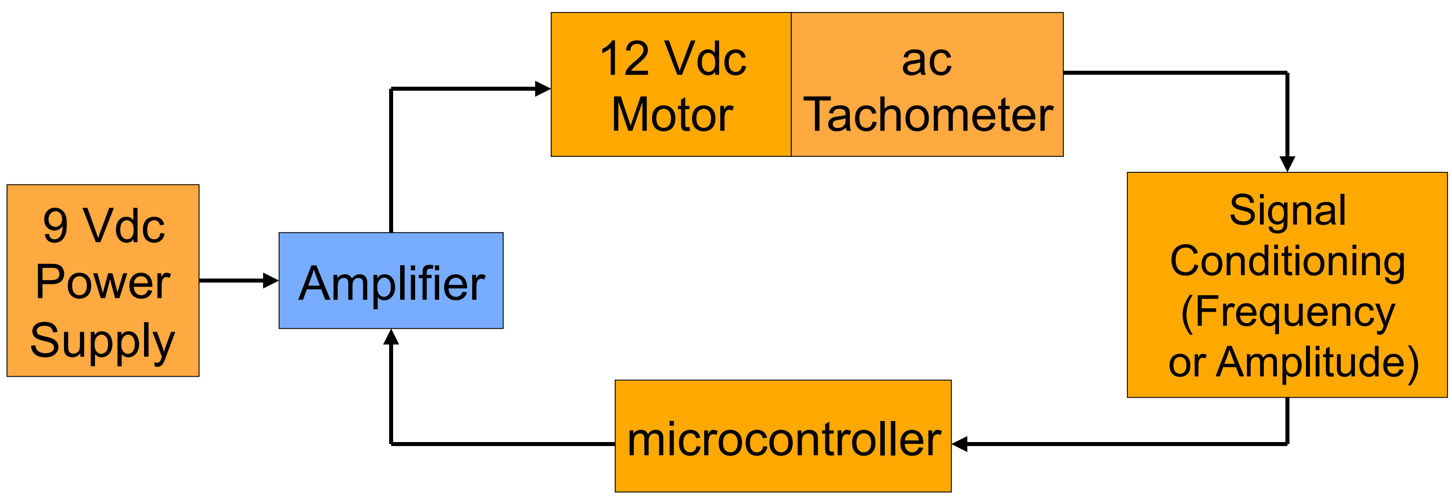
Lab 8. Speed Control of a Dc motor

The Motor Drive

Motor Speed Control Project

1. Generate PWM waveform
2. Amplify the waveform to drive the motor
3. Measure tachometer signal (motor speed)
4. Find parameters of a motor model
5. Control motor speed with a computer algorithm



