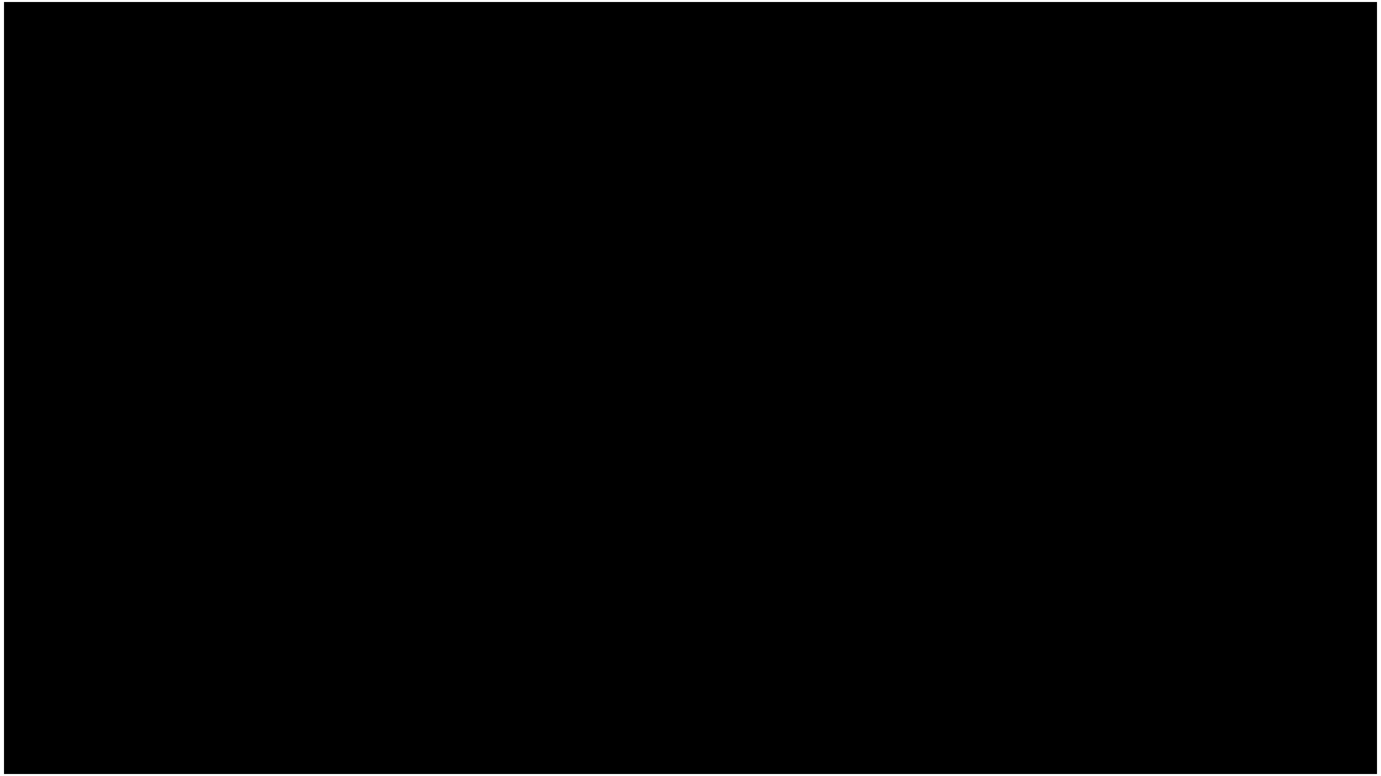
- Non-compliance red pass. Starting next week you will not be allowed in academic spaces (e.g. GMlab)
- To remove non-compliance Go to Dubois or Houston hall for screening test. No reservation required.
- Schedule bi-weekly tests to prevent redpass non-compliance.

Other news: laser cutting/3D printing at Tangen Hall

https://venturelab.smapply.io/prog/venture_lab_membership/

- Open and free to all university students
- Takes up to 15 days to process

Waldo Music – Feel it still – by Portugal the man



More Waldo stuff

- Grouped choreography: After 3.1, similar architecture projects will be grouped and have an optional "dance" routine to composite together into more interesting music video.
- Long Stem Potentiometers are back in stock. If you choose to use a different sensing modality you will receive extra credit.
- Waldo project feedback on Piazza thread:
  - Is my idea too difficult (hard to gauge difficulty)?
  - Is my idea too easy (will be graded poorly for lack of ambition)?

Agenda

01. DC Motors + Solenoids
02. Driving DC motors with H-bridges

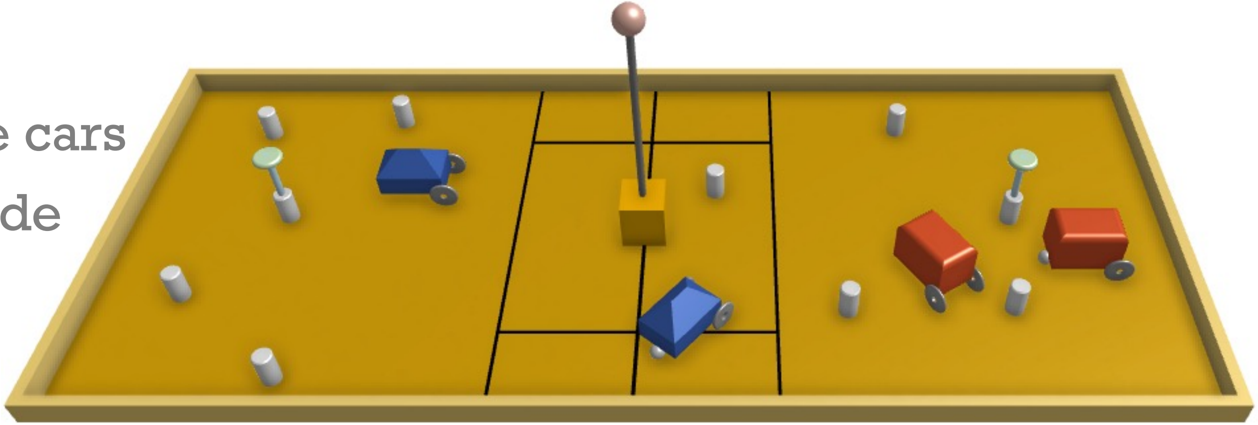
Motor Types

- Many kinds of electric motors:
  - DC motors,
  - AC motors,
  - Brushless motors,
  - Stepper motors,
  - Variable reluctance
  - Permanent magnet
- We will only focus on **DC motors**
  - Most common small motor
  - Simplest to control
  - Cheapest

Where to use motors in this class?

- Lab 4 will include little cars
- Final project will include

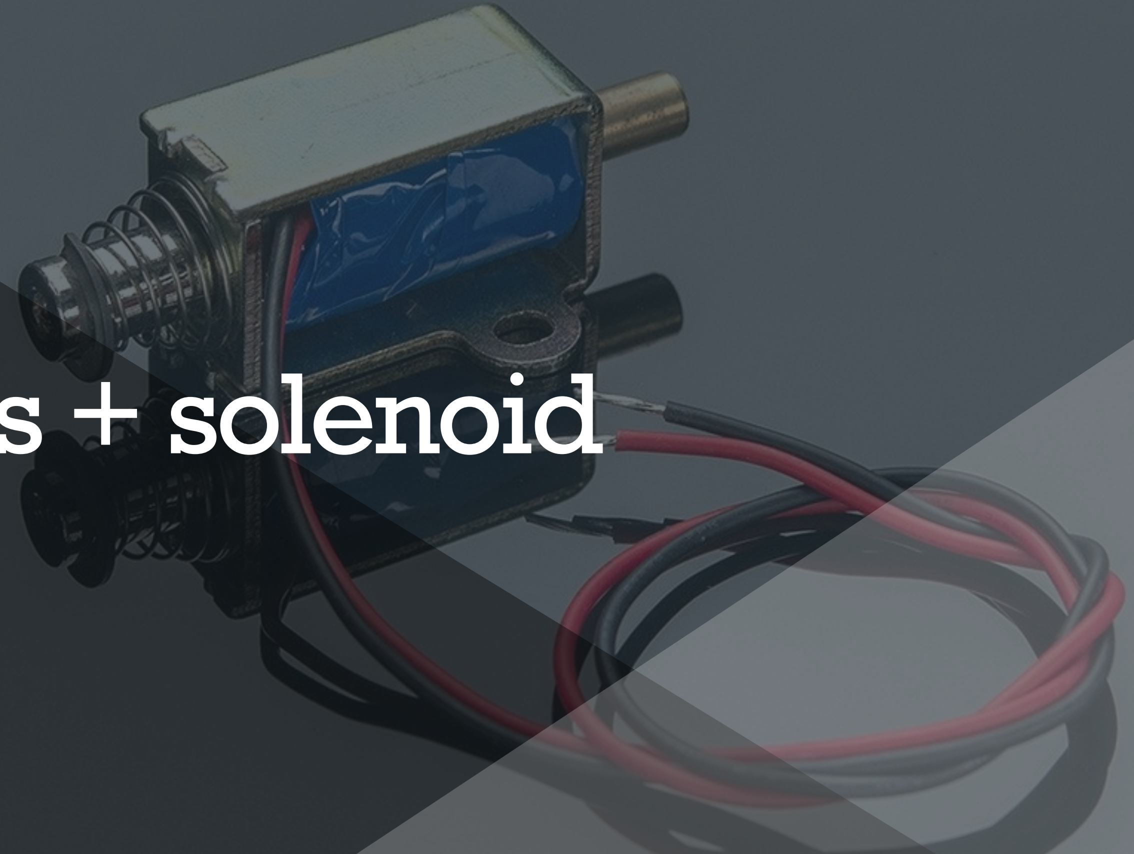
a mobile base



- You may choose motors that will enable fast/strong mobile bases.
- There maybe contact (pushing contests) between vehicles. The winner will often be determined by the chosen motor.

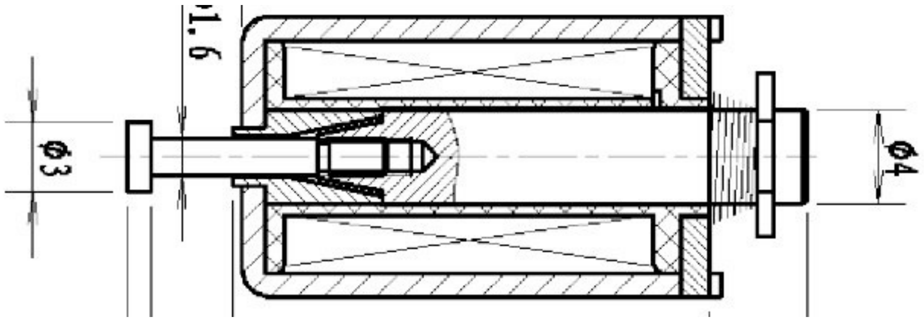
02

DC Motors + solenoid



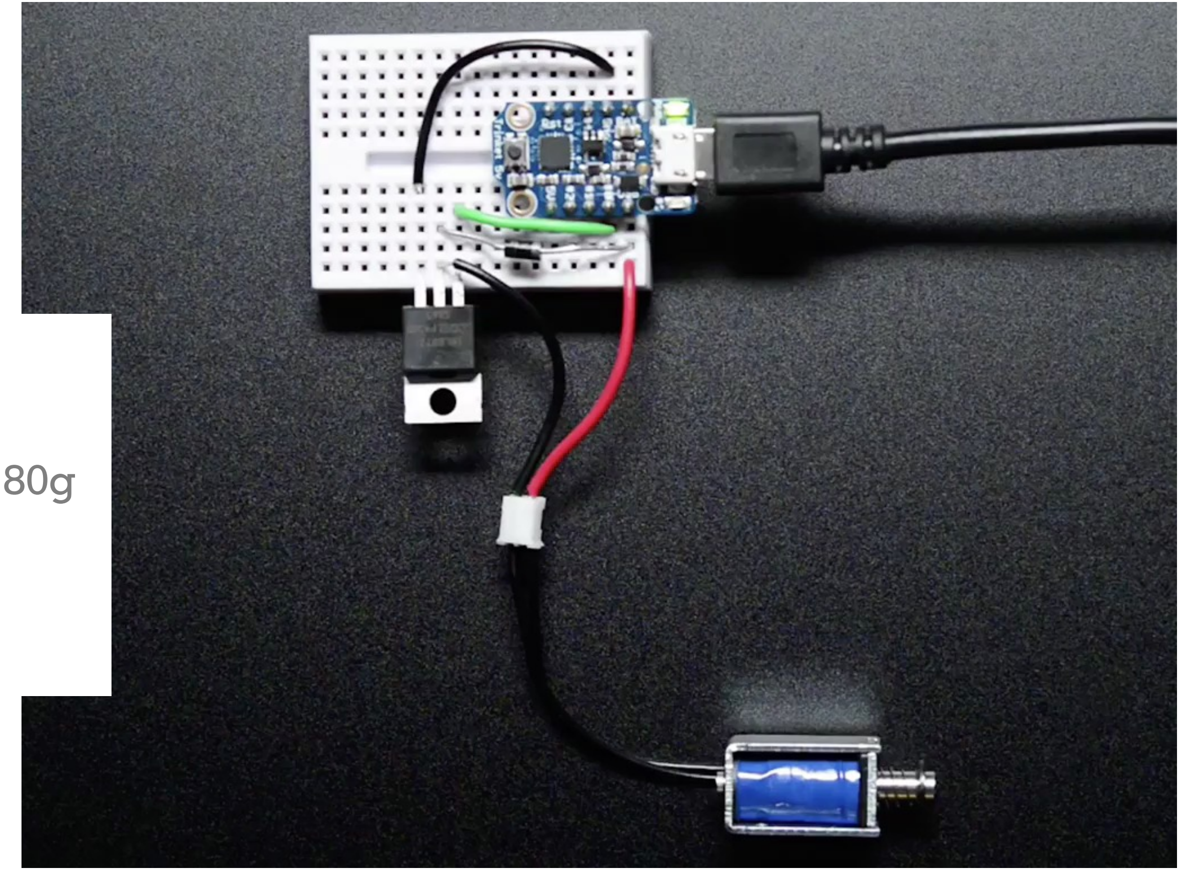
What is a solenoid?

