Lecture 2: Electrical Components and Basic Circuits

ME/AE 6705

Introduction to Mechatronics

Dr. Jonathan Rogers

Lesson Objectives

- Understand basic electrical components and circuit analysis methods
- Understand concept of resistance, capacitance, inductance, and impedance
- Understand op-amp circuits for amplification and input comparison
- Understand electrical switching elements including switches, relays, and transistors
- *Be able to design basic signal conditioning circuits*

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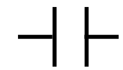
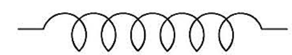
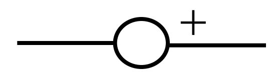
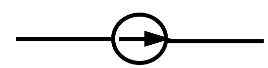
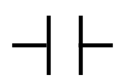
Basic Circuit Elements

Name	Reference Symbol	Circuit Symbol
Resistor	*R*	
Capacitor	*C*	
Inductor	*L*	
Ideal Voltage Source	*V*	
Ideal Current Source	*I*	

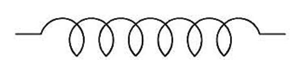
Constitutive Relationships:

$$V = IR$$

$$\frac{dV}{dt} = \frac{1}{C} I$$



$$\frac{dI}{dt} = \frac{1}{L} V$$



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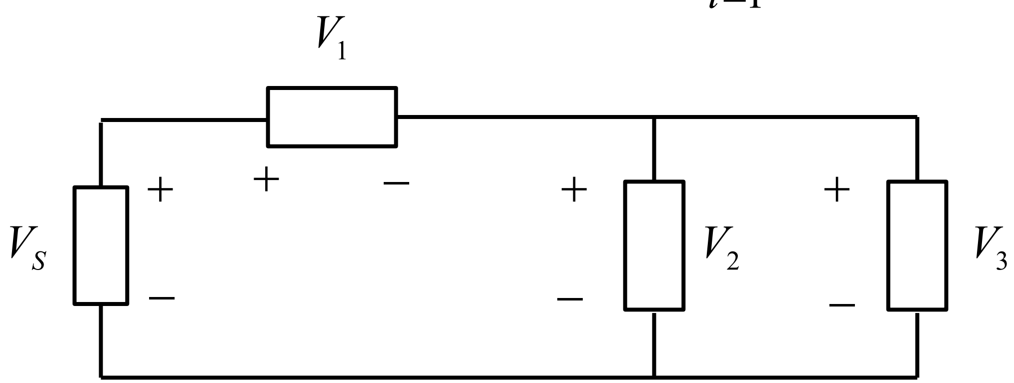
Circuit Analysis

- Kirchhoff's Voltage Law
  - Sum of voltage drops and rises around any closed path in circuit is zero

$$\sum_{i=1}^{N} V_i = 0$$



$$V_S - V_1 - V_2 = 0$$

$$V_S - V_1 - V_3 = 0$$

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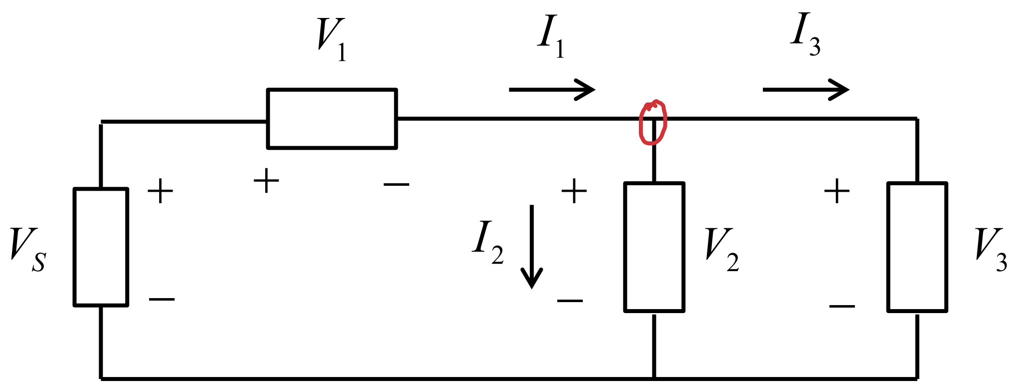
Circuit Analysis

- Kirchhoff's Current Law
  - Sum of current into a node is zero

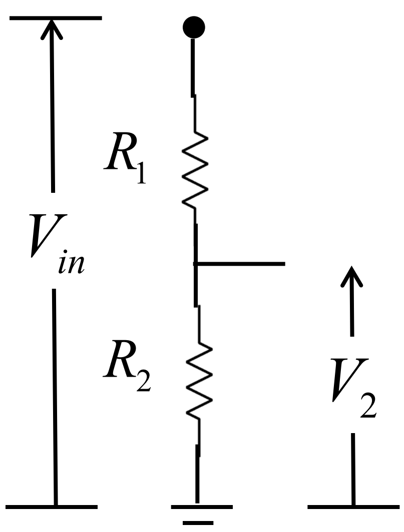
$$\sum_{i=1}^{N} I_i = 0$$



$$I_1 - I_2 - I_3 = 0$$

Circuit Analysis

- By placing two resistors in series and taking voltage between resistors, we create a ***voltage divider***
  - Can be used to step down input source voltage for a sensor or processor (low-power applications)

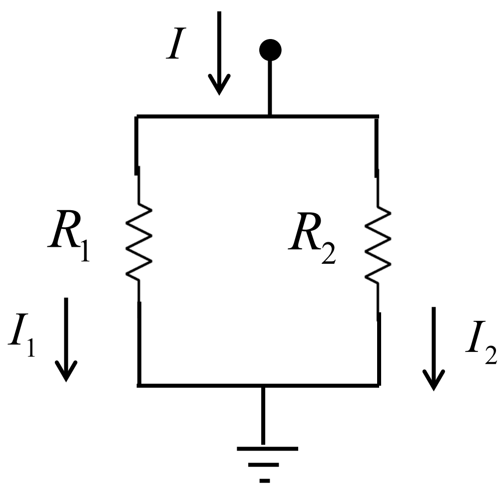


$$V_2 = \frac{R_2}{R_1 + R_2} V_{in}$$

(derived using Kirchhoff's Laws)