Buehler 12 volt permanent-magnet dc motor with tachometer output

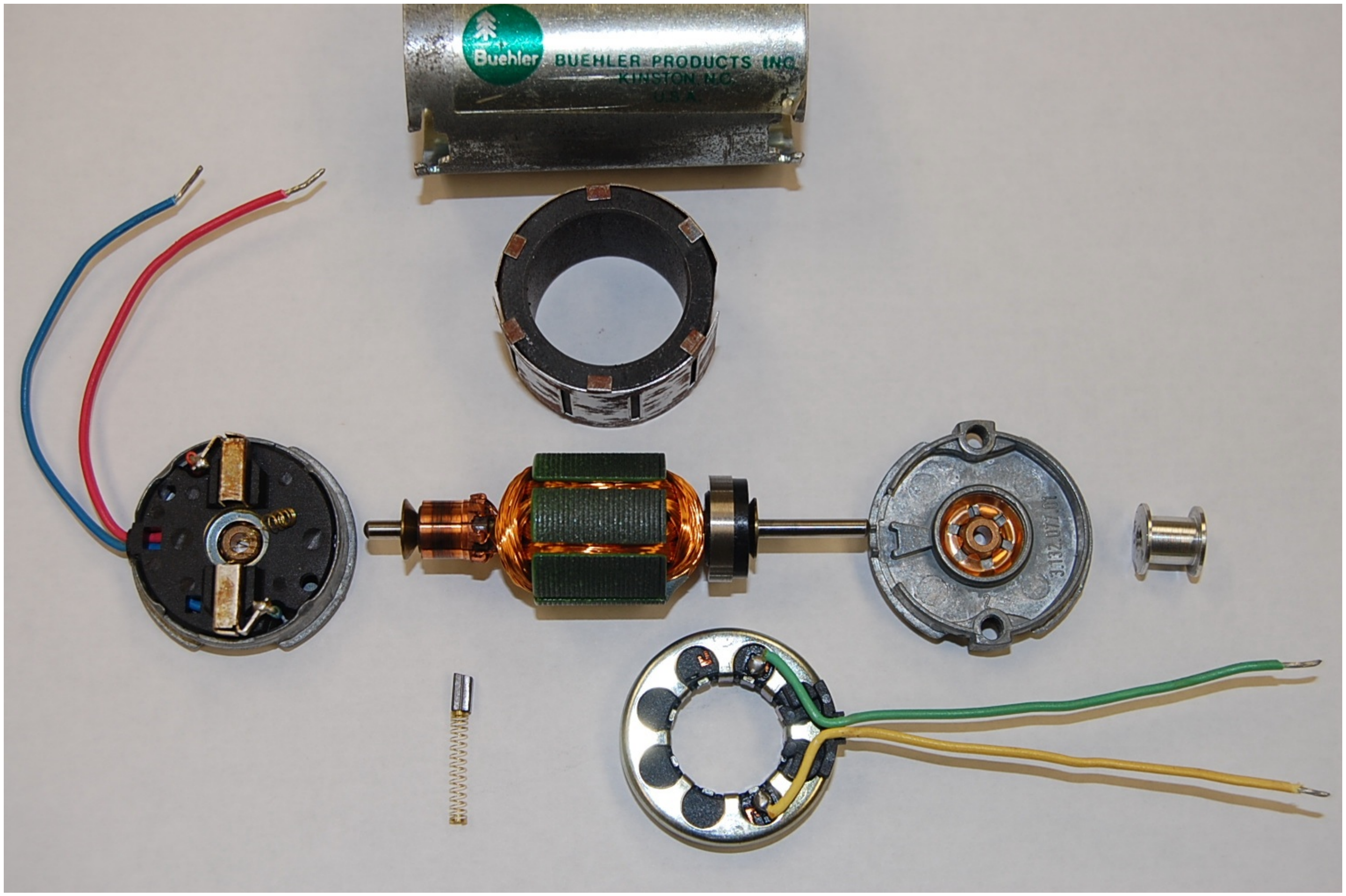
Electrical Connections

yellow/green -- tachometer output

blue/red -- motor winding

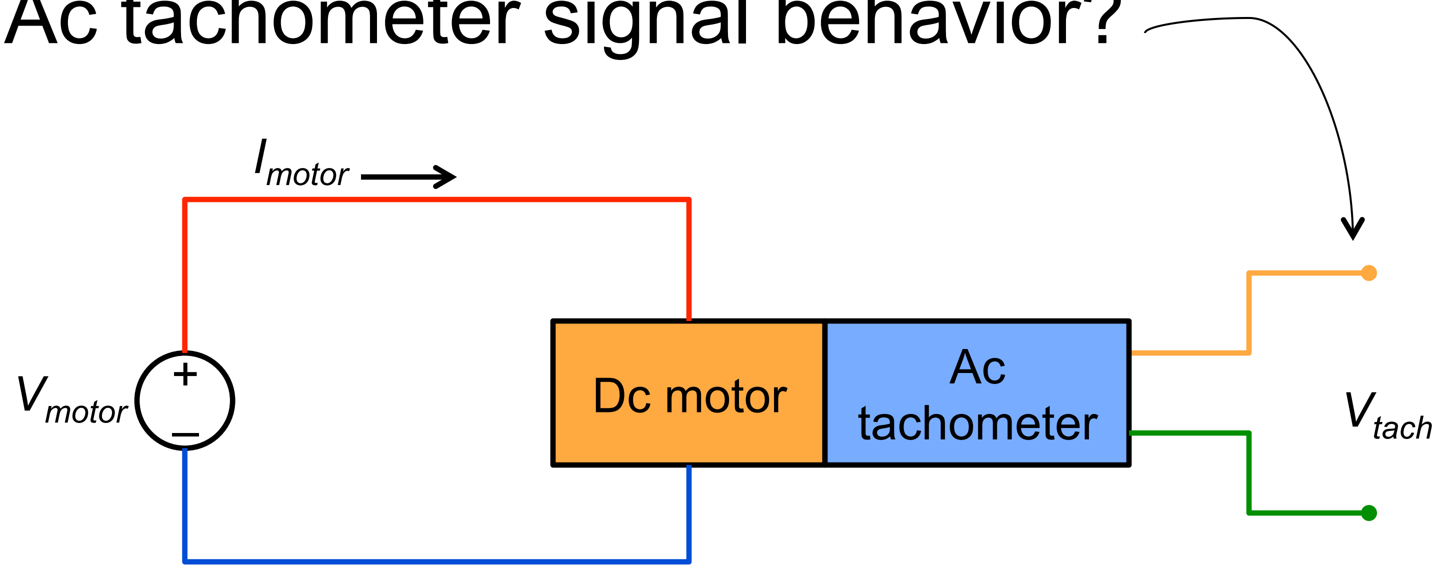
Note: Tachometer wires may not have two colors on some units.

Exploded view

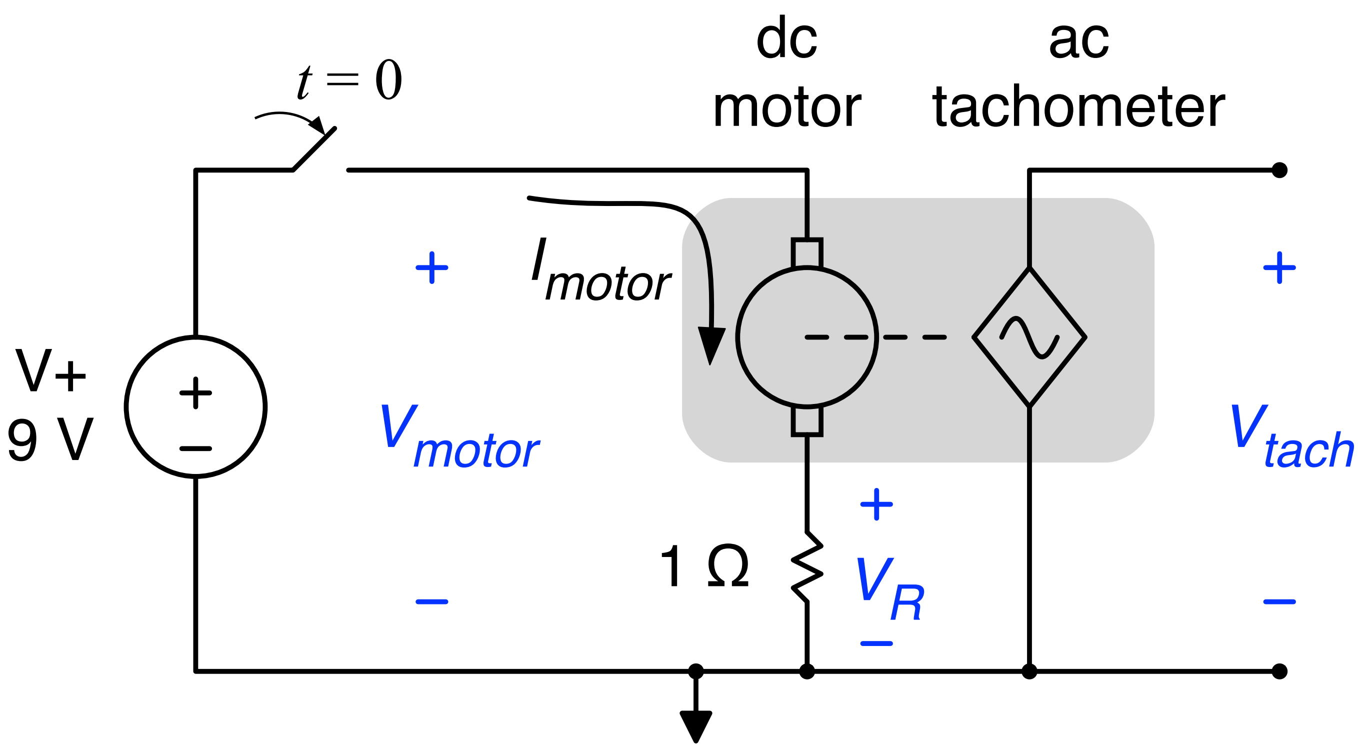


Some questions

- Required power? $P = V_{motor} \times I_{motor}$
- Ac tachometer signal behavior?