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



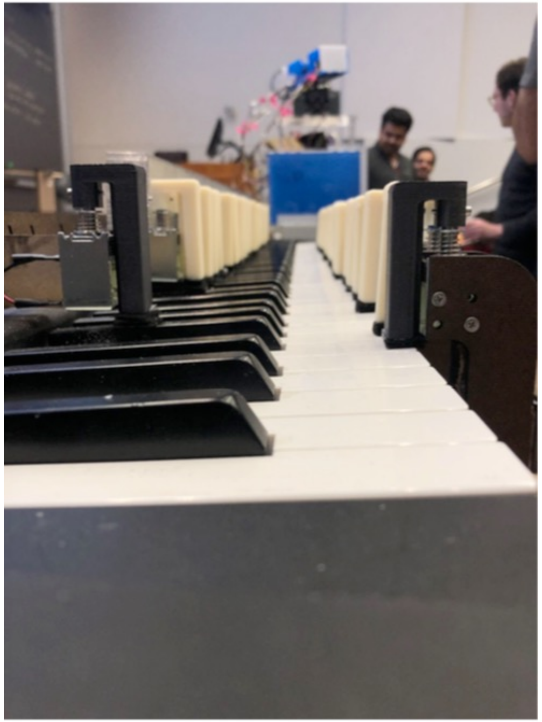
Mini Push-Pull Solenoid (in GM lab)

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



MEAM516 2019 – Solenoid driven music

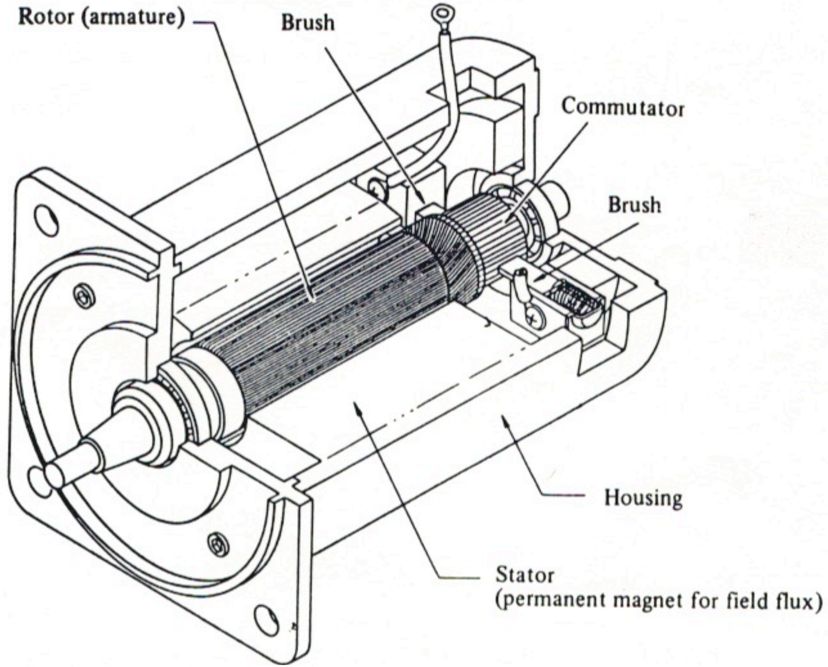
Andrew and his team

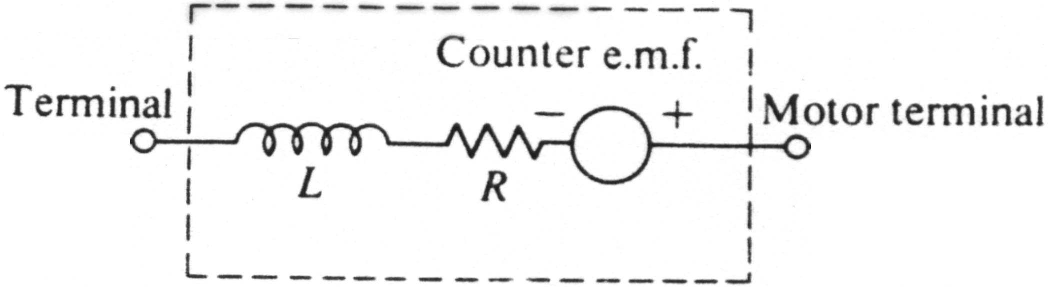


Shaun, Allie and their team

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

Ideal Electrical Model of a DC motor

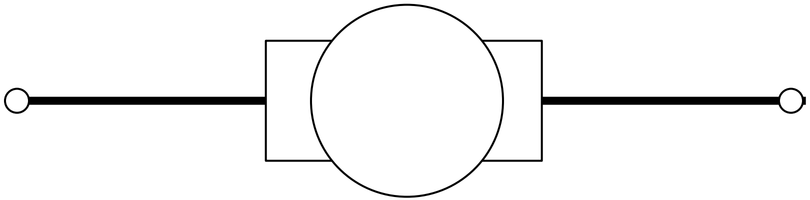




Actuators: Important properties?

Inputs:
- Voltage
- Current

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



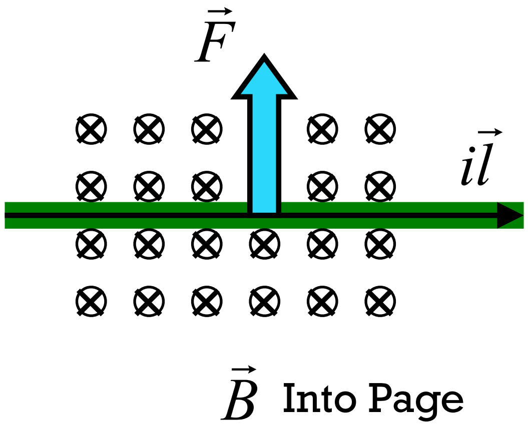
Motor

Solenoid (coil)

Basic Physics: Lorenz Force

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

Force on a Wire Carrying Current Through a Magnetic Field



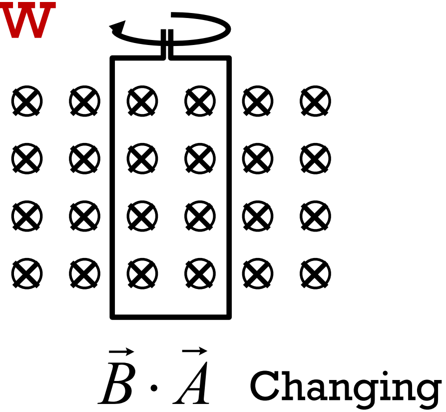
$$\boxed{\tau = K_T i}$$

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

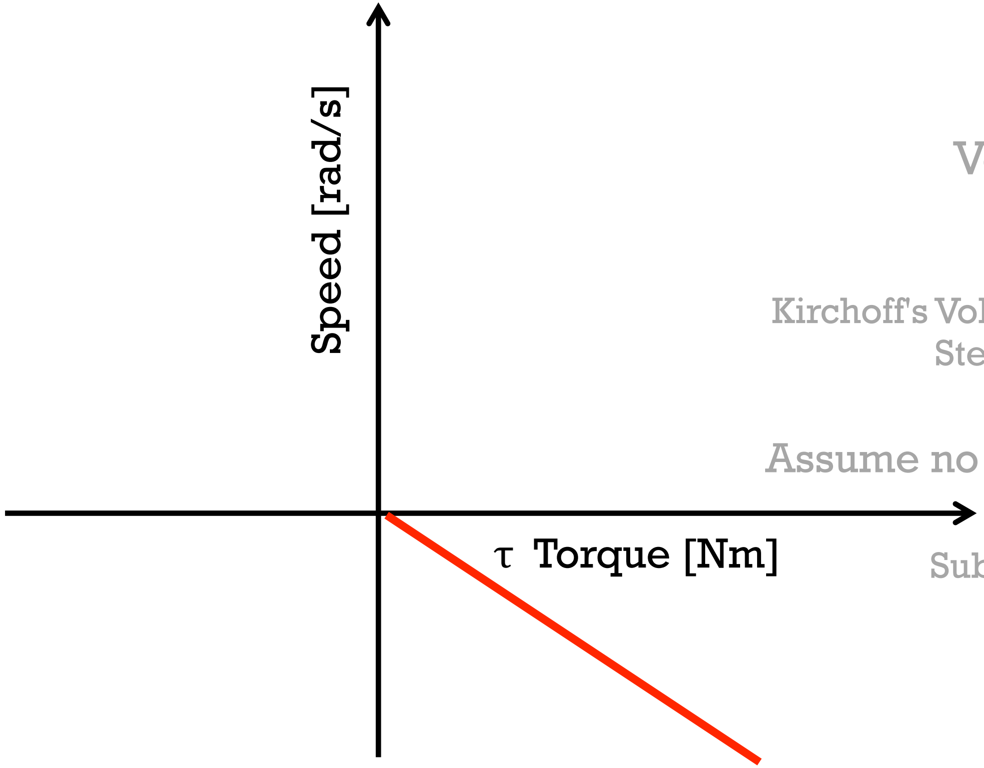


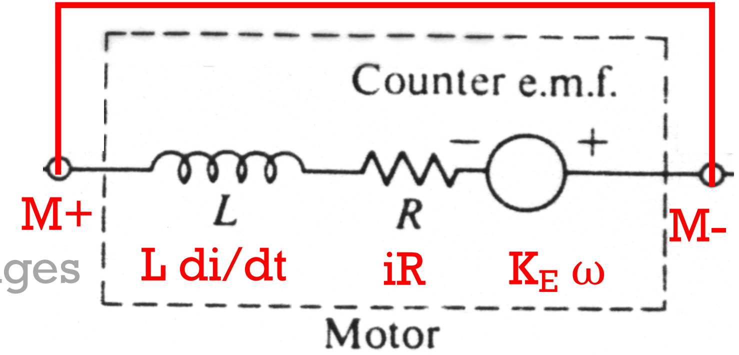
$$\boxed{V = K_E \omega}$$

For some motor with speed constant K_E

Ideal Electrical Model of a DC motor (alone)

Q1: Plot Speed vs Torque





Voltages

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

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

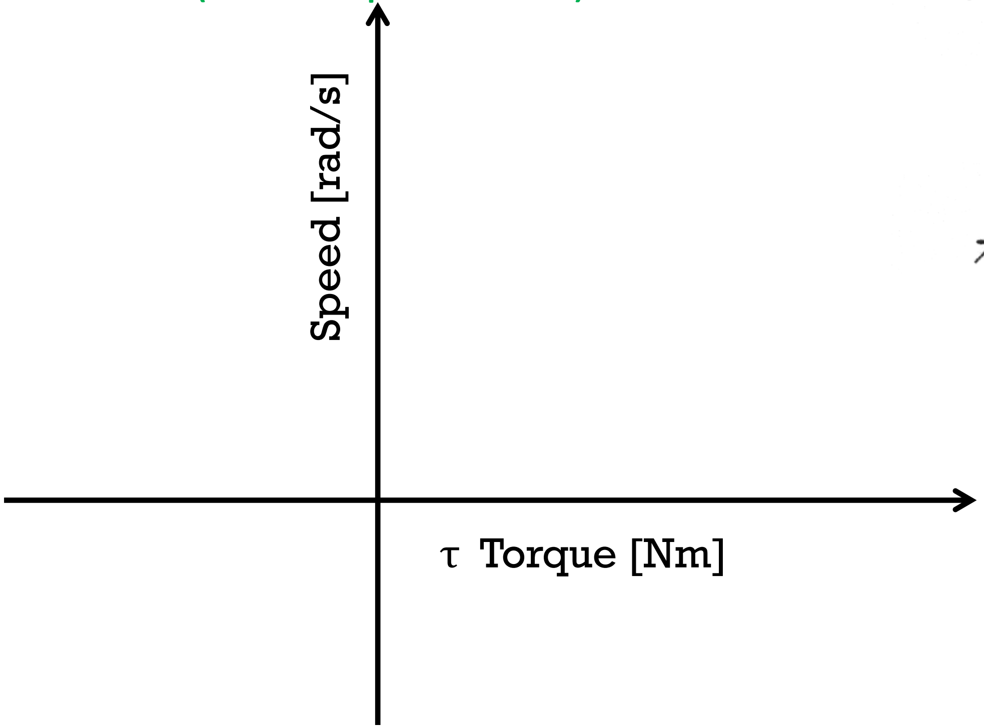
Assume no friction $\tau = K_T i$

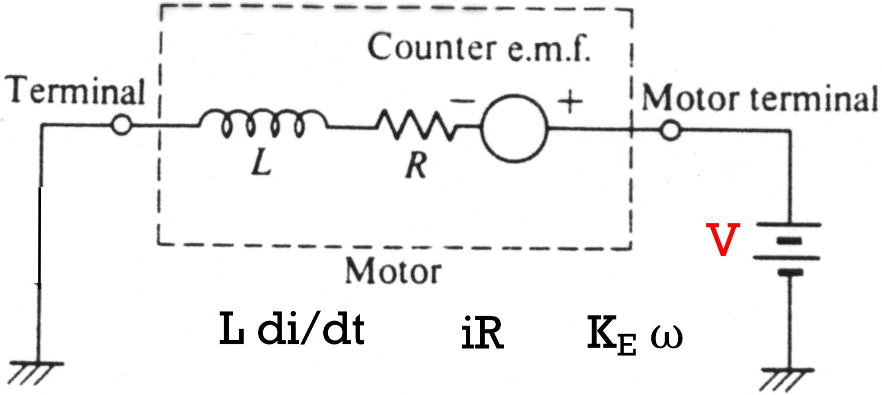
Substitution $0 = 0 + \tau R/K_T + K_E\,\omega$

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?)