Circuit Analysis

- By placing two resistors in parallel and taking current along one branch, we create a ***current divider***

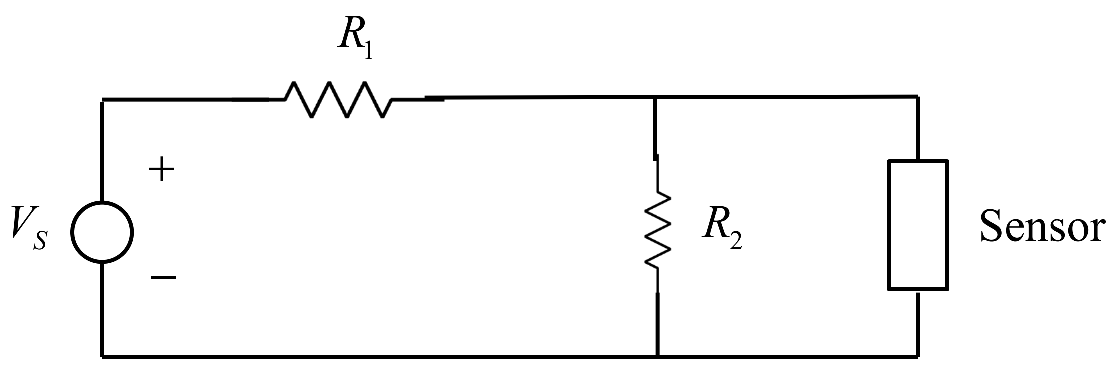


$$I_2 = \frac{R_1}{R_1 + R_2} I$$

(derived using Kirchhoff's Laws)

Example: Designing a Voltage Divider

- Problem: A certain sensor requires an input voltage of 5 VDC. You have a voltage source available which only provides 15 VDC. Design a voltage divider that will allow you to power the sensor from this power supply.



What are R_1 and R_2?

$$\frac{R_2}{R_1+R_2} = \frac{1}{3}$$

$R_2 = 5\ k\Omega$

$R_1 = 10\ k\Omega$

Switch Types

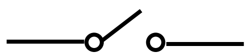
- Switches defined as either **toggle** or **push-button**

pole # of separate circuits controlled

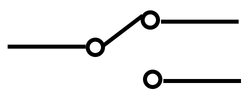
throw · # of different positions / connections each pole can make

Toggle Switches

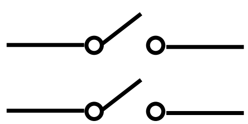
Single Pole, Single Throw (SPST)



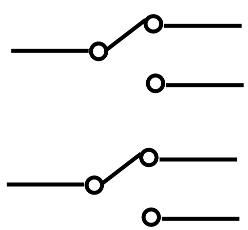
Single Pole, Double Throw (SPDT)



DPST

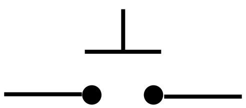


DPDT

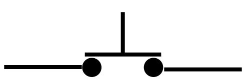


Push-Button Switches

Normally Open (NO)

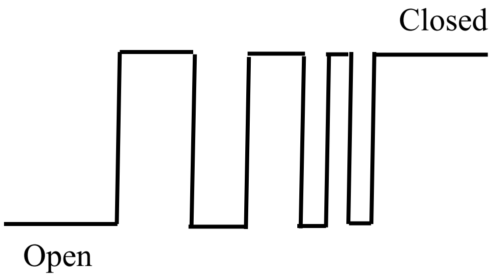


Normally Closed (NC)



Switch Bouncing Phenomenon

Requires use of debouncing circuit.



AC vs DC Signals

$\sin^2 x = \frac{1-\cos 2x}{2}$

- AC (alternating current) signals have sinusoidally varying voltage

$$\frac{1}{T}\int_0^T V^2\,dt = \frac{1}{T}\int_0^T V_0^2 \sin^2(\omega t+\theta)\,dt$$

$$\frac{V_0^2}{T}\int_0^T \frac{1-\cos(2(\omega t+\theta))}{2}\,dt$$

$$\frac{V_0^2}{2T}\Big(\underbrace{\int_0^T 1\,dt}_{T} - \underbrace{\int_0^T \cos(2\omega t+\theta)\,dt}_{\text{integral over one period is 0}}\Big)$$