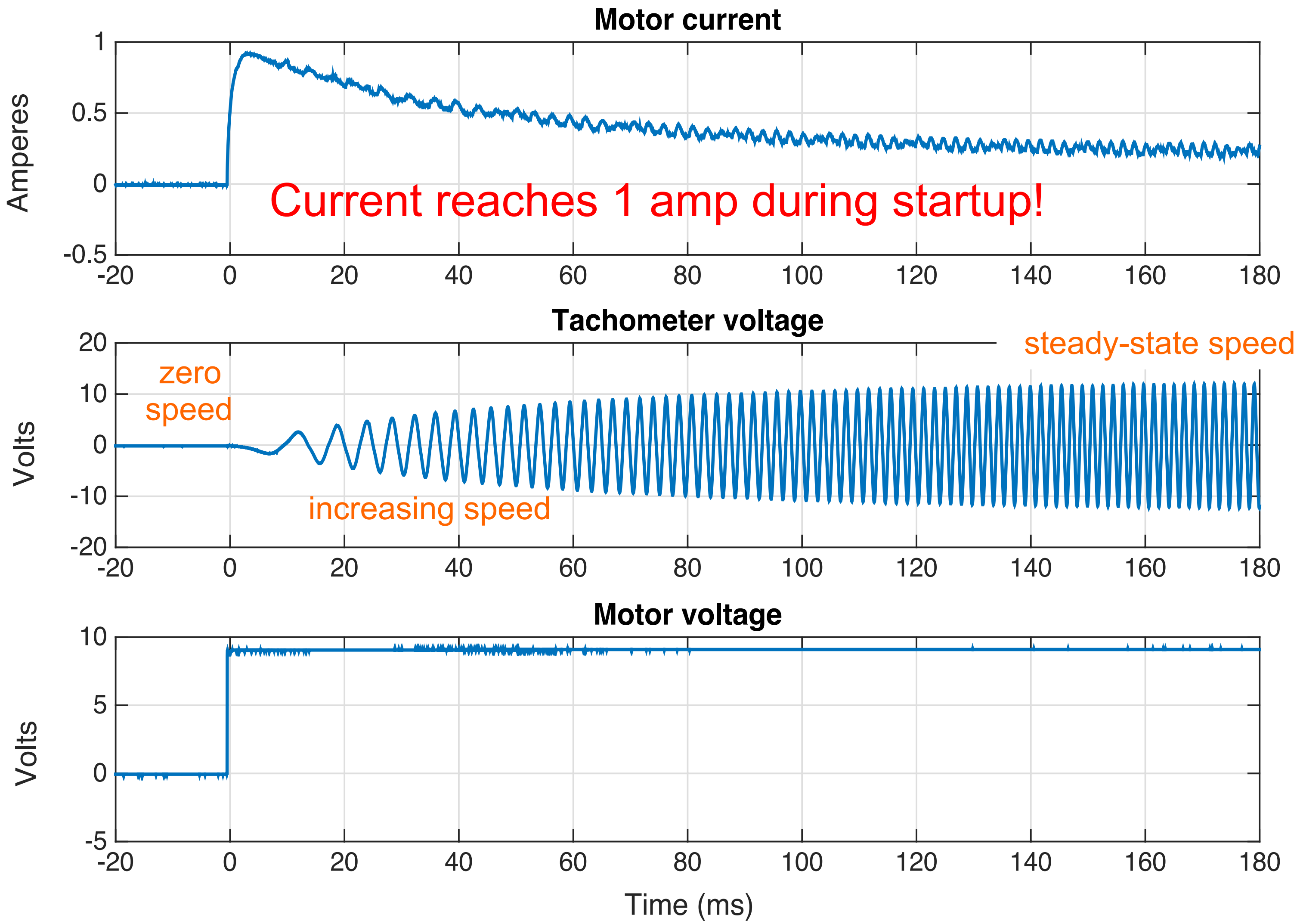


Set up an experiment



- Measure V_{motor}, V_R, and V_{tach}
- $I_{motor} = V_R$ (because $R = 1\ \Omega$)

Experimental results



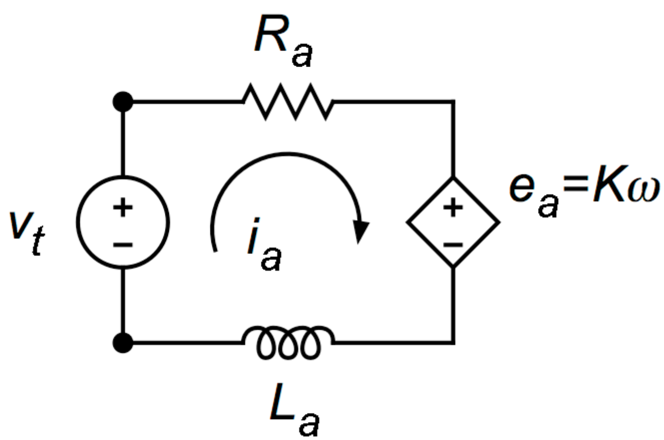
Some observations

- V_{tach} amplitude grows with motor speed
- V_{tach} frequency also grows with speed
- Initial current I_{motor} peaks around 1 A
- Steady state I_{motor} is approx. 250 mA

Why does the process behave this way?