$L\,di/dt \qquad iR \qquad K_E\,\omega$

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

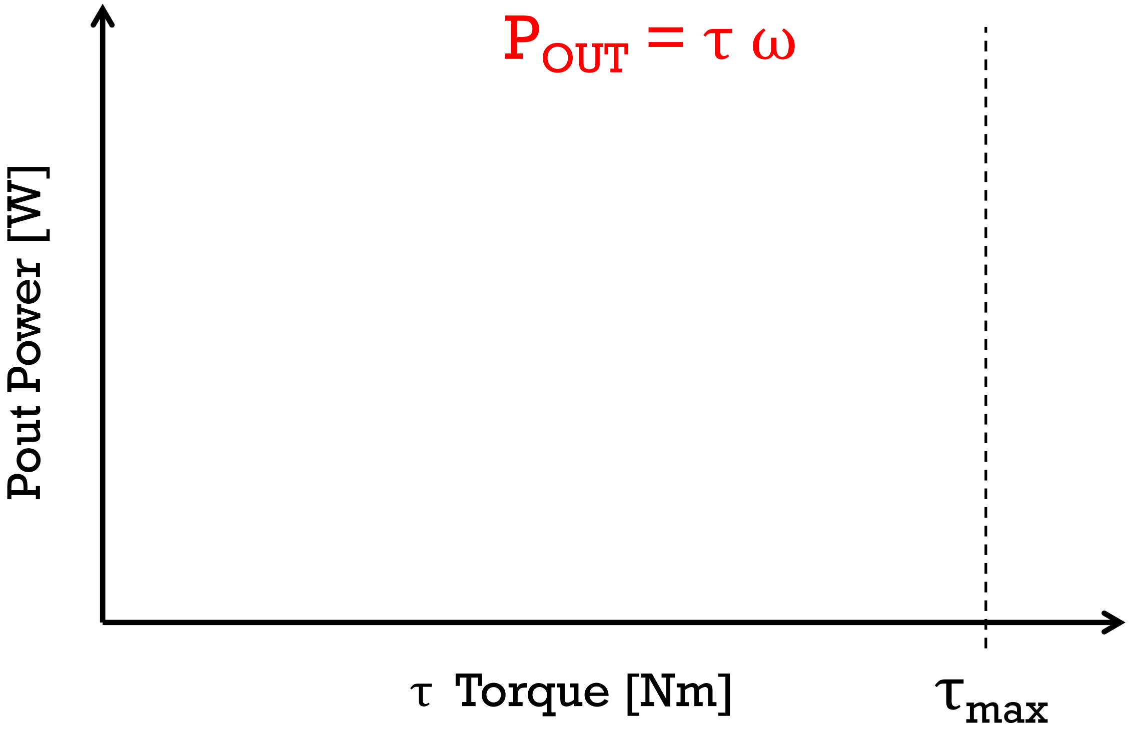
$$V = 0 + iR + K_E\,\omega$$

$$\tau = K_T i$$

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

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

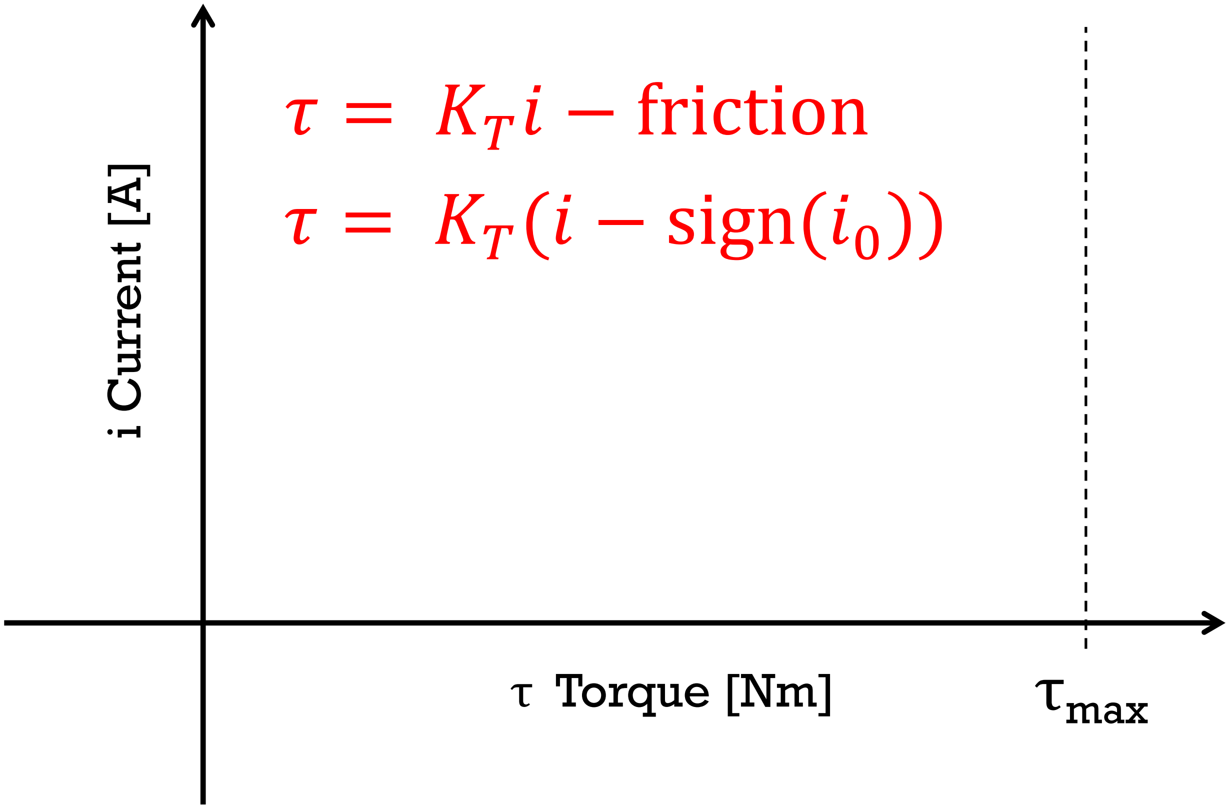
Q3: Plot (Mechanical) Output Power vs Torque (Does the curve hit the origin?)



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

$$\tau = K_T i - \text{friction}$$

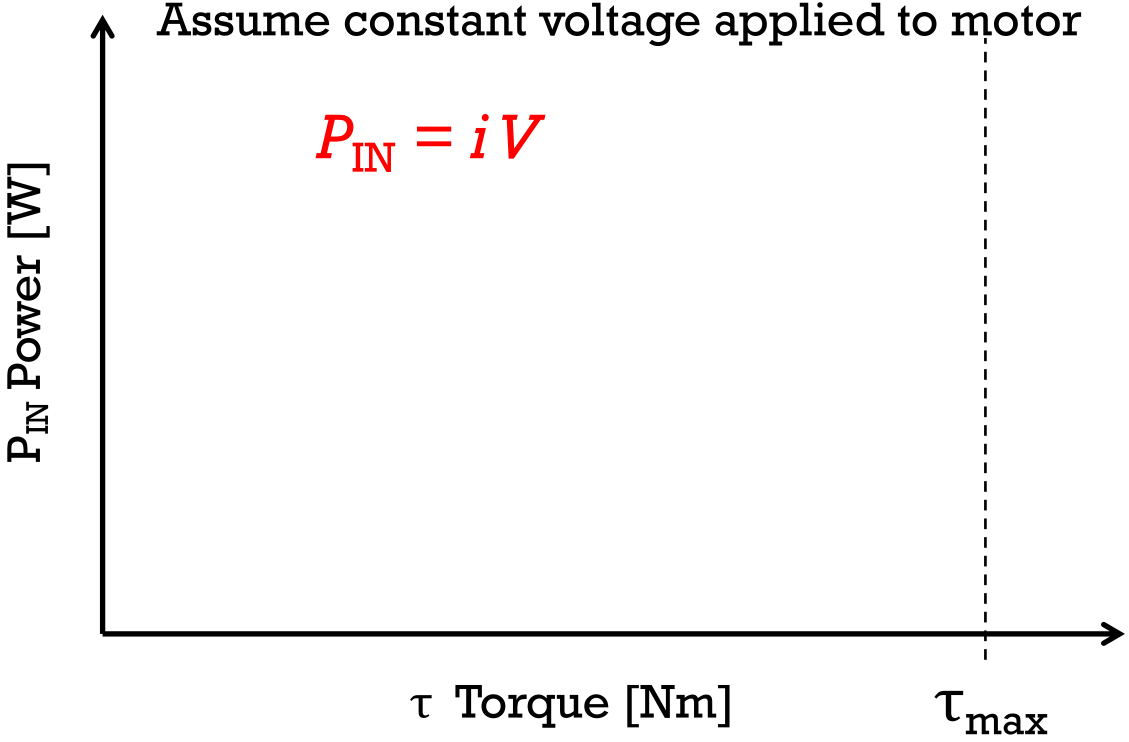
$$\tau = K_T(i - \text{sign}(i_0))$$



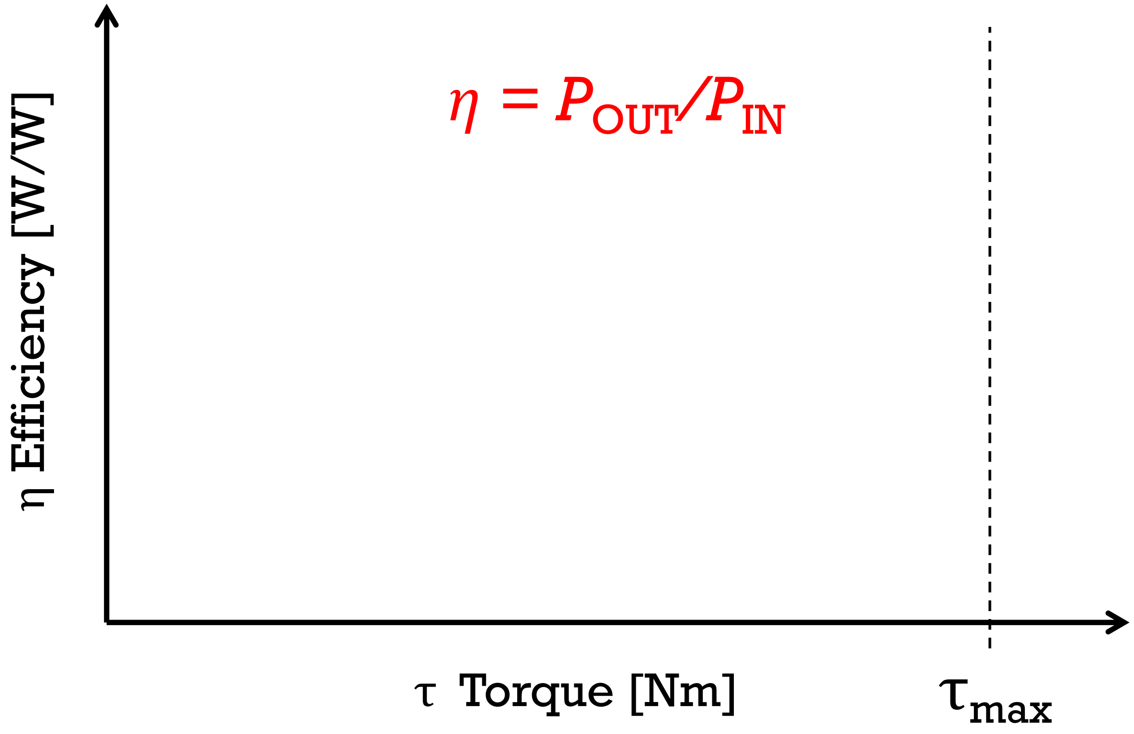
Q5: Plot (Electrical) Input Power vs Torque (Does the curve hit the origin?)

Assume constant voltage applied to motor

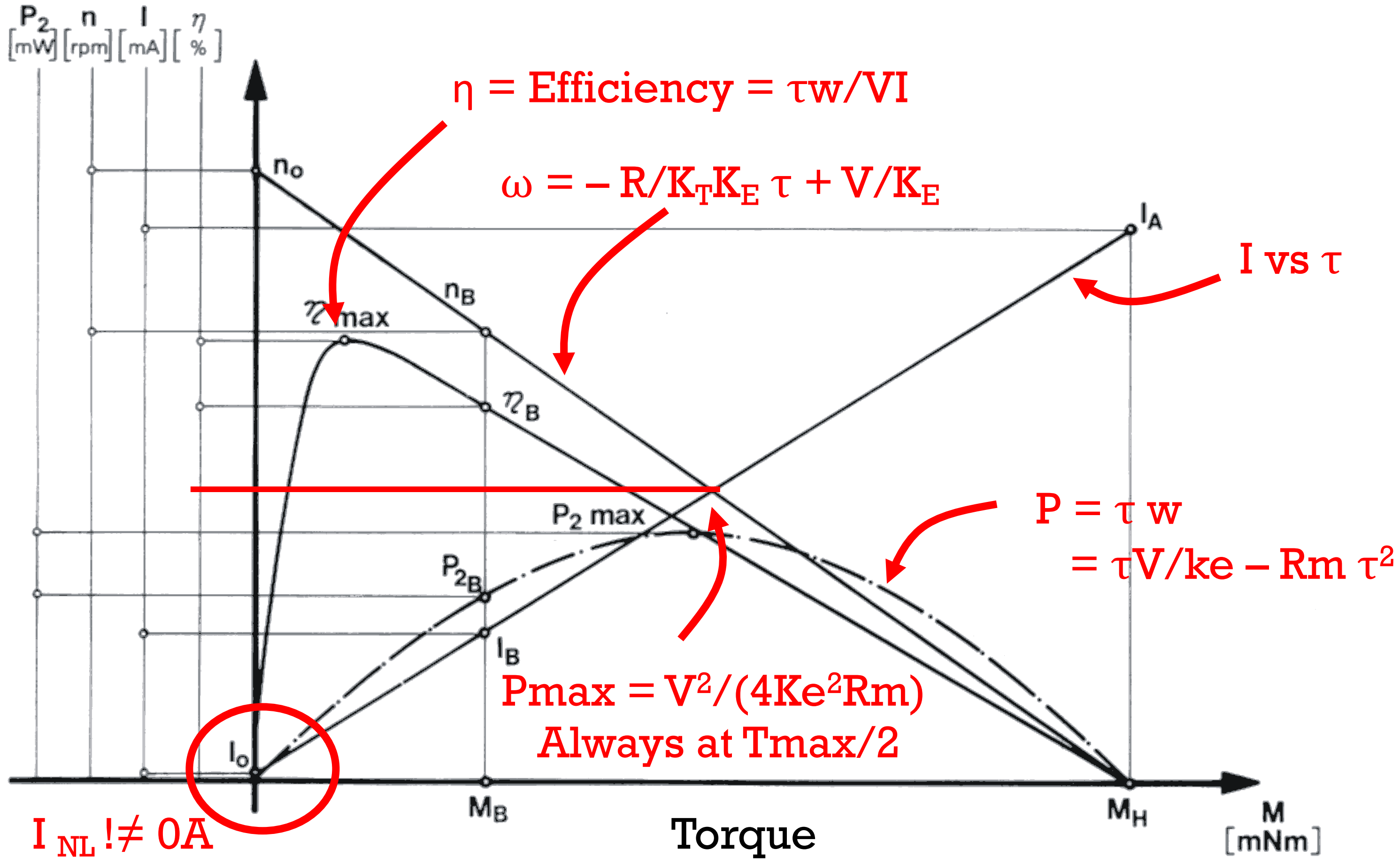
$$P_{\mathrm{IN}} = iV$$



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



Torque vs Everything (for constant motor 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:

$K_T = 1.3524K_E$ [oz-in/A ; V/krpm]

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

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

Motor exercise

You are handed a motor. The only documentation that you can find shows that the motor chosen has Kt = 9.33 in.-oz./A and produces 2.8 in.-oz. at stall when driven at 12V. The design requires that the motor deliver 0.4 in.-oz. at 1500 rpm. The motor was supposed to be driven from a 12V supply. Your boss has asked you:

a) How can I find out how much current the motor will draw at stall ?

b) What is Ke ?

c) How can I find the coil resistance ?

d) Will the design meet the requirements for torque at the given speed? If not, what changes could you suggest? .

e) Estimate the current required when running at the design point.