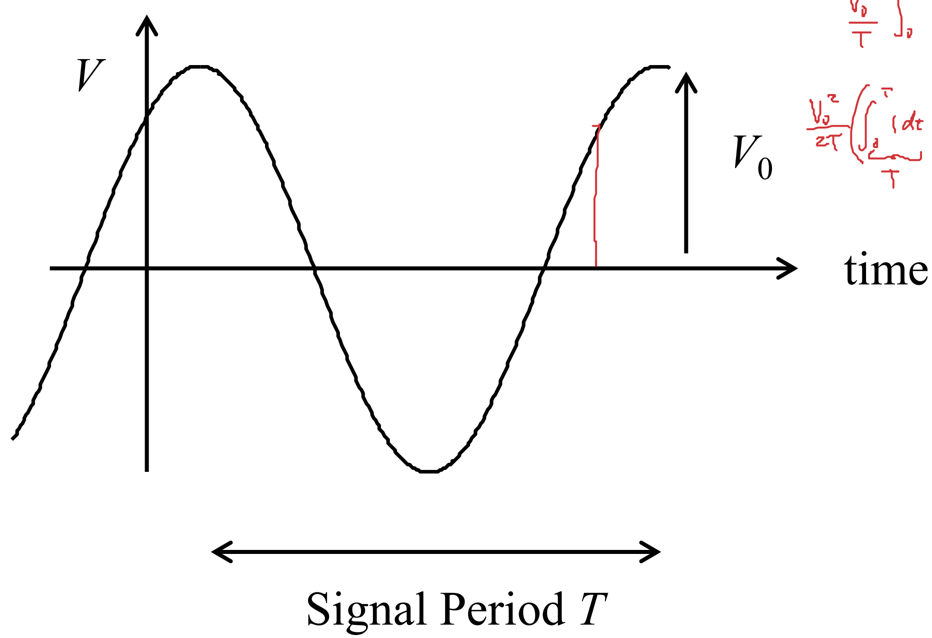
$$\downarrow$$

$$\frac{V_0^2}{2}$$

$$V_{RMS} = \sqrt{\tfrac{1}{2}}\,V_0 \approx 0.707$$

$$V = V_0 \sin(\omega t + \theta)$$

$\omega = 2\pi f = \frac{2\pi}{T}$



DC Voltage occurs when voltage is constant with time ($\omega = 0$).

$$V_{RMS} = \sqrt{\frac{1}{T}\int_0^T V^2\,dt} = 0.707V_0$$

$$I_{RMS} = \sqrt{\frac{1}{T}\int_0^T I^2\,dt} = 0.707I_0$$

Note: AC current from wall is 110 VAC, meaning the RMS voltage is 110 V.

Power

- Power defined as voltage times current

$$P(t) = I(t)V(t) \xrightarrow{\text{DC Voltage}} P = IV = I^2R$$

$\sin(A) \cdot \sin(B) = \frac{1}{2}[\cos(A-B) - \cos(A+B)]$

AC Voltage $\downarrow$

$$P(t) = V_0 I_0 \sin(\omega t + \theta_V)\sin(\omega t + \theta_I)$$ Instantaneous Power

$$P(t) = V_{RMS} I_{RMS} \underbrace{\cos(\theta_V - \theta_I)}$$ Average Power

adjust to bring closer to 0 for more power

Power factor: Measures how much of supplied power is converted into real or useful power.

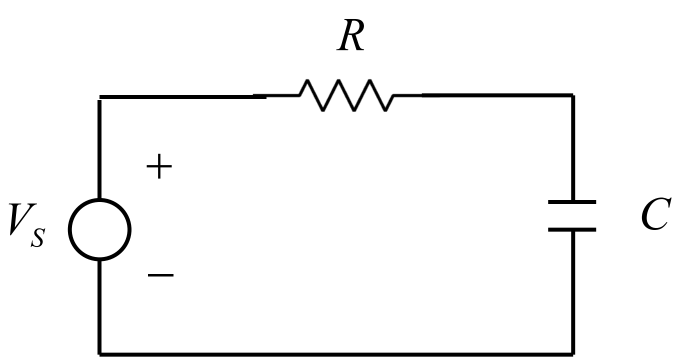
Impedance

- Impedance (Z) is generalization of resistance

$$Z = \frac{V}{I}$$

  - Basically gives us a measure of “resistance” in circuit that includes more elements than just resistors

RC circuit



Kirchhoff’s Voltage Law:

$$V_S(t) = Ri(t) + \frac{1}{C}\int i(t)\,dt$$

$$V_s(s) = R\,i(s) + \frac{1}{Cs}\,i(s)$$

$$\frac{V_s(s)}{i(s)} = R + \frac{1}{Cs}$$

Impedance

- Applying Laplace transform,

$$V_S(s) = Ri(s) + \frac{1}{Cs}i(s) \longrightarrow \frac{V_S(s)}{i(s)} = R + \frac{1}{Cs}$$

If voltage varies sinusoidally with frequency ω, can substitute $s = j\omega$ $\longrightarrow$

$$Z = \frac{V_S(j\omega)}{i(j\omega)} = R + \frac{1}{j\omega C}$$

Impedance due to capacitor

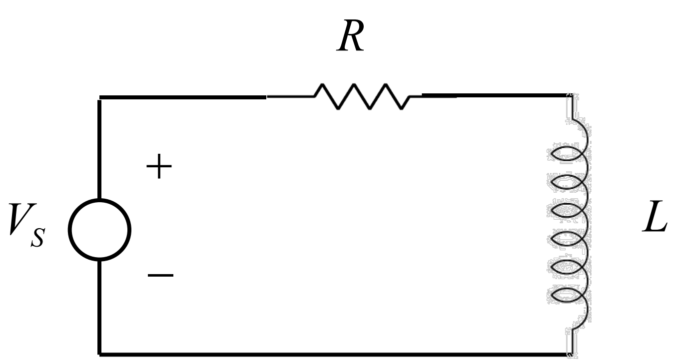
- For DC voltage source, **impedance of RC circuit is infinite** $\omega = 0$
- For AC voltage source, **impedance of RC circuit approaches R as $\omega \to \infty$** high frequency : $Z \to R$

Impedance

- Similar analysis for RL circuit yields:

$$Z = \frac{V_S(j\omega)}{i(j\omega)} = R + j\omega L$$

Impedance due to inductor



Impedance is an imaginary quantity:

$$Z = R + jX$$

R = $\underbrace{\textbf{resistance}}_{\text{real part}}$

X = $\underbrace{\textbf{reactance}}_{\text{imaginary part}}$

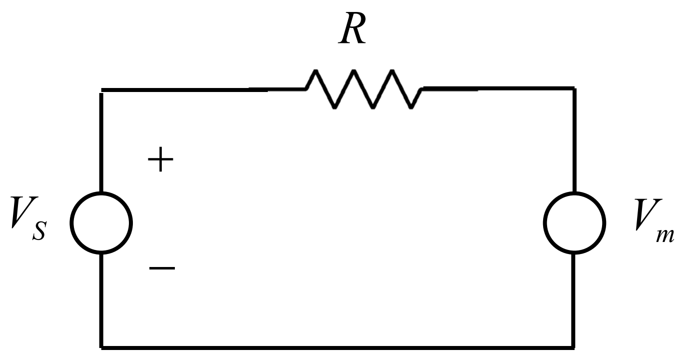
varies w/ frequency

What is impedance of a circuit with just a resistor load R_{total}?