Some analytical modeling…

Motor electro-mechanical models



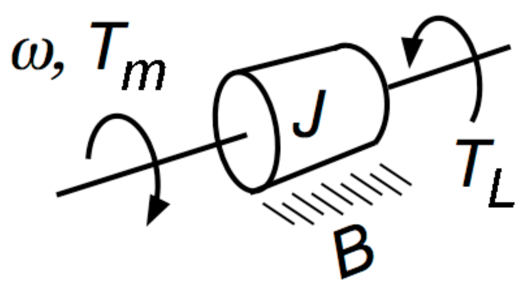
R_a – armature winding resistance

L_a – armature winding inductance

i_a – armature current

V_t – motor terminal voltage

e_a – back emf



T_m – developed torque

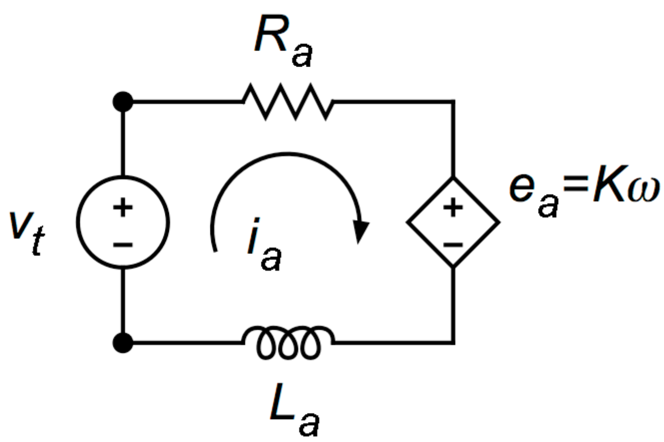
T_L – torque needed for load

ω – rotational speed

B – friction coefficient

J – moment of inertia

Motor electrical dynamics



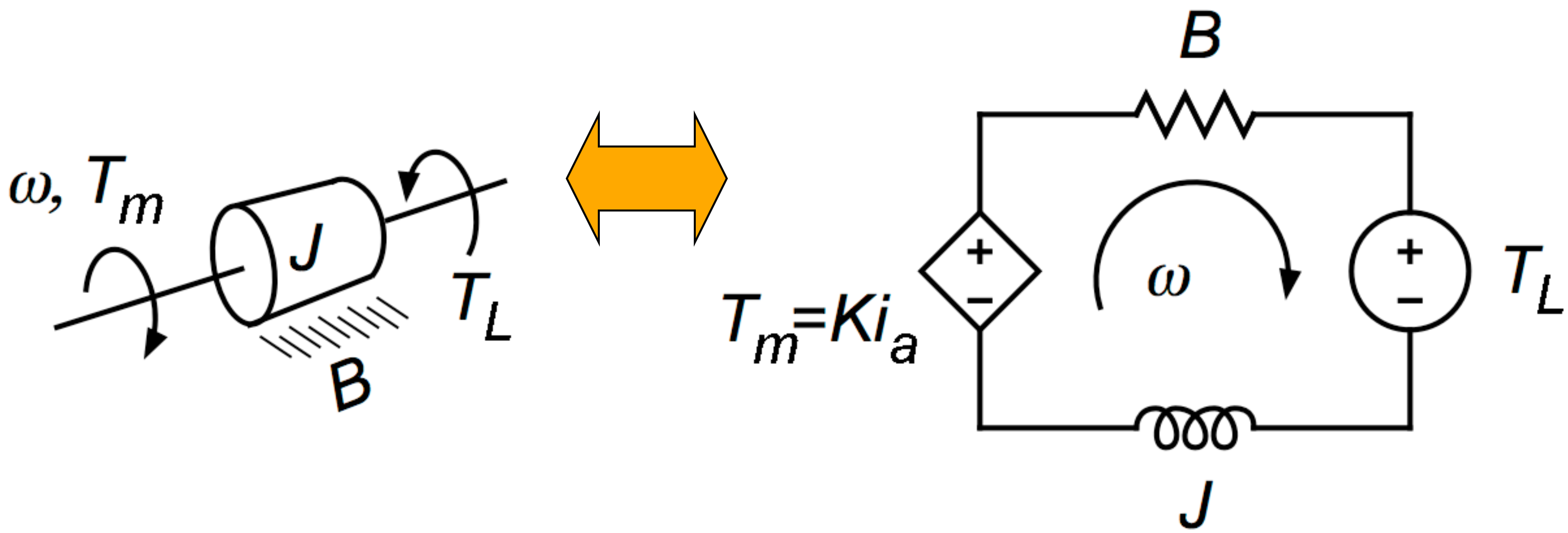
$$v_t = R_a \cdot i_a + L\frac{di_a}{dt} + e_a$$

$$e_a = K\omega_m$$

e_a = "back emf" (electromotive force) generated within armature windings

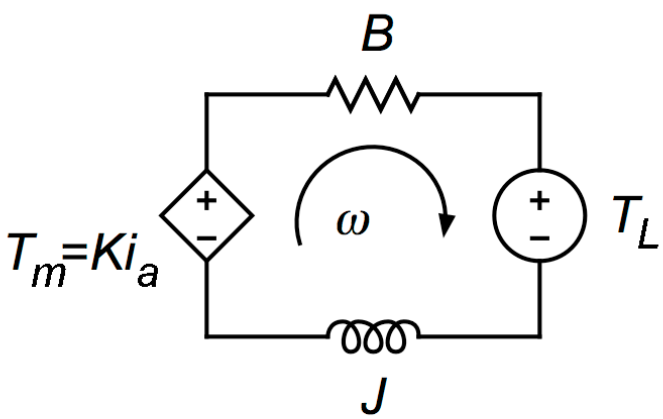
Note: Emf e_a= 0 at standstill, and increases linearly with motor speed. Current i_a is high at low speed.

Mechanical dynamics analogous to electrical circuits!



Equations for these systems
have similar form.

Motor mechanical dynamics



$$T_m = J \cdot \frac{d\omega}{dt} + B \cdot \omega + T_L$$

$$T_m = K \cdot i_a$$

T_m = developed torque increases with current
J = motor moment of inertia
B = motor friction coefficient
ω = angular velocity of the motor
T_L = torque required to drive the load

Laplace transformed equations

- Electrical

$$V_t(s) = R_a \cdot I_a(s) + L_a \cdot sI_a(s) + K \cdot \Omega(s)$$

- Mechanical

$$K \cdot I_a(s) = J \cdot s\Omega(s) + B \cdot \Omega(s) + T_L(s)$$

Steady state analysis (s=0)