You may assume that there are no internal losses within the motor.

for reference: $K_T = 1.3524 K_E$ [oz-in/A ; V/krpm]

DC Motor Specs

(Maxon Motor catalog)

Labeled by power rating

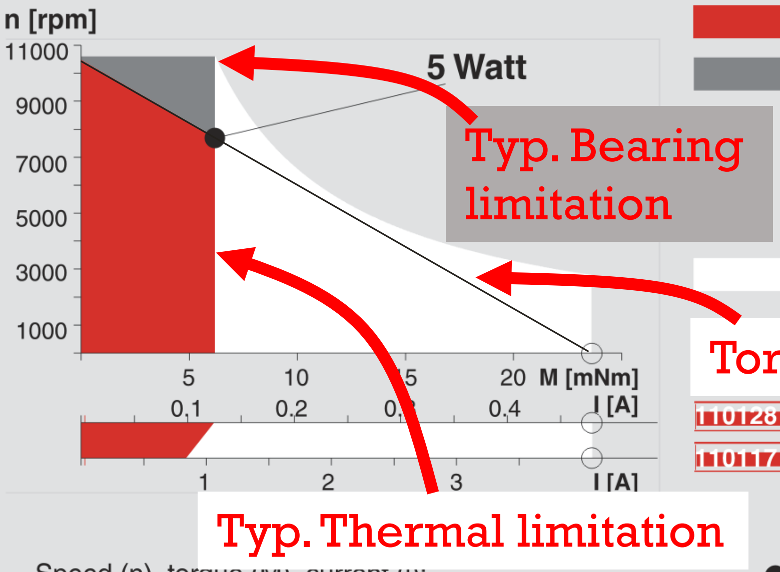
Stall current?

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	1220	972	[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).

Torque Speed Curve

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)

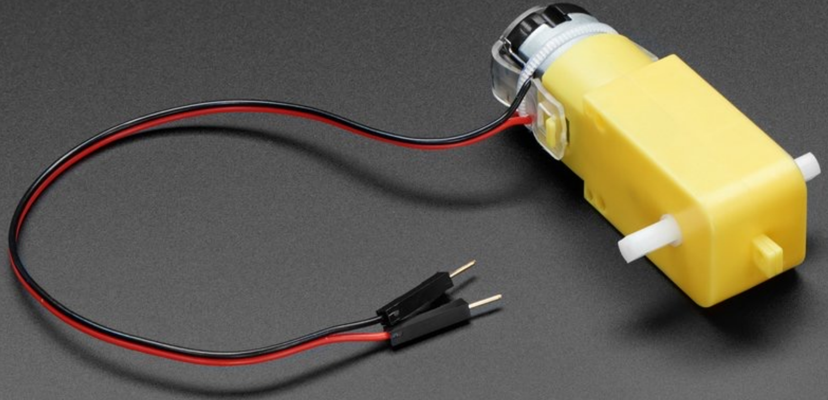
○ Starting current I_A at nominal voltage (Line 7) as well as related stall torque

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

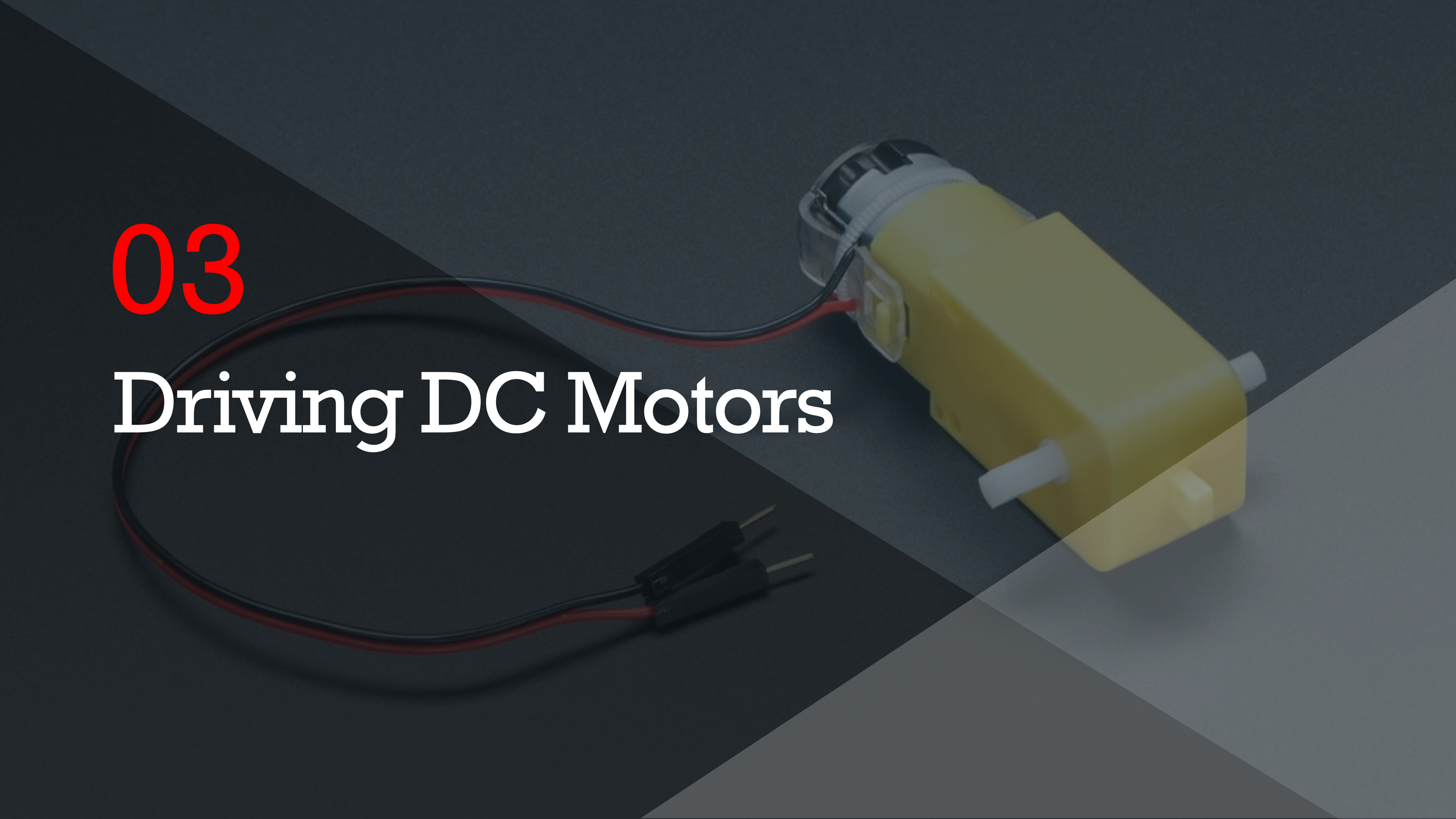
110128 Winding number with the related current curve at the appropriate torque.

Motors provided for Lab 4

- 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

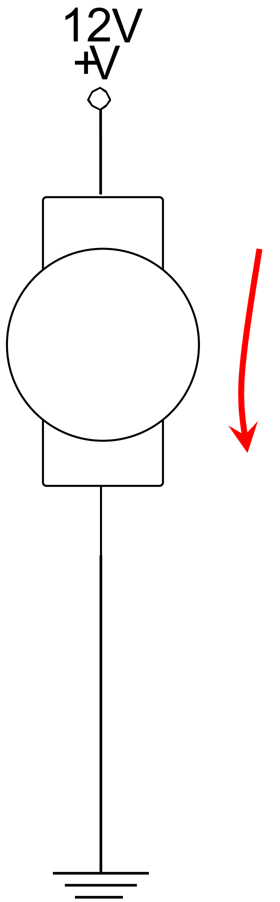

03
Driving DC Motors

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 for Lab 4 ~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

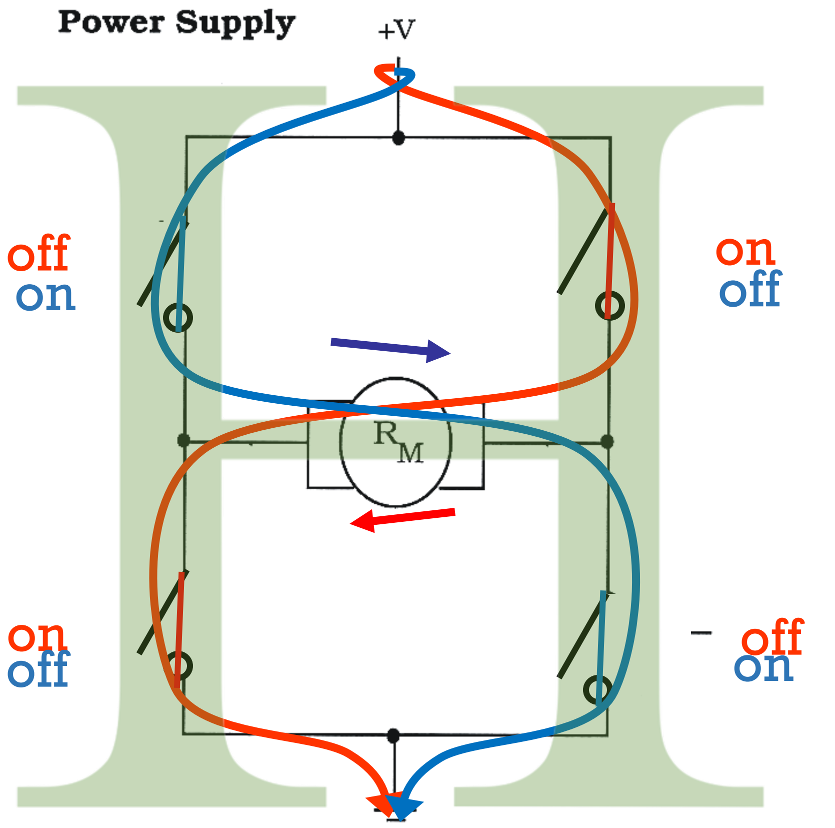
GM Lab Options for Driving Large Currents

- 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



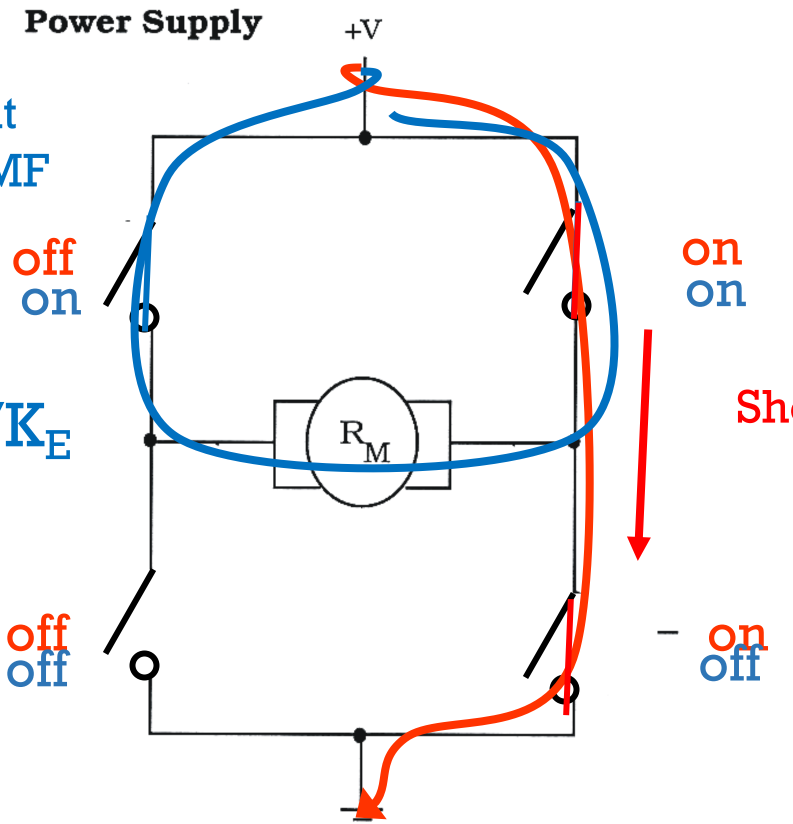
Change current in motor changes direction

Other Switch Options

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

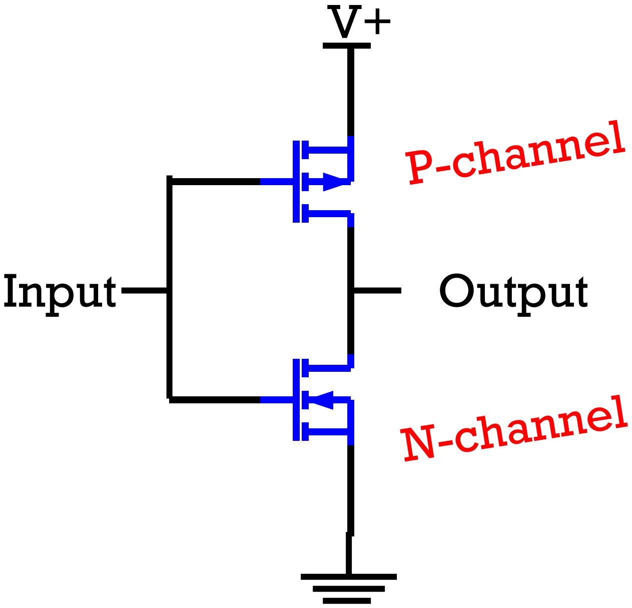
$$\omega = -R/K_T K_E\,\tau + V/K_E$$

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

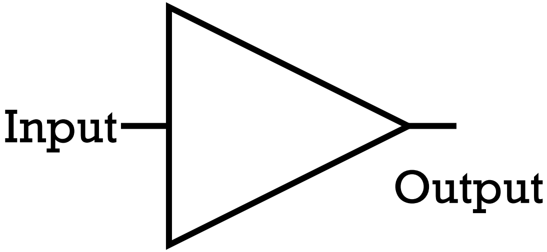


Short from V+ to GND
Very bad!