Impedance: Practical Considerations

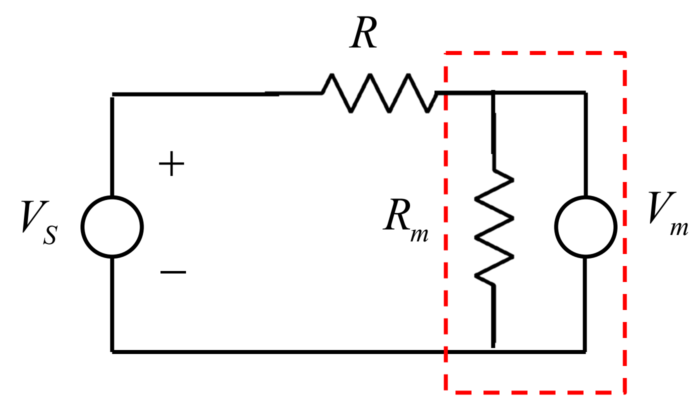
Voltmeters have finite impedance

Ideal Voltmeter



$$V_m = V_S$$

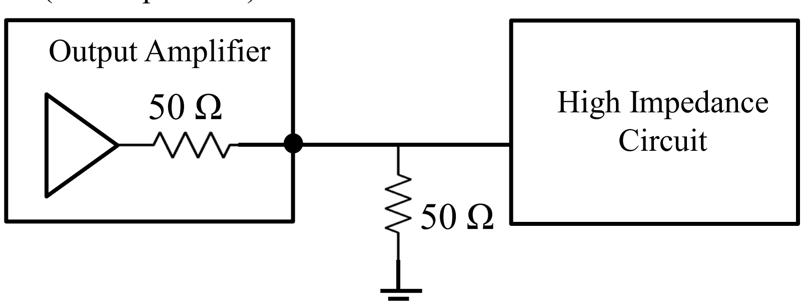
Actual Voltmeter
(impedance R_m)



$$V_m = \frac{R_m}{R_m + R_S} V_S$$

- When connecting electrical devices together, important to make sure **impedances are matched**
- Otherwise high-impedance device can reflect back signal produced by low-impedance device
- **Impedance matching** can be accomplished by adding appropriate resistors to circuit

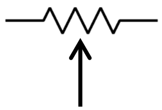
Function Generator
(low impedance)



Potentiometers

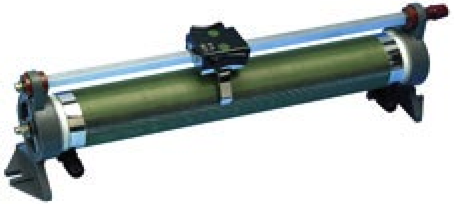
- Potentiometers and rheostats are variable resistors
  - Potentiometers have three terminals
  - Rheostats have two
- Useful for user interfaces, or to adjust resistor value to precise level needed in circuit design
  - Resistors only come in discrete values

Potentiometer Symbol



Potentiometer

Rheostat



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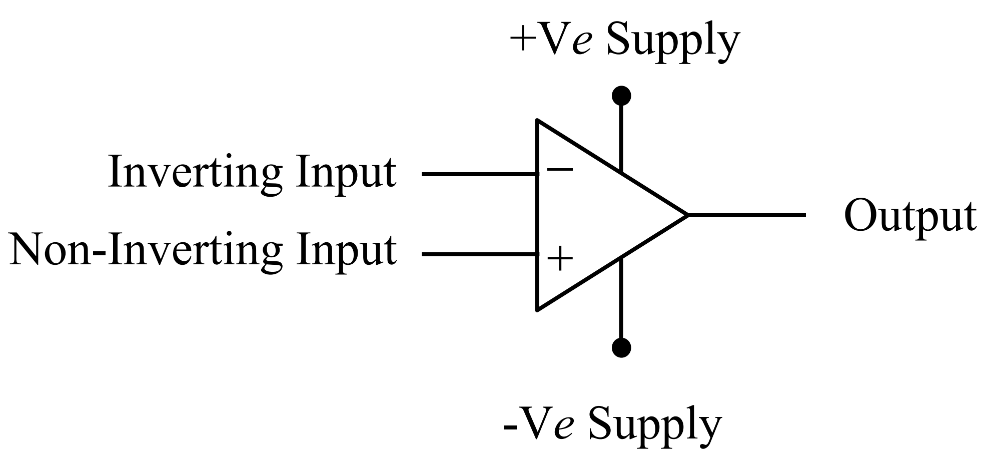
Op-Amps

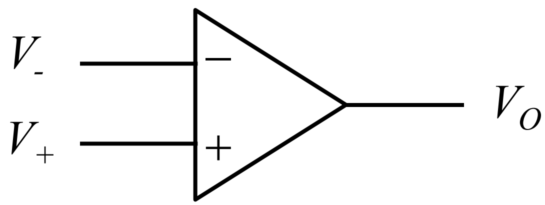
- Operational amplifiers are important circuit components
  - Used in signal amplification and other common circuits
  - Built from transistors, diodes, resistors, capacitors