- Electrical steady state

$$V_t = R_a \cdot I_a + K \cdot \Omega$$

- Mechanical steady state

$$K \cdot I_a = B \cdot \Omega + T_L$$

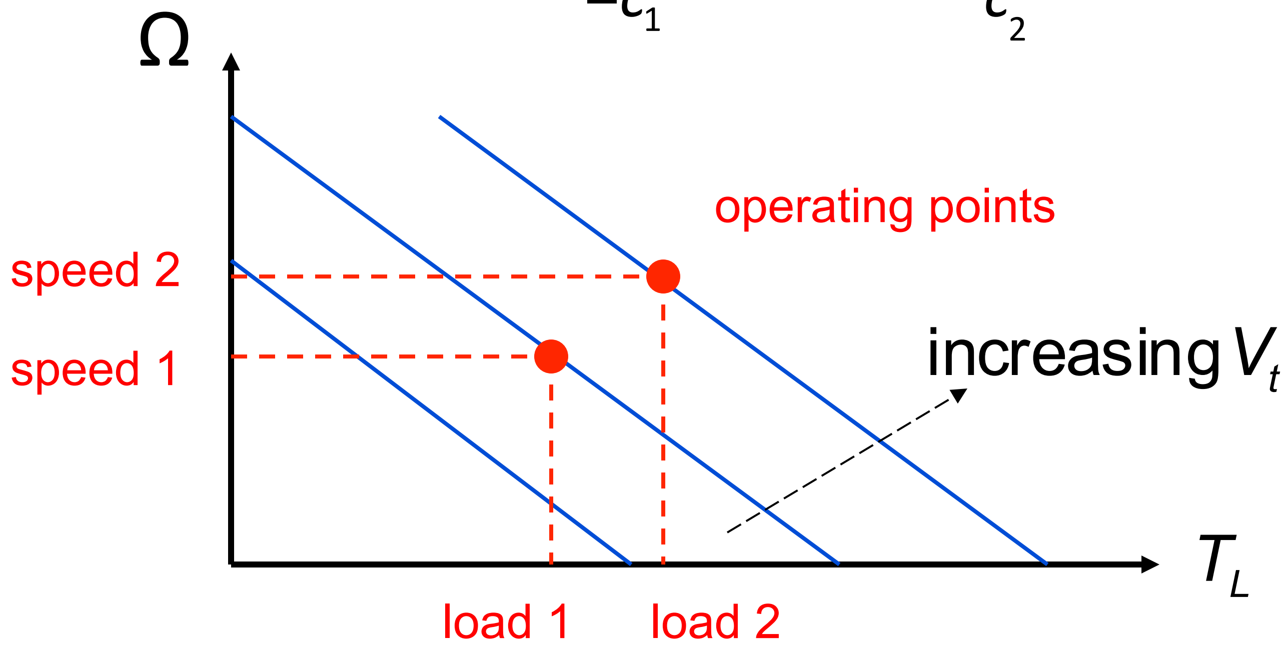
- Solve for speed

$$\Omega = -\frac{R_a}{R_a B_m + K^2} \cdot T_L + \frac{K}{R_a B_m + K^2} \cdot V_t$$

Motor speed vs. load torque

- Speed is related to load torque and terminal voltage

$$\Omega = -\underbrace{\frac{R_a}{R_a B_m + K^2}}_{-c_1} \cdot T_L + \underbrace{\frac{K}{R_a B_m + K^2}}_{c_2} \cdot V_t$$



What we now know:

- For a given load, motor speed is proportional to voltage applied to its terminals
- Use of a PWM signal allows the ***average*** voltage of the signal to be varied by varying duty cycle

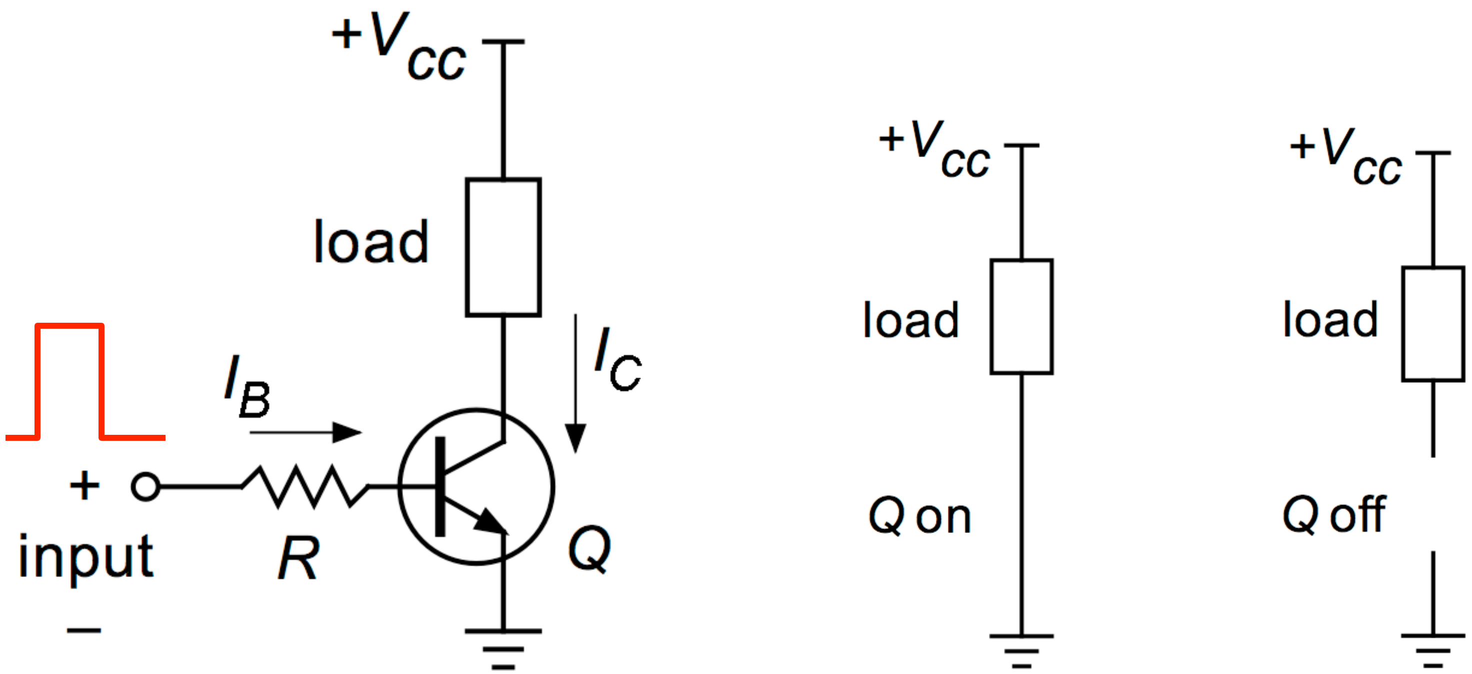
$$V_{avg} = V_{digital}\left(\frac{T1}{T1+T2}\right)$$