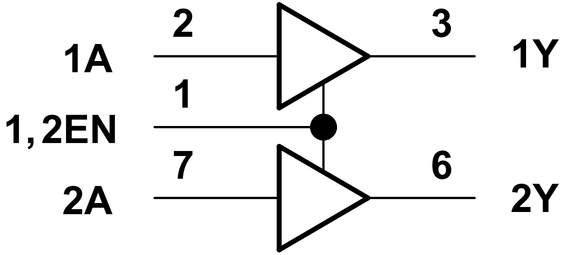
Half H-Bridge



Rough schematic



Half-bridge Symbol

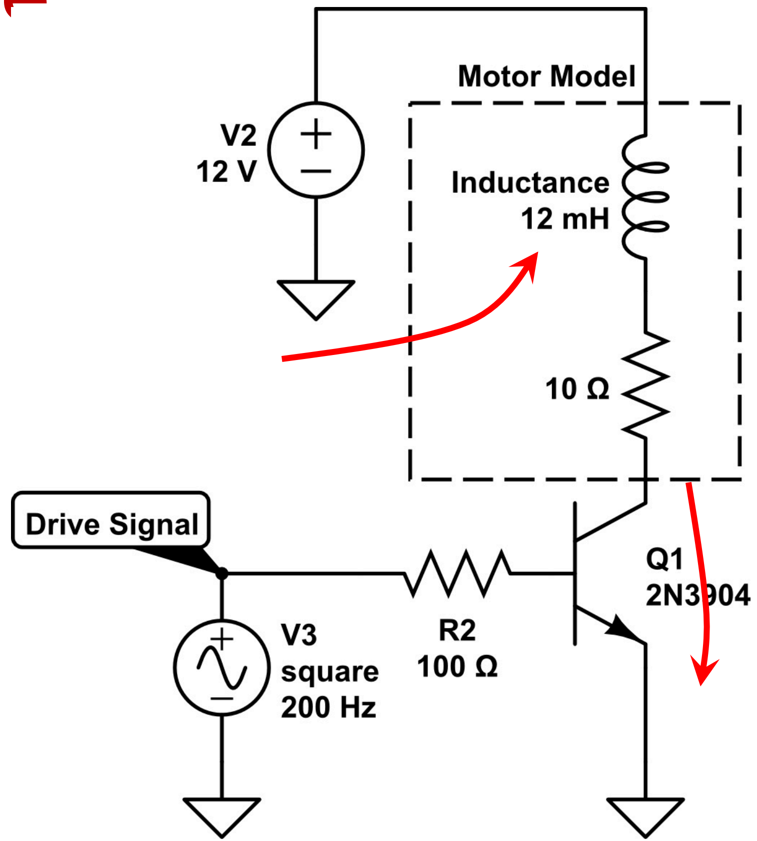


Typ H-bridge Schematic

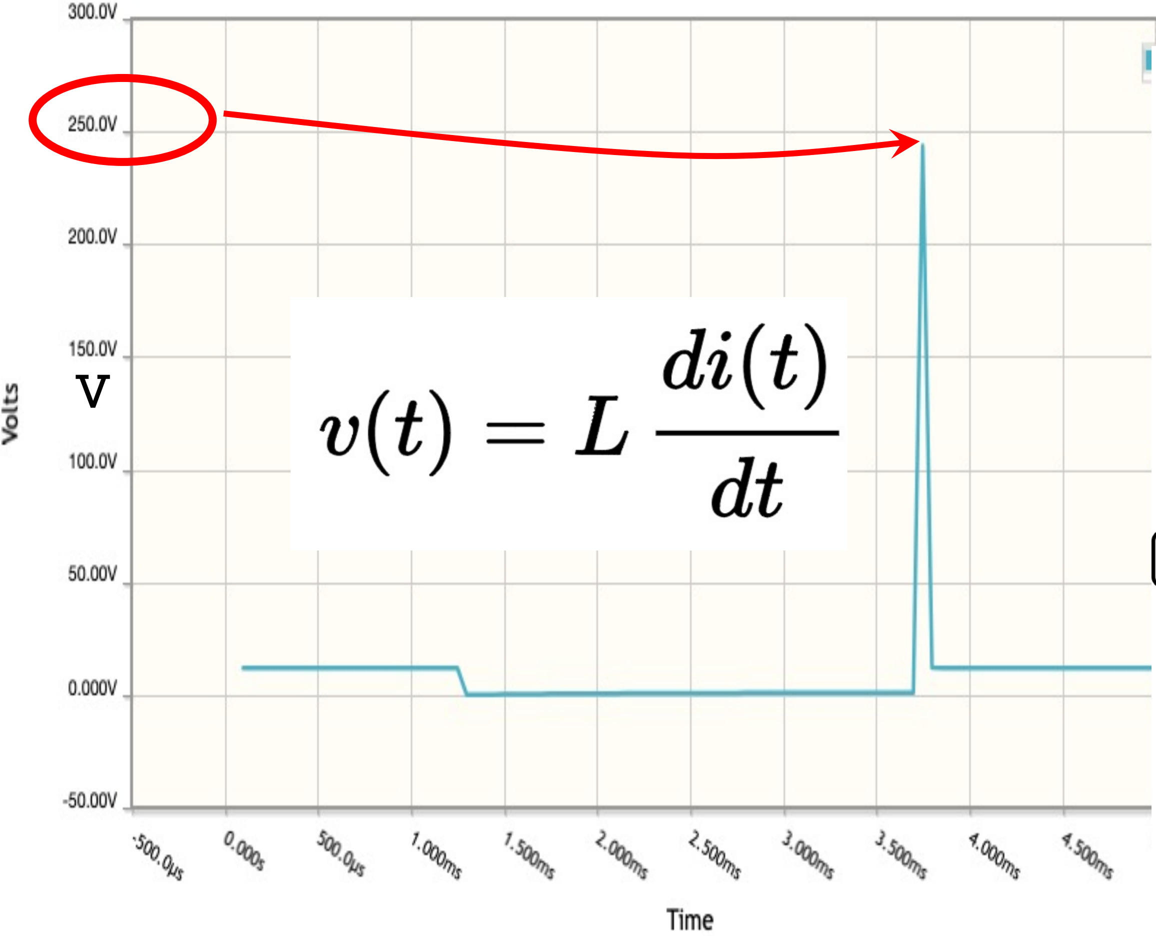
Recall
Effect of Large Inductance

Circuit simulation package

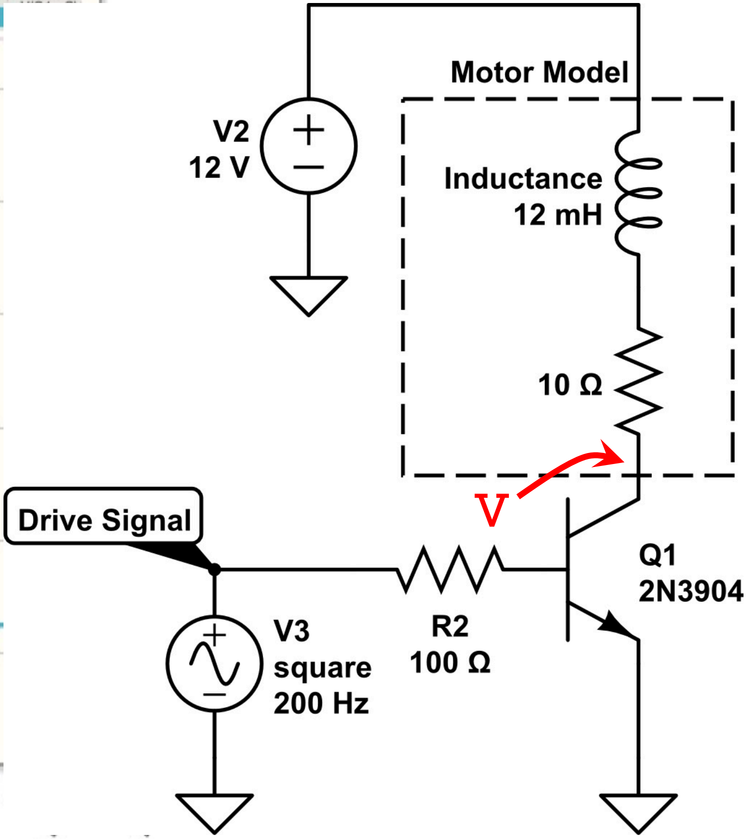
$$v(t) = L\frac{di(t)}{dt}$$



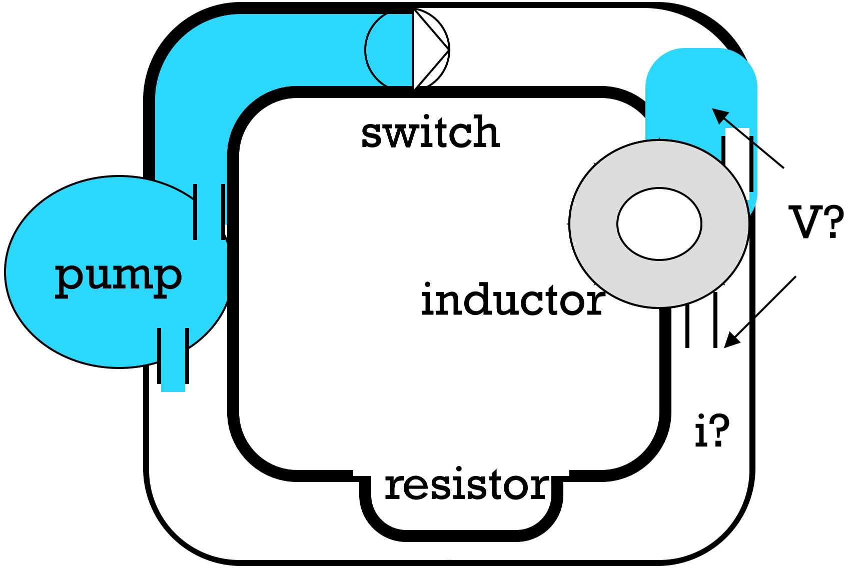
Collector Voltage



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



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

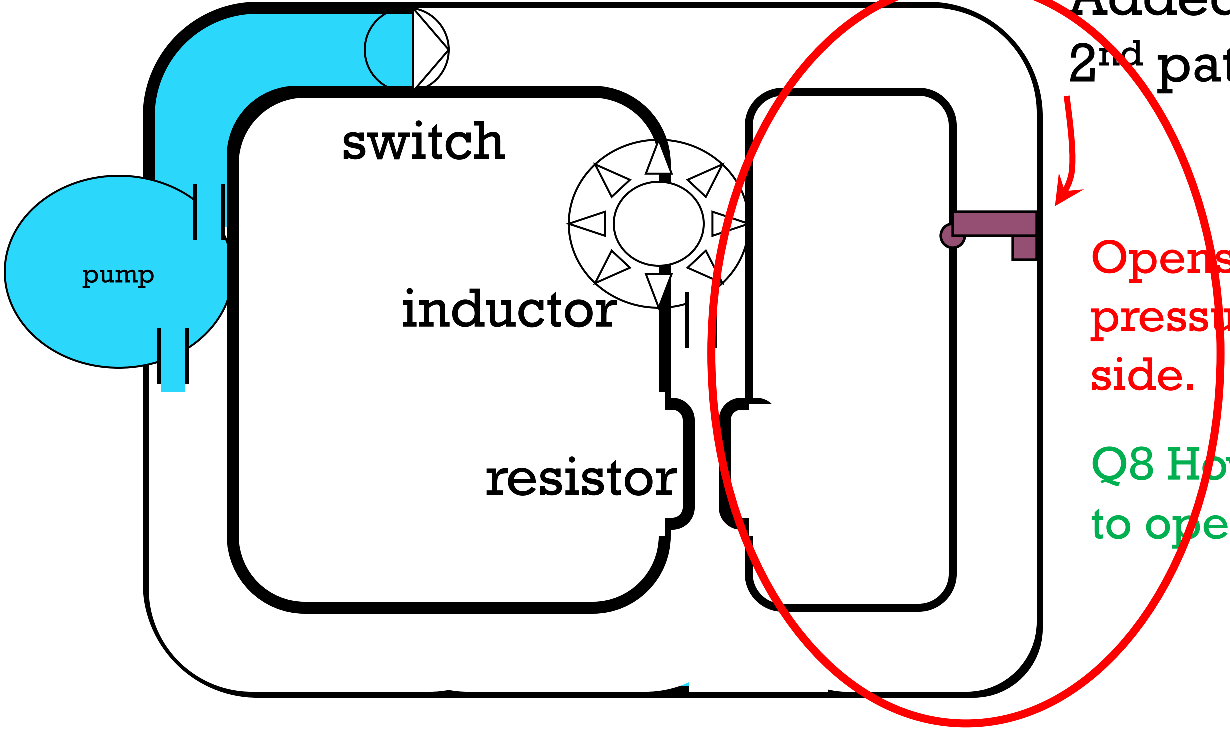
no current in inductor

Steady state

voltage equal on both (0)