Supply voltage is typically +/- 15V

Op-Amps

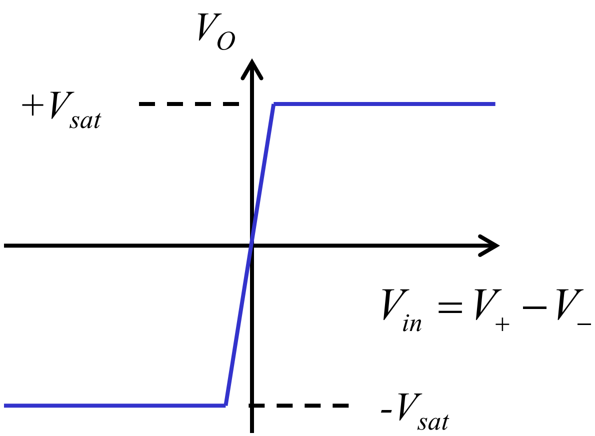
- Open-loop operation of op-amps



V_O saturates at V_{sat} which is typically slightly smaller than supply voltage (~13V)

$$V_O = K_{OL}\left(V_+ - V_-\right)$$

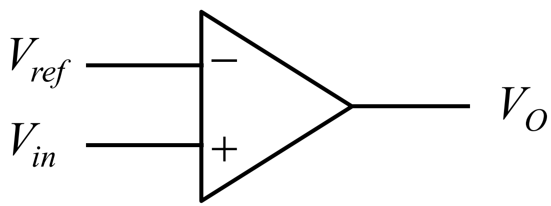
$$K_{OL} \approx 10^5 \text{ or } 10^6$$



Except for voltage comparators, op-amps not used in “open loop” configuration often.

Op-Amps

- Comparator Op-Amp Circuit
  - Useful application of open-loop op-amp
  - Used on-board microcontrollers
  - (Still requires supply voltage, although terminals not shown)



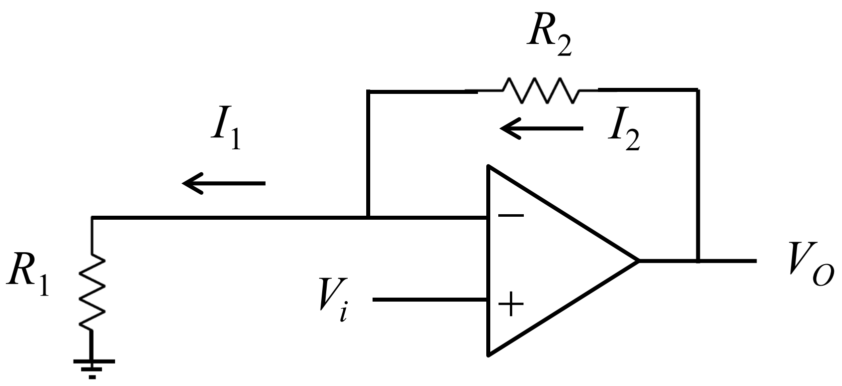
$$V_O = \begin{cases} +V_{sat} & \text{if } V_{in} > V_{ref} \\ -V_{sat} & \text{if } V_{in} < V_{ref} \end{cases}$$

Example use:

- Set output ON when sensor input exceeds certain threshold output.

Op-Amps

- Non-Inverting Op-Amp
  - Used to amplify voltage signal
  - For instance, signal conditioning for sensor

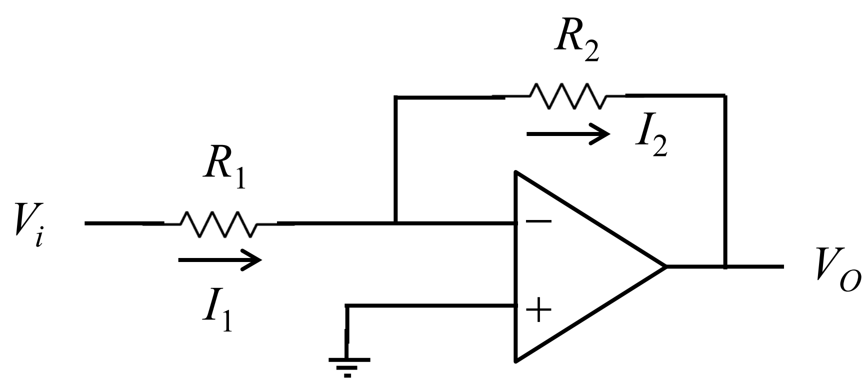


$$V_O = \frac{R_1 + R_2}{R_1} V_i = \left(1 + \frac{R_2}{R_1}\right) V_i$$

- By sizing R_1 and R_2 appropriately, can amplify V_i to value we need at output V_O
- Since resistors only come in discrete values, sometimes need to make R_1 or R_2 a potentiometer so it can be tuned to precise value we need.

Op-Amps

- Inverting Op-Amp
  - Used to amplify voltage signal and invert it
  - Also used in signal conditioning