T1 = “ON” time
T2 = “OFF” time

- We have a 12 Vdc motor (max. terminal voltage is 12 Vdc)
  - A 3 volt signal will be insufficient to produce full speed, PLUS …
  - Motor may draw 1 ***A*** of current, whereas microcontroller output pins can typically supply only ***milliamperes***

Idea: Use a single transistor switch to amplify the digital PWM signal to drive the motor

Basic transistor switch



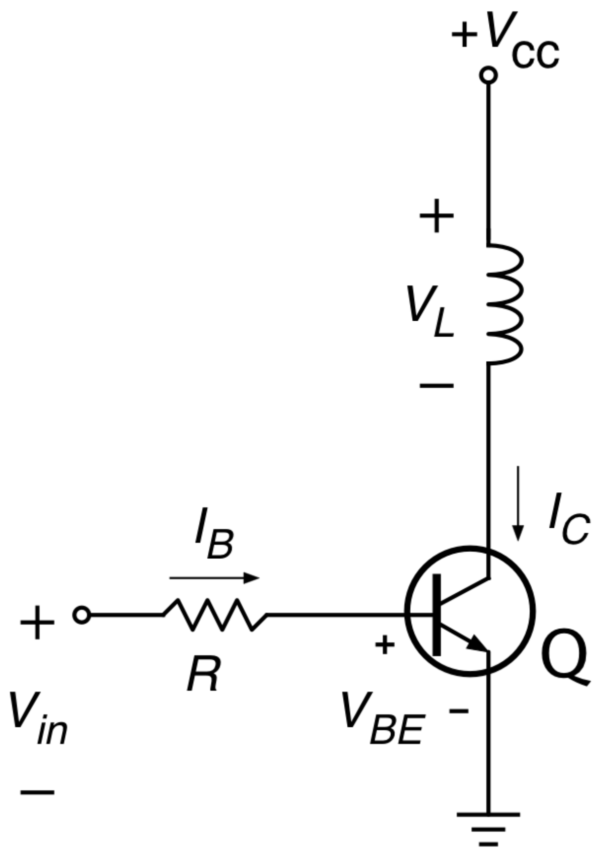
(ideal models)

Switching an inductive load
(motor winding)

- Inductor voltage-current law:

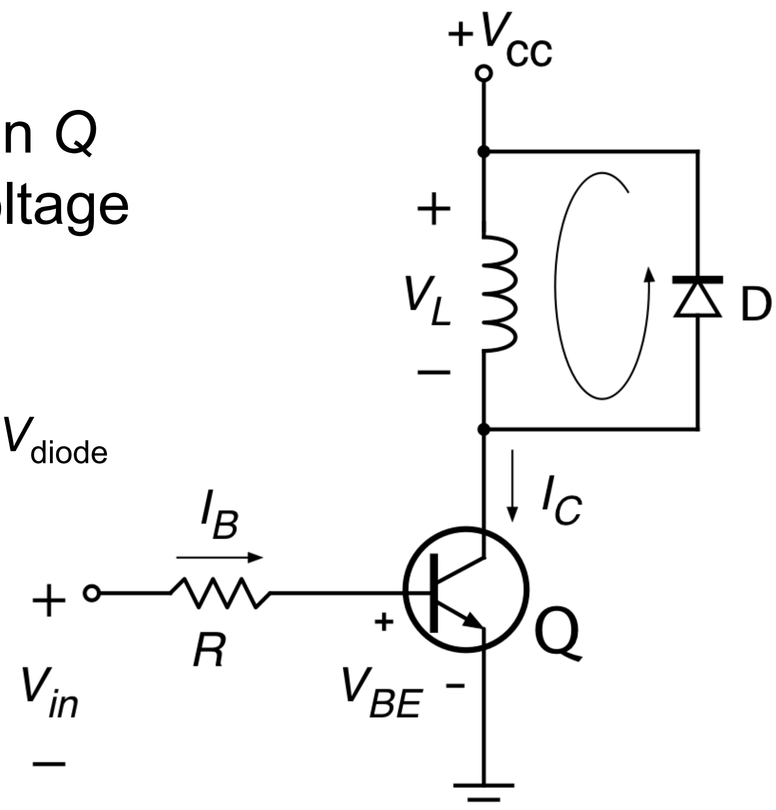
$$V_L(t) = L\frac{di_C}{dt}$$

- As current i_C is switching <u>*off*</u>,
  - di_C/dt is large and <u>*negative*</u>
  - Inductor voltage V_L is large and <u>*negative*</u>
  - Collector voltage > V_{cc}
- Q may be destroyed!