no current in inductor

Large inductance with clamping diode



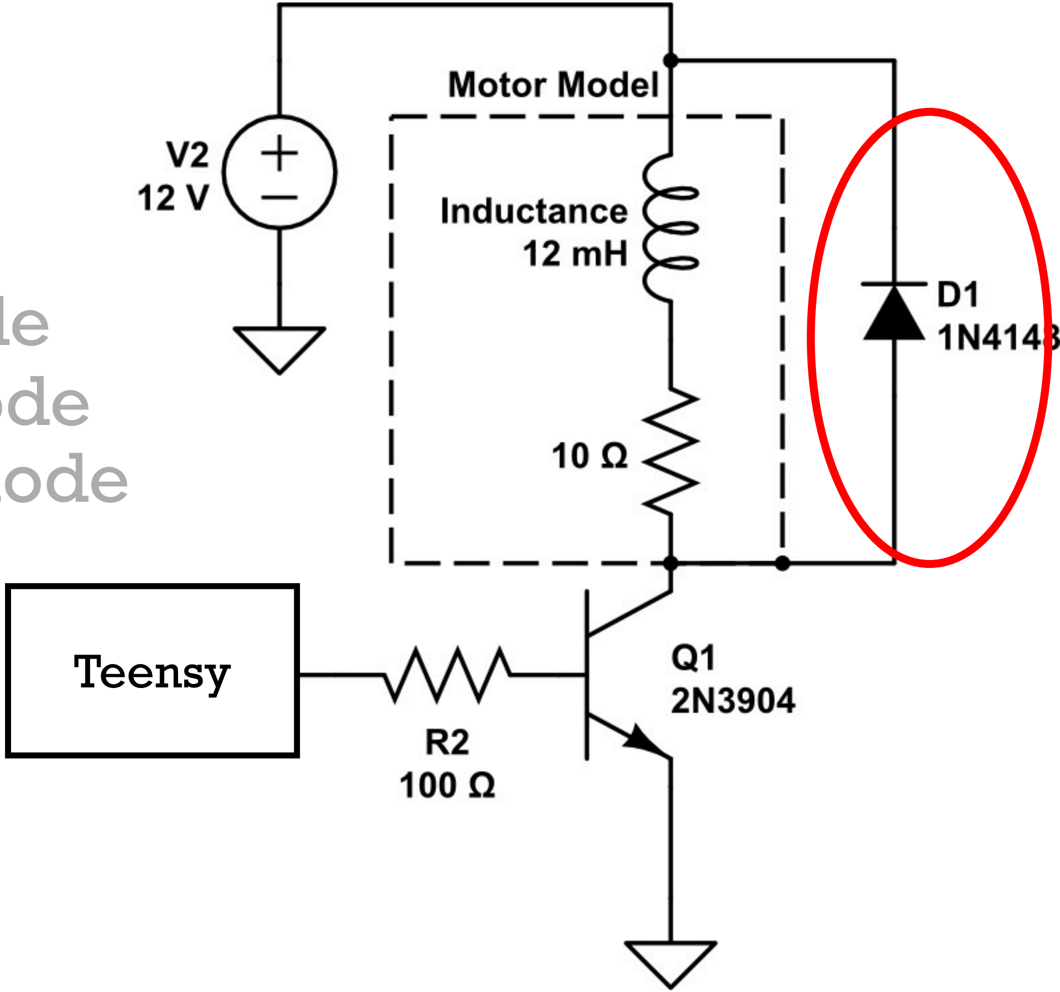
Added diode and 2nd pathway

Opens with larger pressure on bottom side.

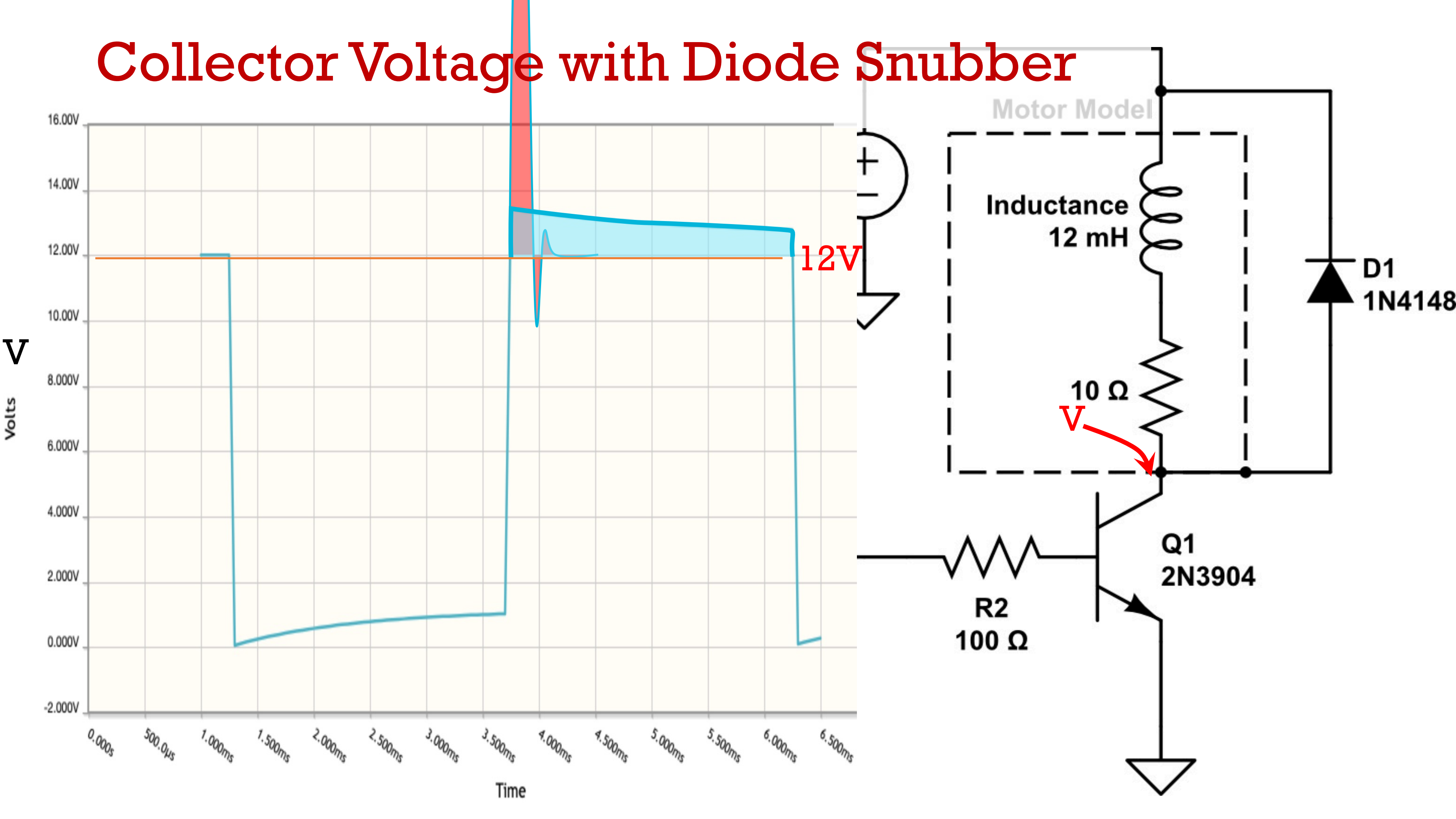
Q8 How much voltage to open?

Snubber Diode

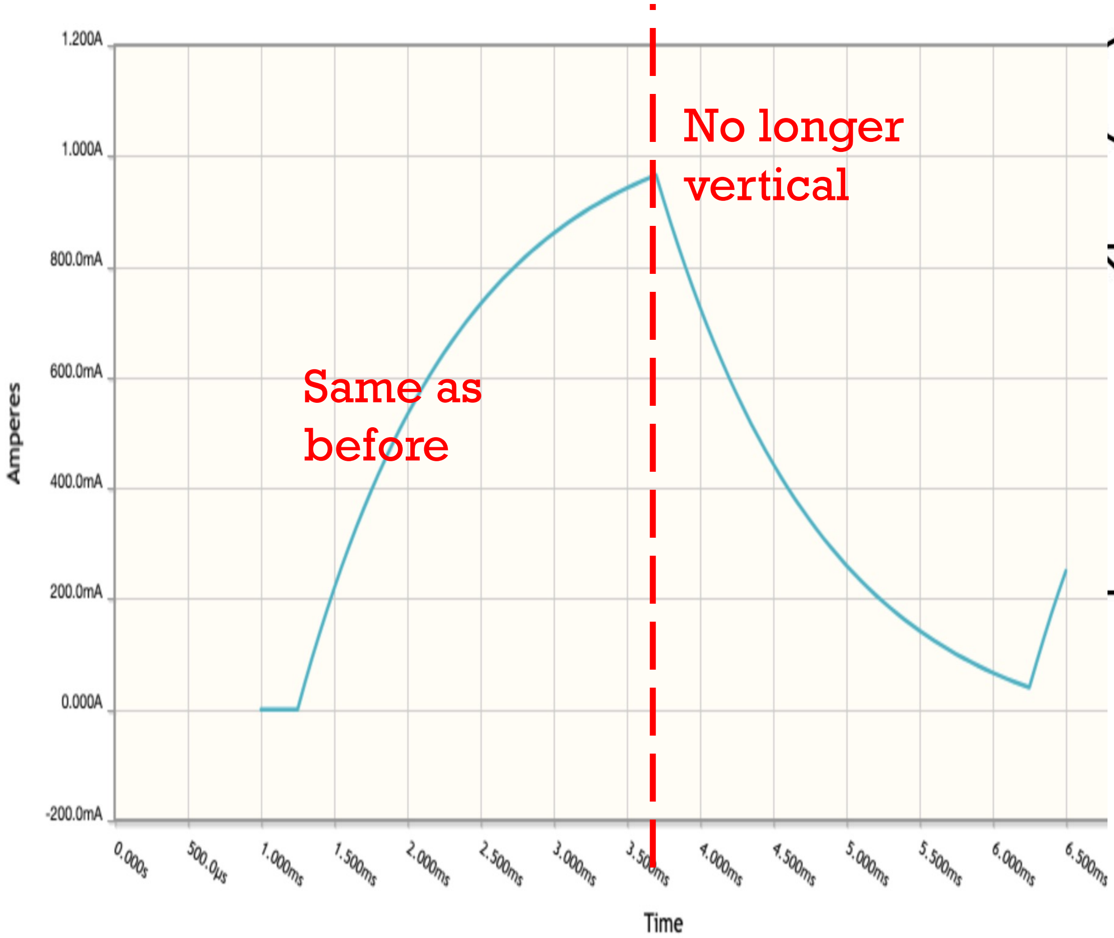
AKA Flyback Diode
AKA Clamp Diode
AKA Suppression Diode
AKA Commutation Diode
AKA Free Wheeling Diode