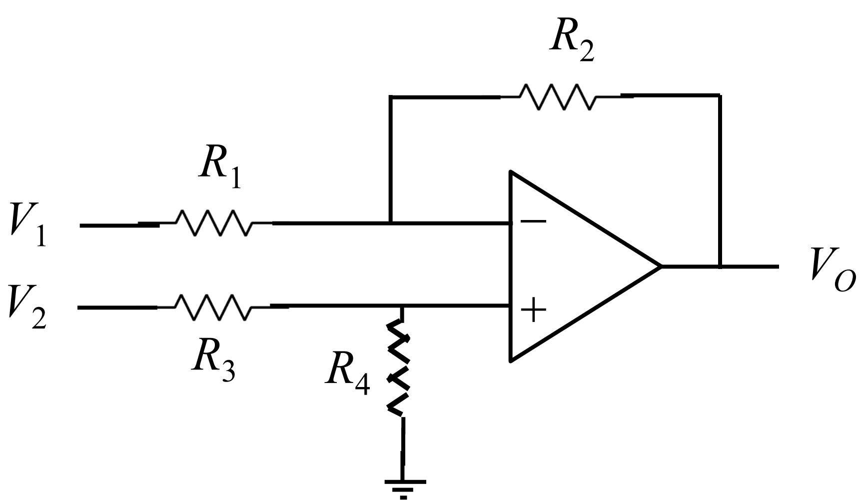


$$V_O = -\frac{R_2}{R_1} V_i$$

- Again, by sizing R_1 and R_2 appropriately, can amplify V_i to value we need at output V_O

Op-Amps

- Differential Op-Amp
  - Used to provide a measure of the difference between two voltage inputs



$$V_0 = \frac{R_2}{R_1}\left(V_2 - V_1\right) = K_P\left(V_2 - V_1\right)$$

Example Use: Amplify difference between voltage outputs on arms of Wheatstone bridge used to measure strain.

Example: Signal Amplification

- Using an op-amp, design a circuit that takes an input voltage V_i and produces an output voltage $V_O = kV_i$ which is tunable from $1 \leq k \leq 10$. Determine the circuit components needed and an expression for the value of *k*.

$V_0 = \left(1 + \frac{R_2}{R_1}\right) V_i$

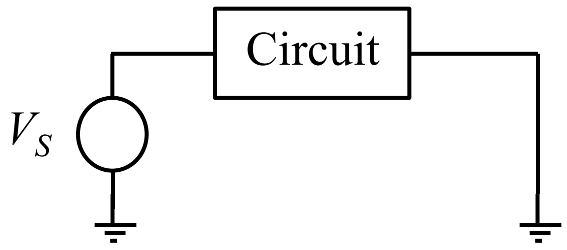
$0 \leq \frac{R_2}{R_1} \leq 9$

$R_1 = 1\,k\Omega$

$R_2 = [0, 9]\,k\Omega$ potentiometer

Grounding

- Ground loops can cause series problems (bias and noise) in circuit design
  - Must make sure that all ground points are connected to <u>same</u> ground (**common ground**)
  - Connections to multiple different grounds can cause feedback current between grounds



Bad idea…these grounds may be at different electrical potentials.

Grounding

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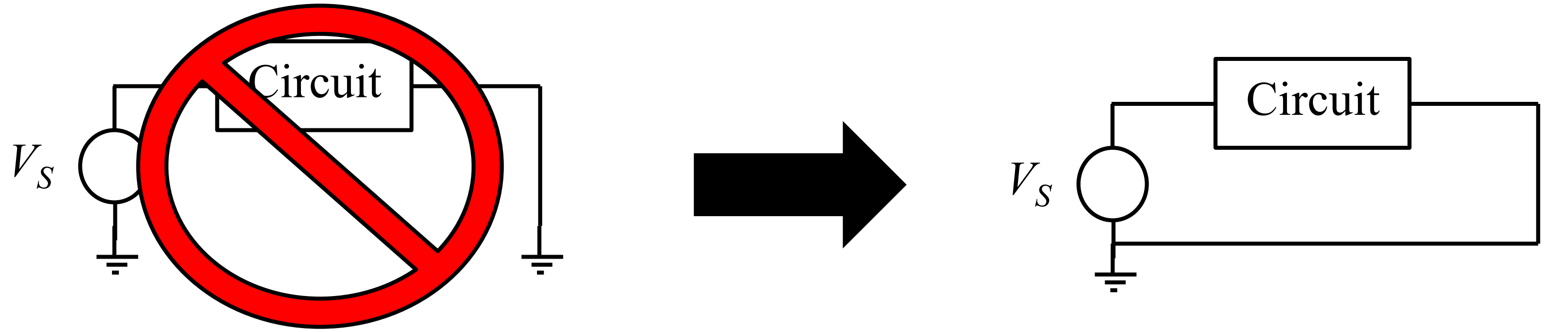


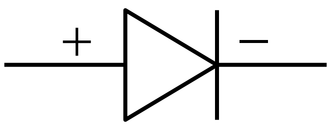
Semiconductors

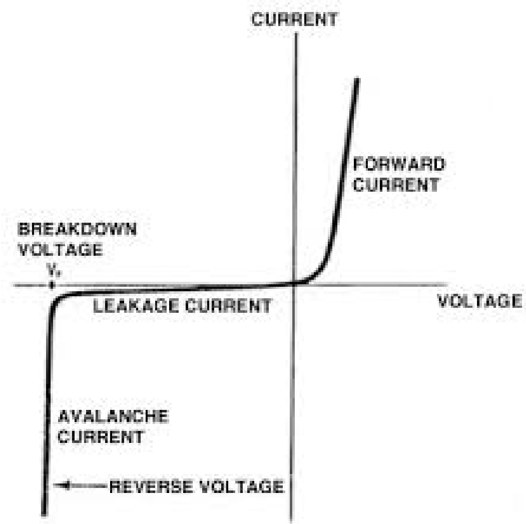
- Semiconductors are special materials that are between conductors and insulators
- They can be made to conduct current if sufficient voltage is present
- Most important semiconductor device is the transistor, which can be viewed as a solid-state switching device
  - Logic gates
  - Interface between processors and mechanical devices

Diodes

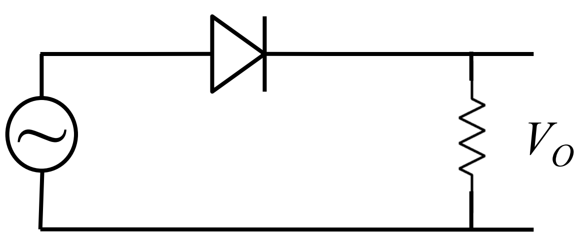
- Diodes are semiconductor devices that only allow current to flow one way