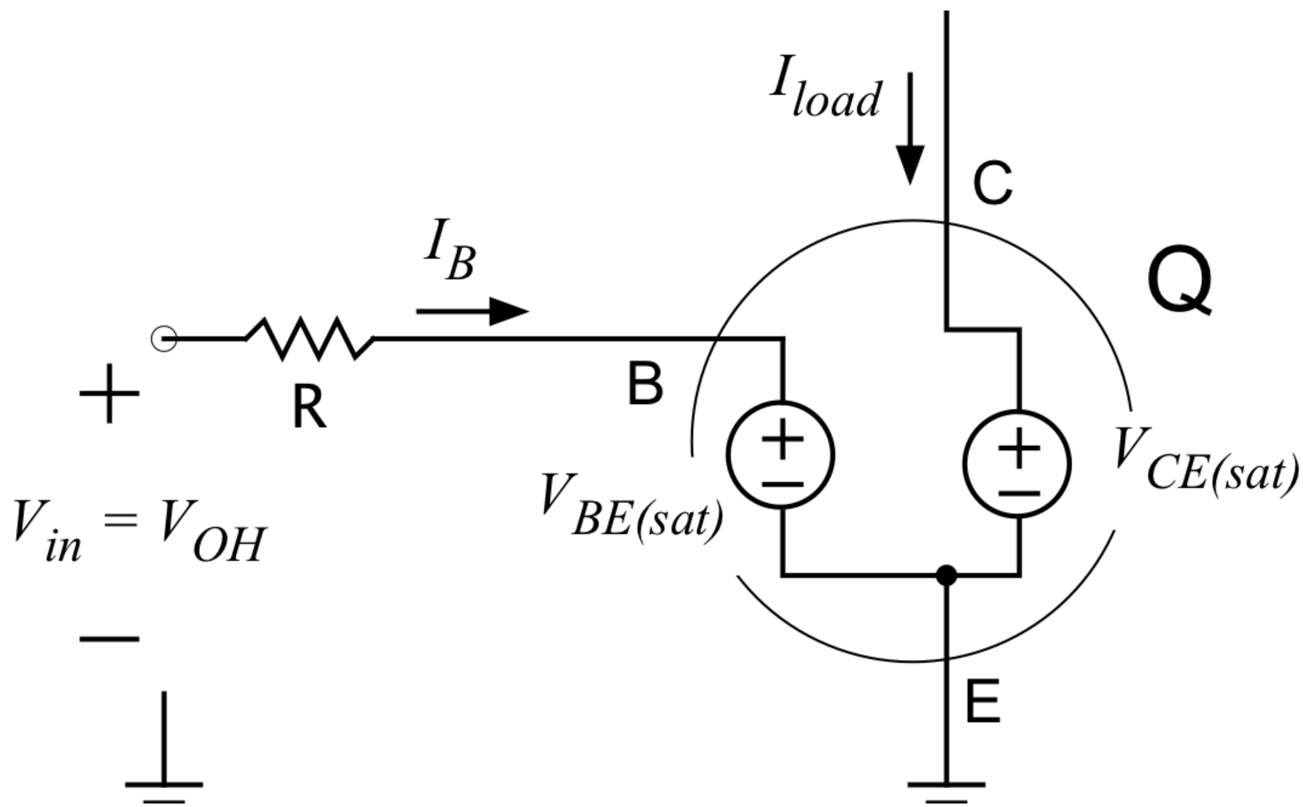


Switching an inductive load
(need to protect switch *Q*)

- Use anti-parallel diode *D!!!*
  - reverse biased when *Q* is ON
  - gives alternate current path when *Q* switches OFF (when inductor voltage becomes negative)
  - protects *Q*
    - Collector voltage is clamped to $V_{cc}+V_{diode}$
  - a.k.a. *freewheeling* diode



Drive design practical model



Drive design considerations

- Maximum load current, I_{LOAD}
- Transistor characteristics
  - current gain, h_{FE}
  - voltage $V_{BE(sat)}$ in saturation mode
- Microcontroller limitations
  - digital pin output voltage (high), V_{OH}
  - digital pin output current, $I_{IO} \approx 20$ mA (max)

Design equations

- Constraints for base current in the ON state

$$I_{IO} > I_B >> \frac{I_{LOAD}}{h_{FE}}$$

- Calculate base series resistance, *R*

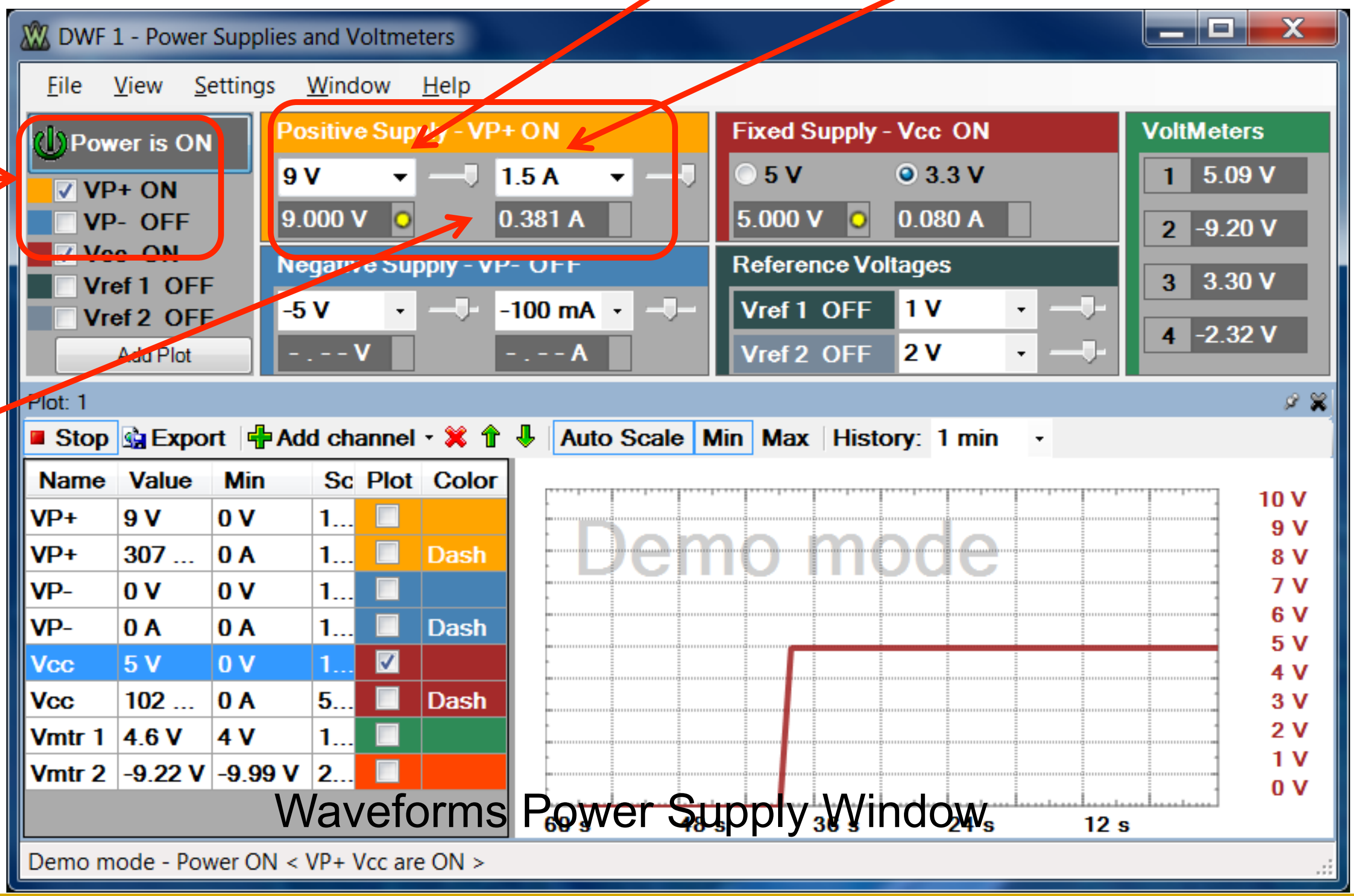
$$R = \frac{V_{OH} - V_{BE(sat)}}{I_B}$$