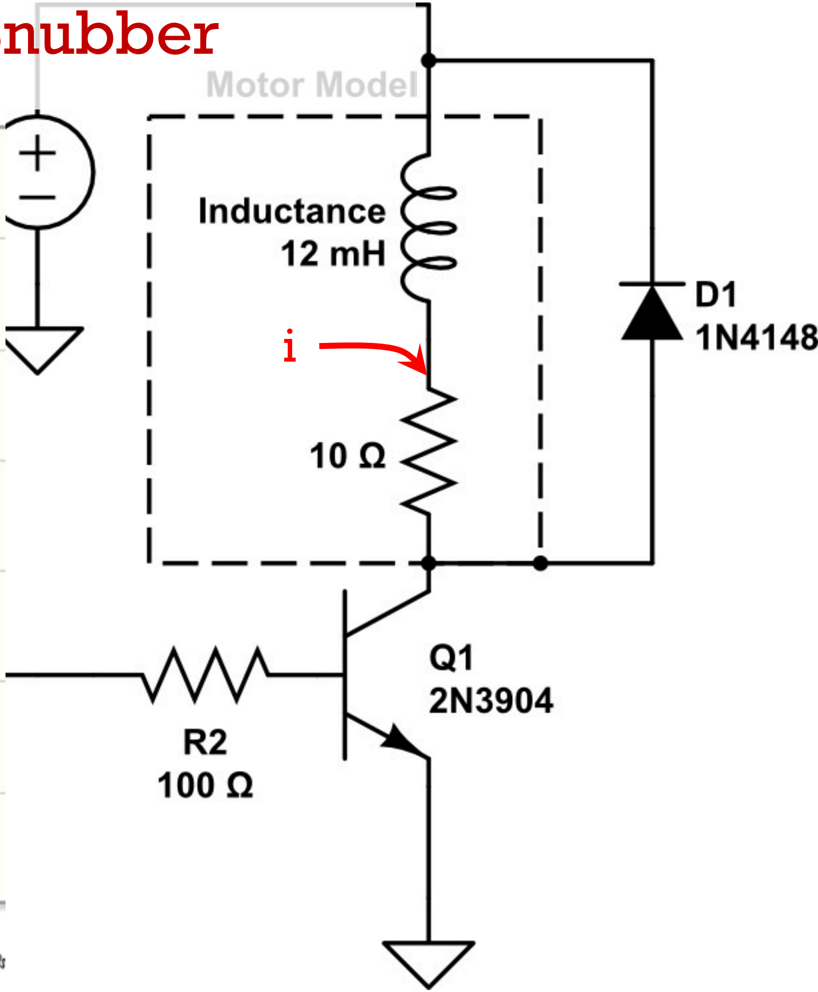


Collector Voltage with Diode Snubber

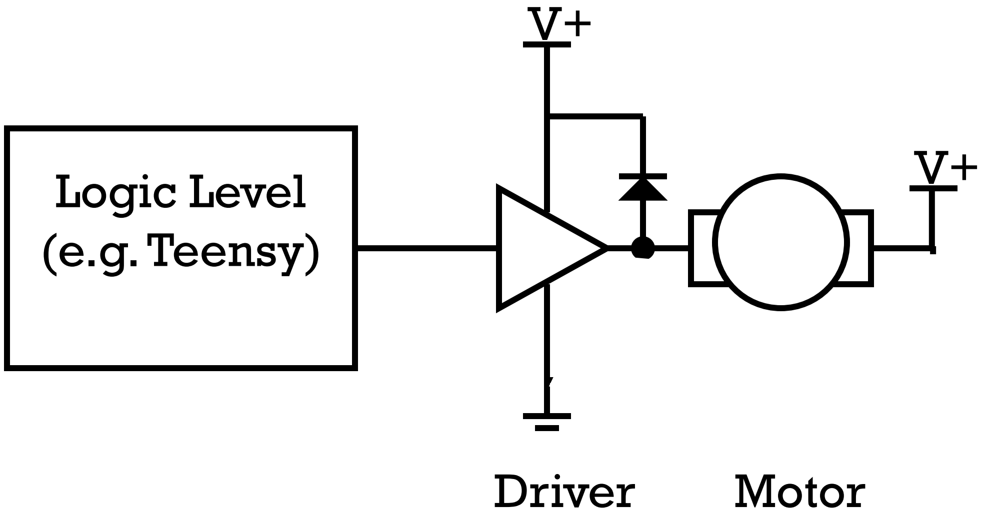


Inductor Current with Diode Snubber



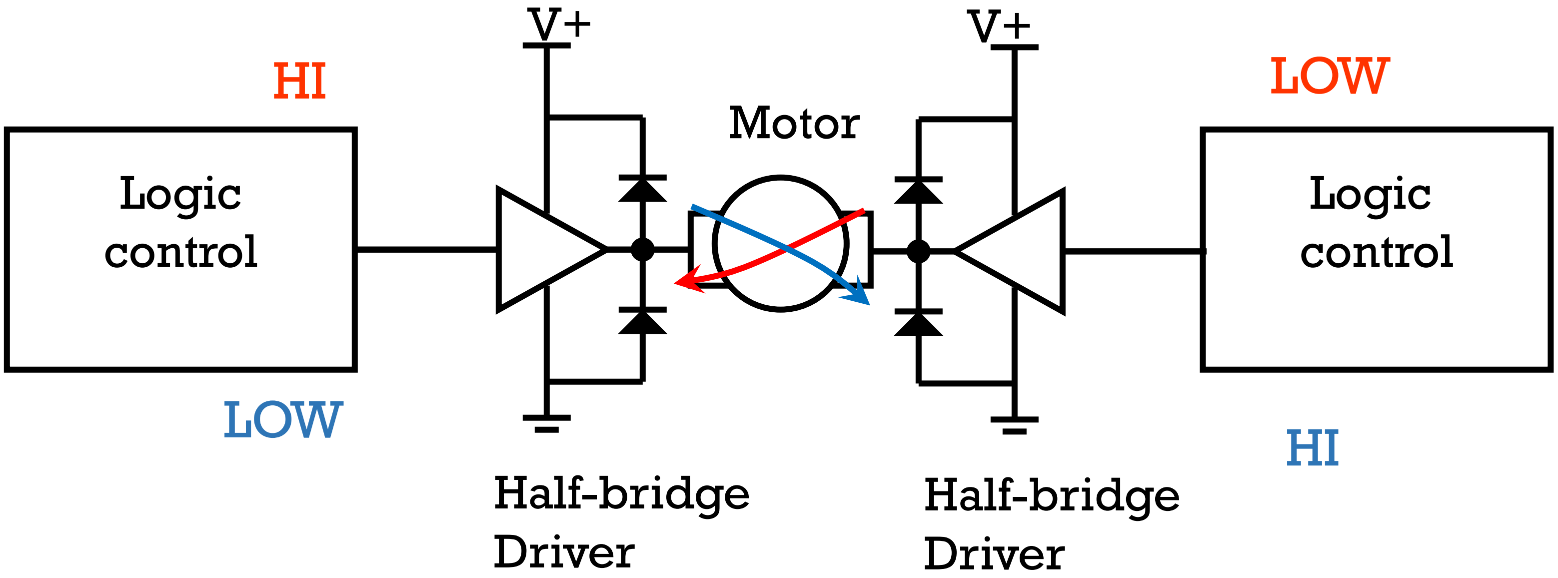


So how do we drive a motor with Logic output?



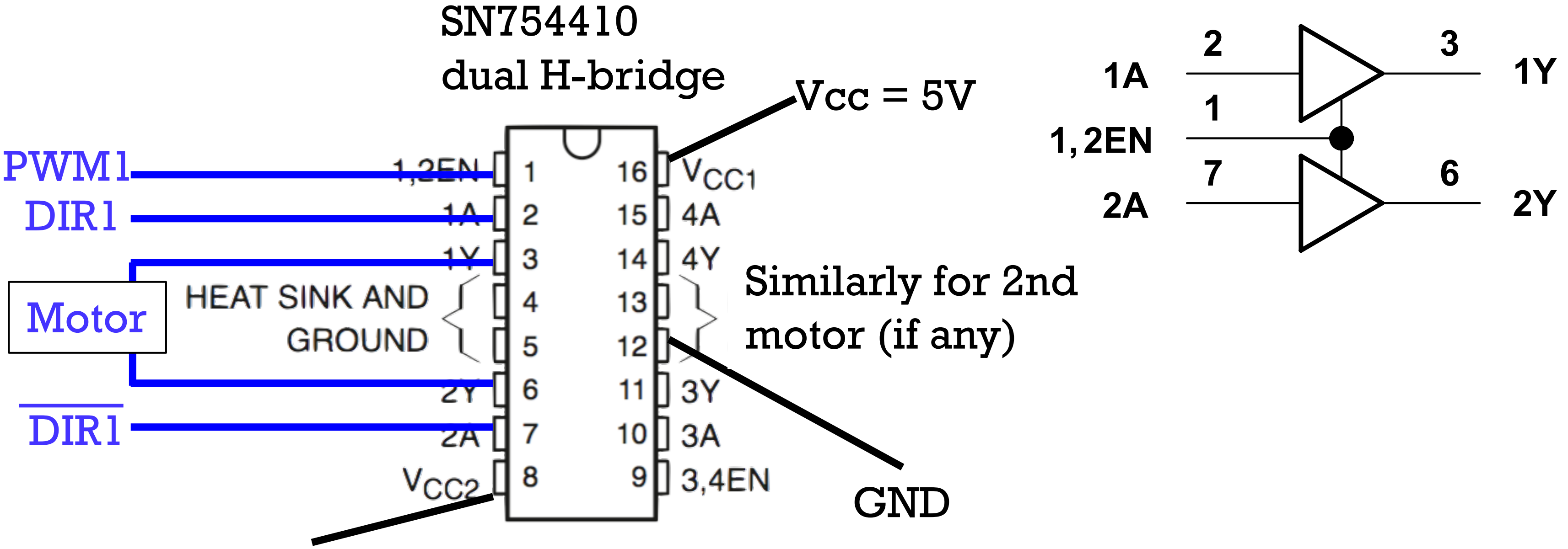
Q9: Draw a snubber diode for the protecting against a negative spike

Two half-bridges w/clamping diodes



H-Bridge in ministore SN754410

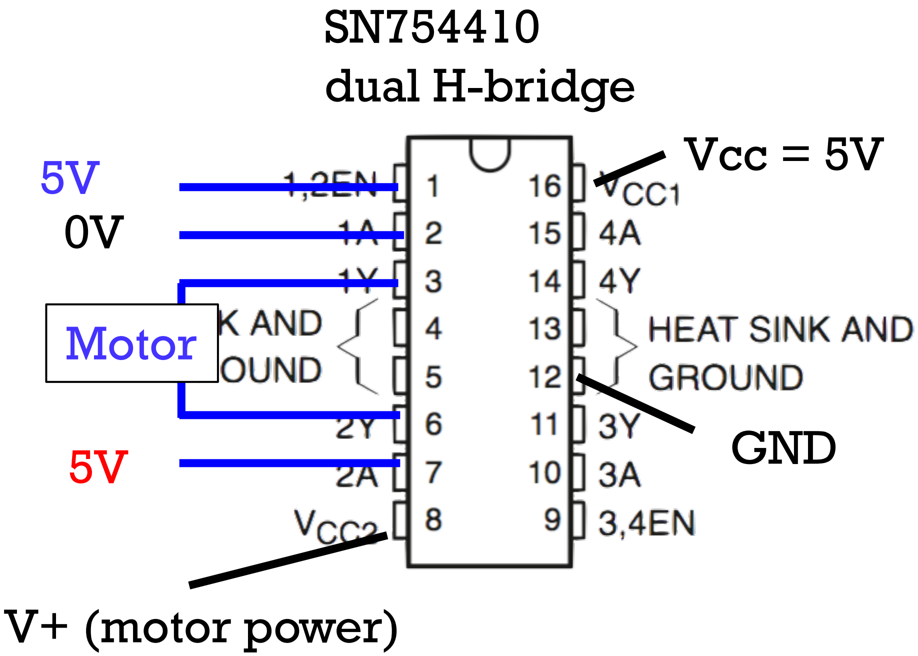
- When using the h-bridge to switch directions on a motor in the circuit below, it will be equivalent to swapping 6V and ground across the motor.



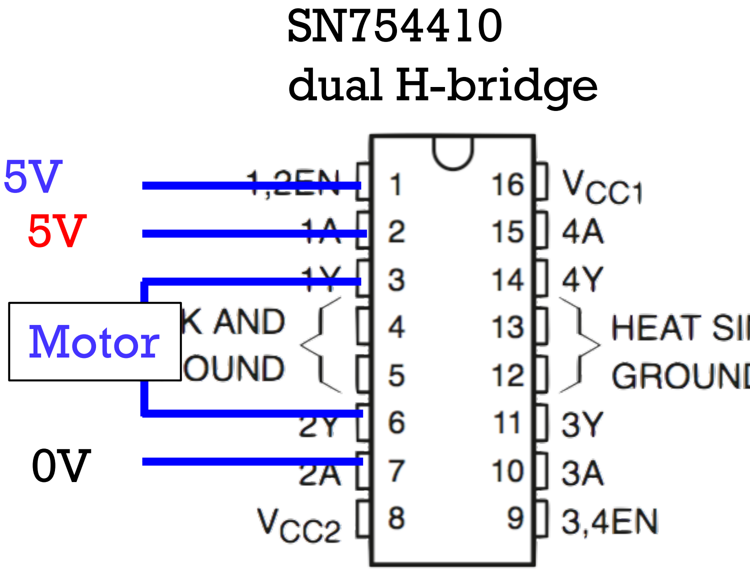
V+ (motor power) = 6V or whatever is powering your motor