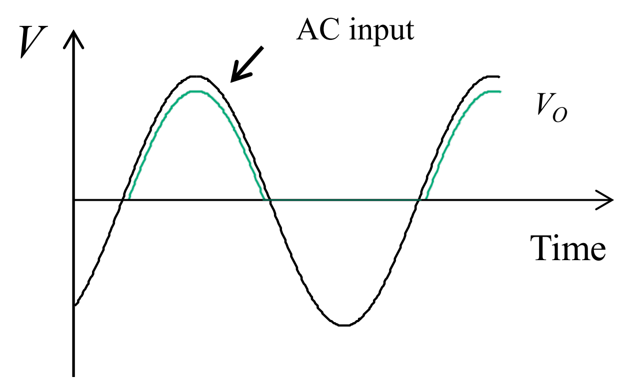
Symbol





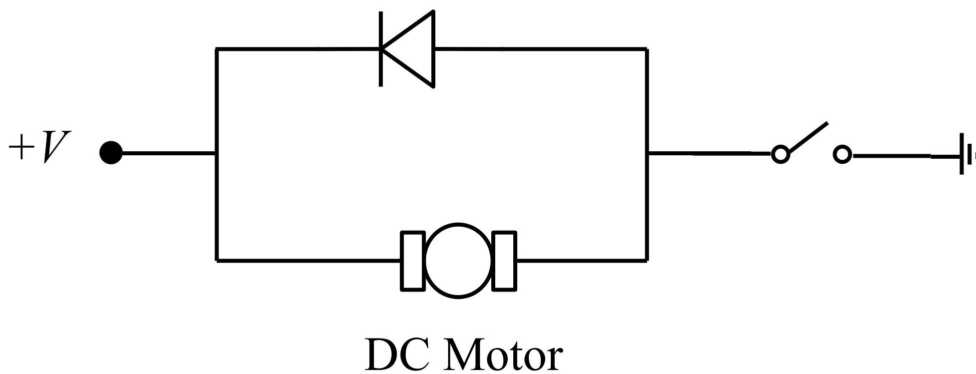
Example Use: Rectify AC voltage into DC voltage.





Flyback Diodes

- Consider following circuit for motor control using switch

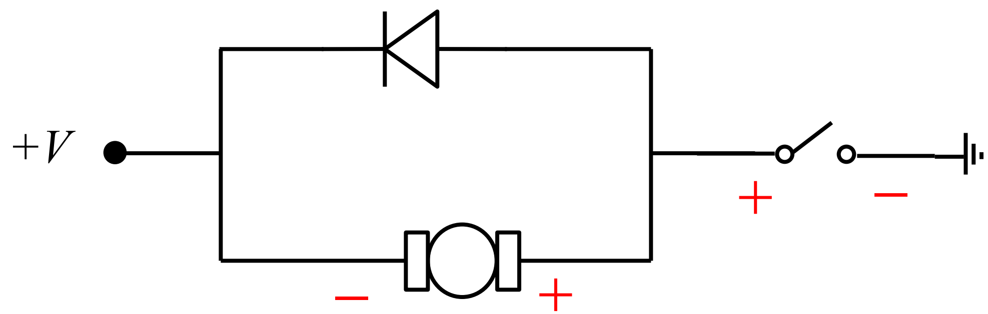


- Motor has high inductance L
- When motor switched off, voltage develops across motor terminals according to:

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

Flyback Diodes

- Consider following circuit for motor control using mechanical switch



DC Motor

Just after switch closing…

as $i(t) \rightarrow 0$

$\frac{di(t)}{dt} \rightarrow$ large negative value

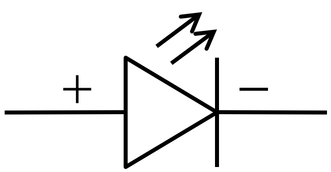
$$V = L\frac{di(t)}{dt}$$

- High voltage of opposite polarity across switch terminals just after closing
- May cause wear on switch due to arcing, or may blow out transistor
- **Flyback diode provides an alternative path for current in motor coil and mitigates arcing**

LED's and Photodiodes

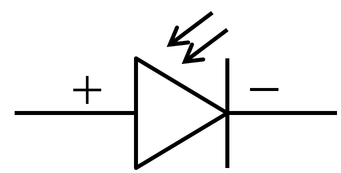
Light Emitting Diodes

- Emit light when "forward biased"
- Have voltage drop of about 2V when on
- Colors determined either by semiconductor material or plastic housing over diode



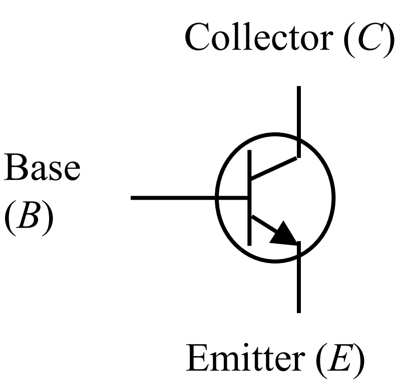
Photodiodes

- Opposite of LED
- Amount of current diode passes is proportional to amount of light it receives
- Commonly used as light sensors (i.e., nightlight)



BJT Transistors

- Bipolar Junction Transistors (BJT's) are common circuit elements used primarily for switching
- Idea is that we can switch a current path on or off by activating a second "base" path