EE Board variable power supply

Positive Supply
VP+ output voltage & current limit

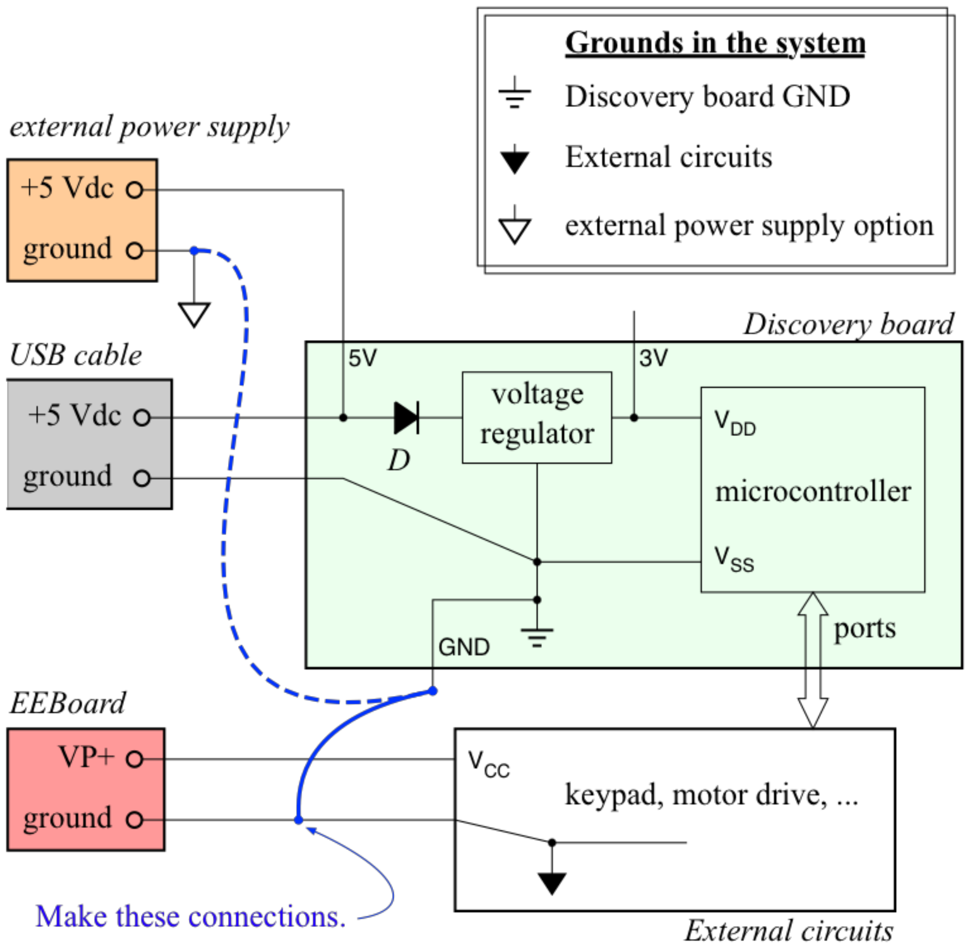
VP+ ON

Actual
VP+
Current



Waveforms Power Supply Window

Connect grounds of multiple power supplies



Lab procedure

- Verify proper PWM signal generation
- Study amplifier behavior
  - Measure V_{in}, V_{BE}, V_{CE}
  - Compare to theoretical assumptions
- Study motor behavior
  - Measure tachometer output (yellow/green leads)
  - Plot motor speed vs. PWM signal duty cycle
  - Repeat for several PWM signal frequencies
  - Analyze data and discuss results

Choice of devices

- Transistor (*Q*)
  - 2N3904 is cheap but under-rated for current
  - 2N2222 has higher current rating
  - Both may be destroyed if motor is stalled
- Diode (*D*)
  - 1N4001 is a rectifier diode: a bit slow, has large diameter leads
  - 1N4148 (or 1N914) is a switching diode: faster, but has low current rating (but is not expensive)

2N2222 NPN transistor data

Source: Fairchild Semiconductor

Absolute Maximum Ratings			
Symbol	Parameter	Value	Unit
V_{CEO}	Collector-emitter voltage (base open)	40	V
V_{CBO}	Collector-base voltage (emitter open)	75	V
V_{EBO}	Emitter-base voltage (collector open)	6	V
I_C	Collector current	1	A

Electrical Characteristics					
Symbol	Parameter	Conditions	min	max	Unit
h_{FE}	Dc current gain	I_C = 150 mA, V_{CE} = 1 V	50		
$V_{CE(sat)}$	Collector-emitter saturation voltage	I_C = 150 mA, I_B = 15 mA		0.3	V
$V_{BE(sat)}$	Base-emitter saturation voltage	I_C = 150 mA, I_B = 15 mA	0.6	1.2	V

2N3904 NPN transistor data

Source: Fairchild Semiconductor

Absolute Maximum Ratings			
Symbol	Parameter	Value	Unit
V_{CEO}	Collector-emitter voltage (base open)	40	V
V_{CBO}	Collector-base voltage (emitter open)	60	V
V_{EBO}	Emitter-base voltage (collector open)	6	V
I_C	Collector current	200	mA

Electrical Characteristics					
Symbol	Parameter	Conditions	min	max	Unit
h_{FE}	Dc current gain	I_C = 100 mA, V_{CE} = 1 V	30		
$V_{CE(sat)}$	Collector-emitter saturation voltage	I_C = 50 mA, I_B = 5 mA		0.3	V
$V_{BE(sat)}$	Base-emitter saturation voltage	I_C = 150 mA, I_B = 5 mA		0.95	V

1N4148 switching diode data

Source: Fairchild Semiconductor

Absolute Maximum Ratings			
Symbol	Parameter	Value	Unit
V_{RRM}	Maximum repetitive reverse voltage	100	V
I_O	Average rectified forward current	200	mA
I_F	Dc forward current	300	mA
I_C	Collector current	200	mA

Electrical Characteristics					
Symbol	Parameter	Conditions	min	max	Unit
V_F	Forward voltage	I_F = 100 mA		1	V
I_R	Reverse leakage	V_R = 20 V		0.025	μA
t_{rr}	Reverse recovery time	I_F = 10 mA, V_R = 6 V, I_{rr} = 1 mA, R_L = 100 ohm		4	ns