SN754410 example

Motor full on forward

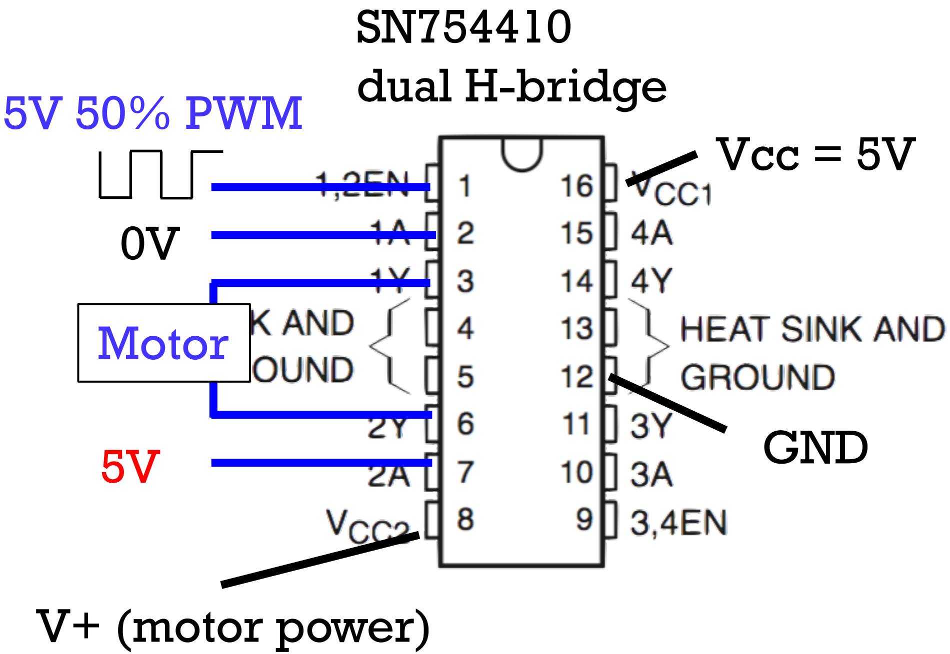


Motor full on backward

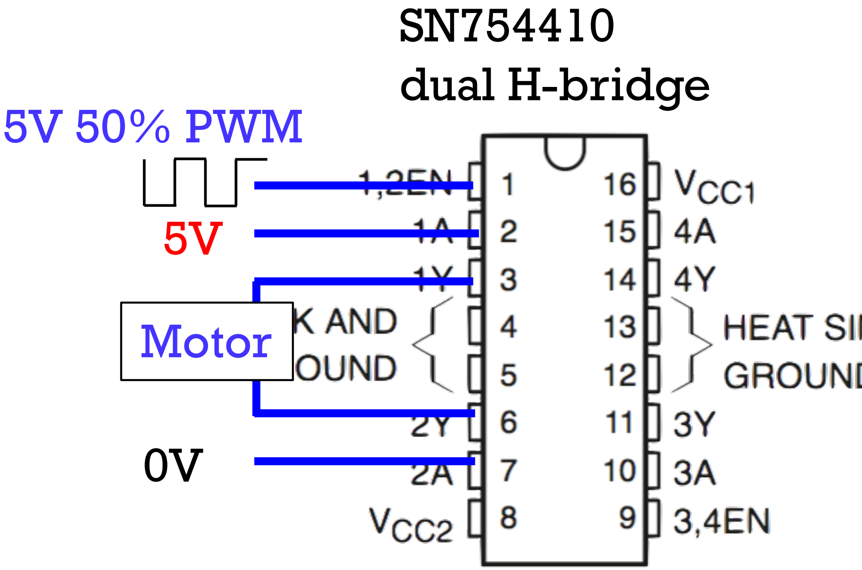


SN754410 example

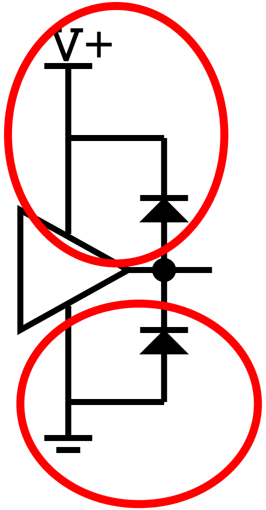
Motor half on forward



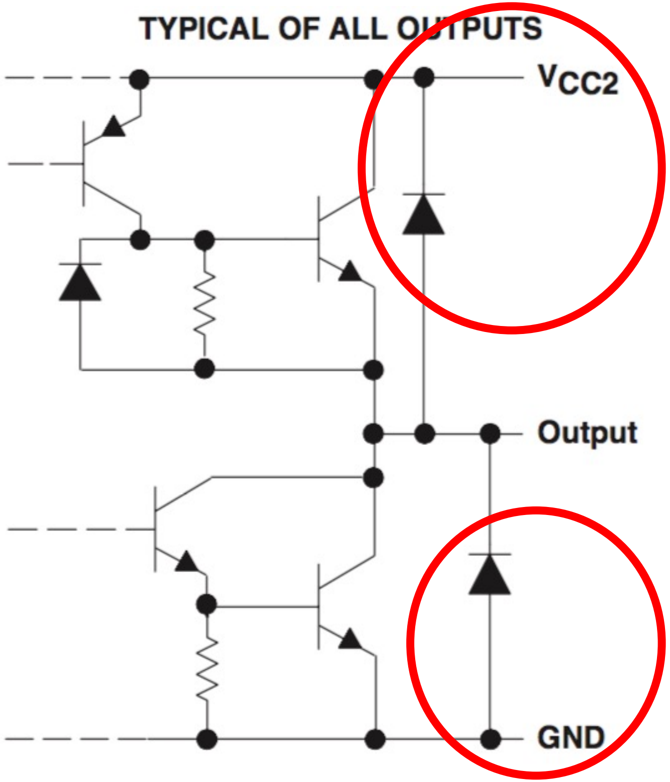
Motor half on backward



SN754410 output stage w/diode clamps

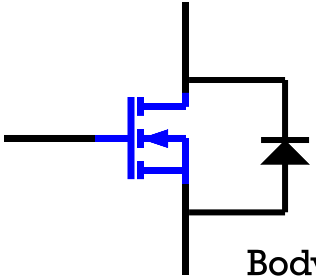


From SN754410 Datasheet:

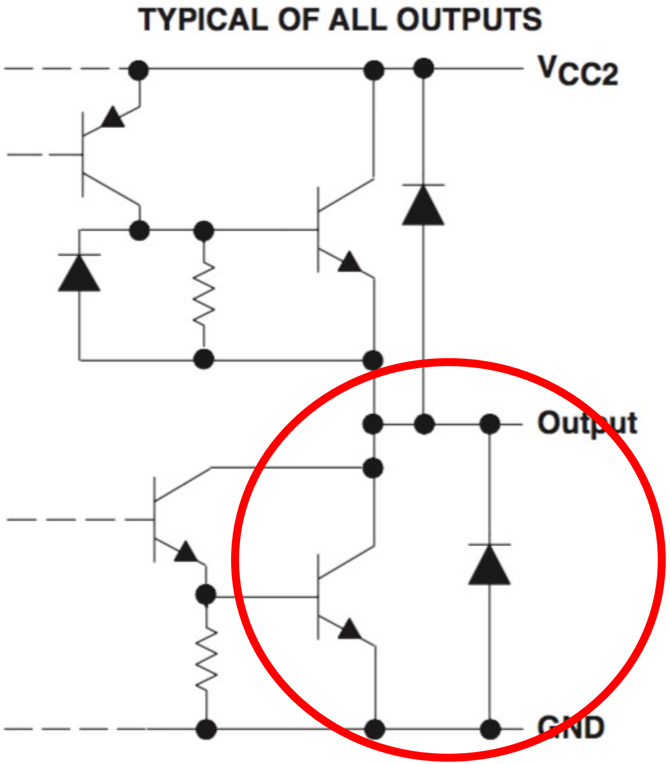


MOSFETs Body Diode

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



From SN754410 Datasheet:



Caveat with SN754410

SN754410
QUADRUPLE HALF-H DRIVER

SLRS007B – NOVEMBER 1986 – REVISED NOVEMBER 1995

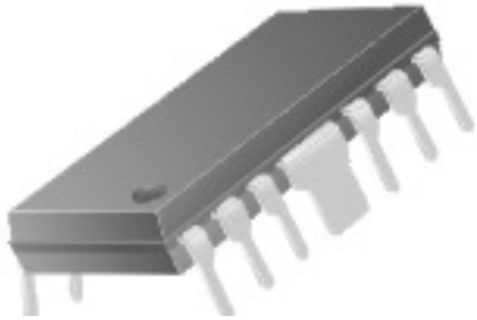
electrical characteristics over recommended ranges of supply voltage and free-air temperature (unless otherwise noted)

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	

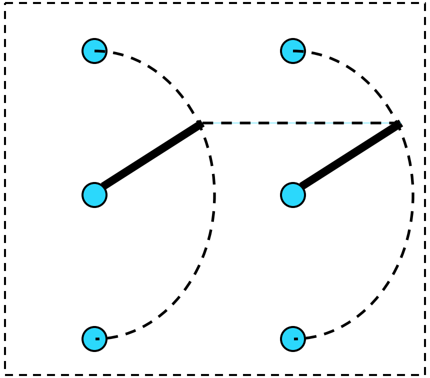
Q10: What if you were driving a motor with 5V, what is the worst case scenario for motor performance (i,e., smallest voltage across the motor?)

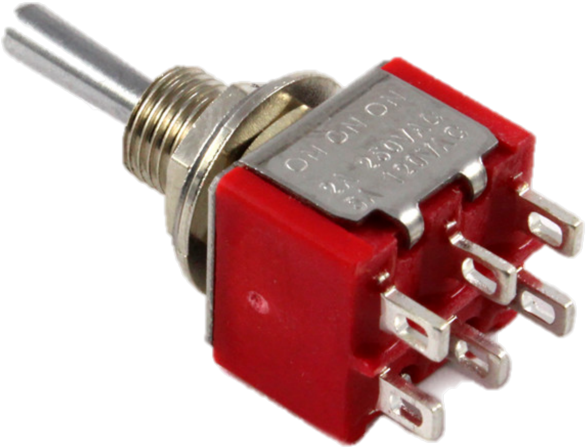
FAN8100

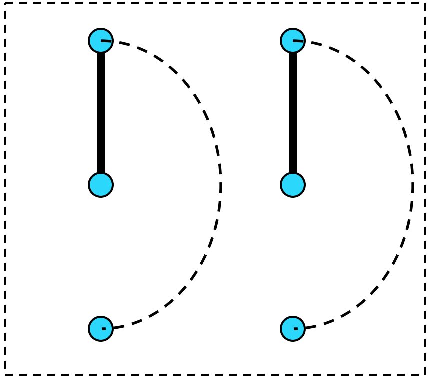
- Obsolete chip from Rochester Electronics LLC (sells large min qty obsolete stock for cheap...)
- Has better V_{OH}. Better current driving 1.5A ea channel
- Datasheet available on Canvas -> files-> Resources
- Caveat: double wide ground pins are used as heatsink fins (won't fit in protoboard) you need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



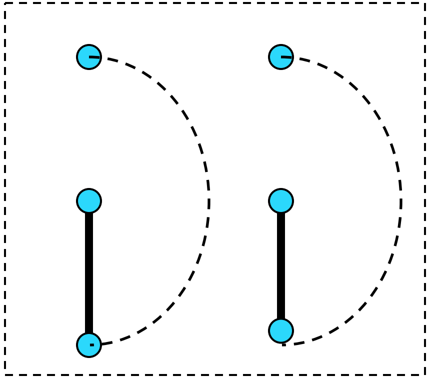
Double pole double throw switch





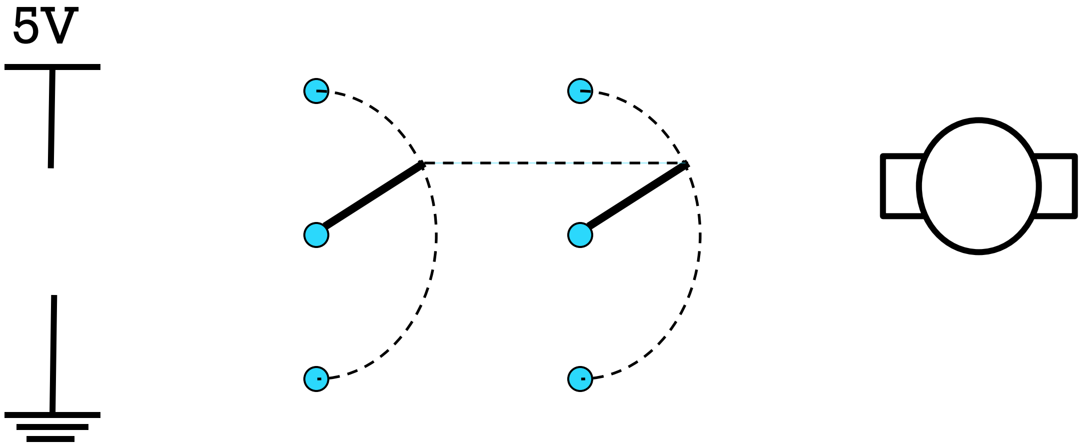


Switch up



Switch down

Double pole double throw switch as h-bridge



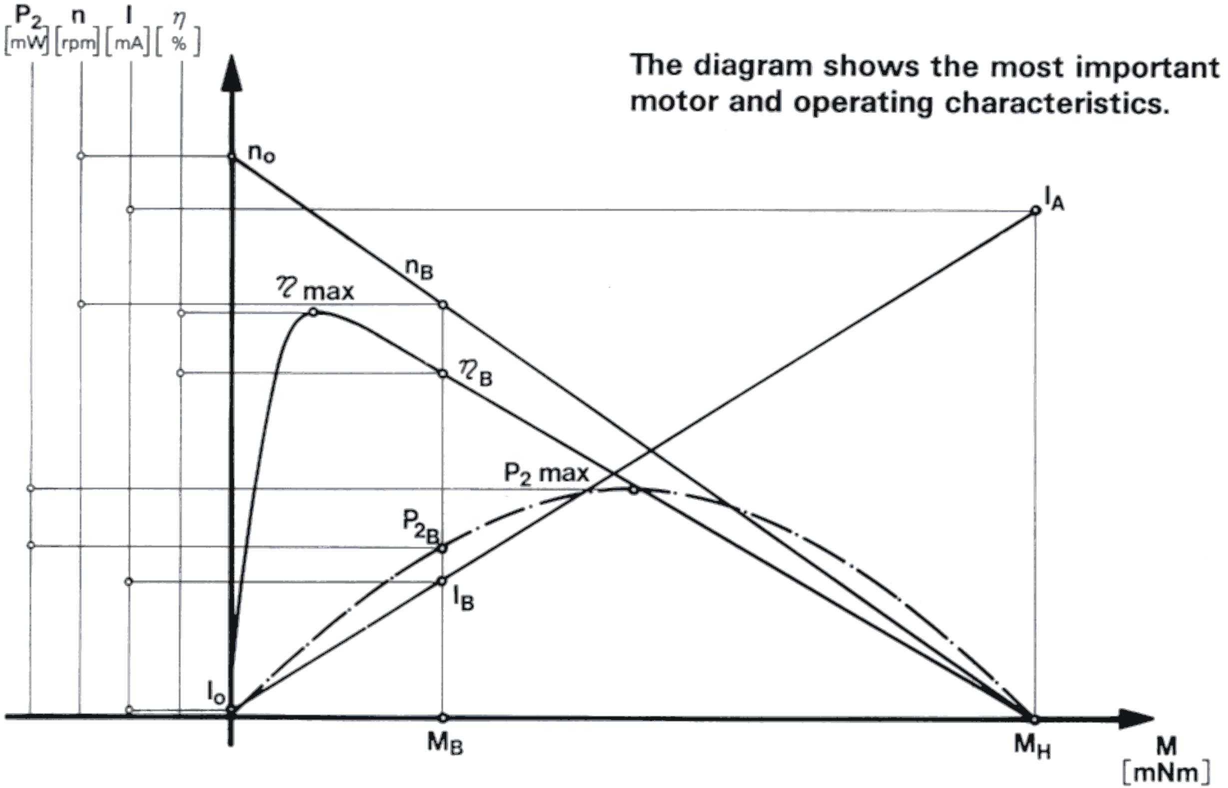
Q8: Connect power ground and motor leads to the 6 leads of a DPDT connections to form an h-bridge

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.

Motor Exercise – Choosing motor for a design

- Often you motor specs include specific points (stall torque, no-load speed etc.) but will need to know torque @ some speed or other design point.



Motor exercise

You are handed a motor. The only documentation that you can find shows that the motor chosen has Kt = 9.33 in.-oz./A and produces 2.8 in.-oz. at stall when driven at 12V. The design requires that the motor deliver 0.4 in.-oz. at 1500 rpm. The motor was supposed to be driven from a 12V supply. Your boss has asked you:

a) How can I find out how much current the motor will draw at stall ?

b) What is Ke ?

c) How can I find the coil resistance ?

d) Will the design meet the requirements for torque at the given speed? If not, what changes could you suggest?

e) Estimate the current required when running at the design point.

You may assume that there are no internal losses within the motor.

for reference: $K_T = 1.3524 K_E$ [oz-in/A ; V/krpm]

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