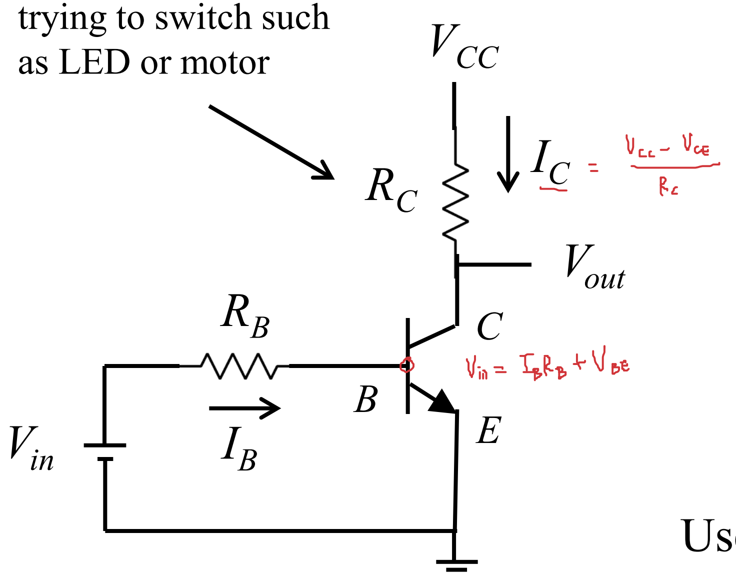
- BJT is current controlled device where amount of current supplied at *B* determines current flow from *C* to *E*
- Small base current allows much larger current to flow from collector to emitter
- Two important states: Off, and Saturation State
- Voltage at emitter (V_E) always lower than voltage at base (V_B) by about 0.6V
- Must always have $V_C > V_E$

$$V_{BE} = V_B - V_E \qquad V_{CE} = V_C - V_E$$

BJT Transistors

- Transistor Switch Circuit

Can be load we are trying to switch such as LED or motor



- Suppose we want to control current flow I_C using input voltage V_{in}
- When $V_{in} = 0$, no current flows between collector and emitter and thus $I_C = 0$ (and $V_{out} = V_{CC}$)
- Question: What voltage V_{in} is required to switch transistor from off state to saturation state (allowing current to flow through load)?

Use KVL: $$V_{in} = I_B R_B + V_{BE}$$

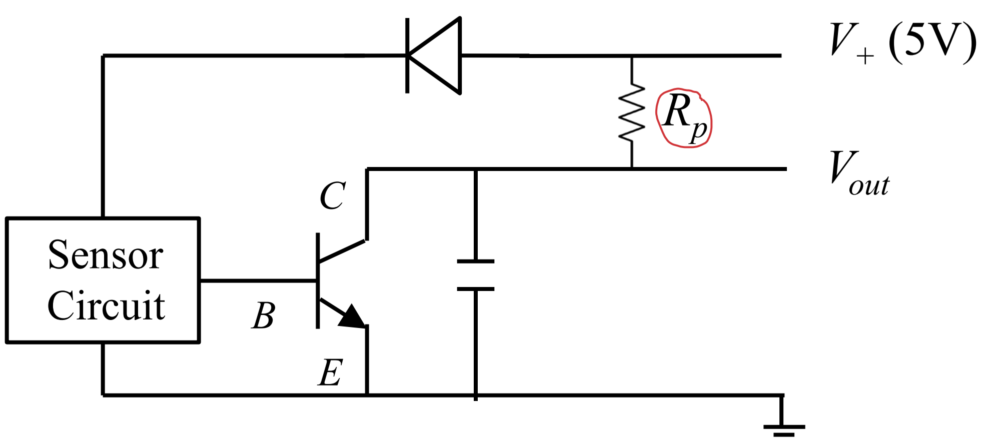
Use KCL: $$I_C = \left(V_{CC} - V_{CE}\right) / R_C$$

Property of BJT's just before saturation: $$I_B = I_C / \beta \qquad (\beta \approx 100)$$

Equations can be solved to determine V_{in}

BJT Transistors

- Open Collector Output
  - Used often to take sensor output and convert to digital high (5V) or low (0)



- Output of sensor drives base of transistor
- R_p is "pull-up" resistor connected from reference voltage V_+ to output V_{out}
- When sensor is low, transistor is in OFF state and no current flows from C to E $\rightarrow V_{out} = 5\text{V}$
- When sensor is high, transistor is in saturation and current flows from C to E $\rightarrow V_{out} \approx 0$

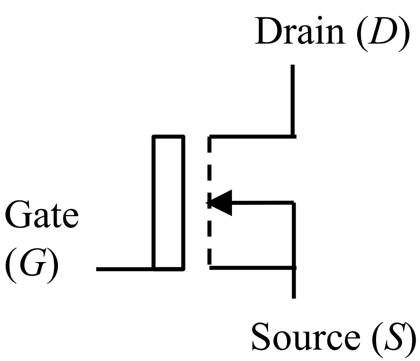
BJT Transistors

- Common specifications (found in component datasheet)

Part #	Max V_{CE}	Max V_{BE}	Max I_C	Power Dissipation at 25 deg C
2N3904	40 V	6 V	200 mA	0.625 W
TIP29	40 V	6 V	1 A	30 W
TIP102	100 V	5 V	8 A	80 W

MOSFET Transistors

- Metal-Oxide Semiconductor Field Effect Transistors (MOSFET's) are another type of transistor commonly used for switching
- Unlike BJT's, MOSFET's use voltage as switching signal rather than current



- MOSFET is voltage controlled device where voltage supplied at G determines current flow from (or resistance between) D to S
- Two important states: Off and Saturation State
- When transistor is off, drain-source resistance is very high → no current flows from D to S
- When transistor is ON, drain-source resistance is very low (< 1 Ω) and current flows from D to S
- Internal resistance at gate is very high (10^{14} Ω) – thus no current flows into gate (gate circuit "separate" from drain-source circuit)

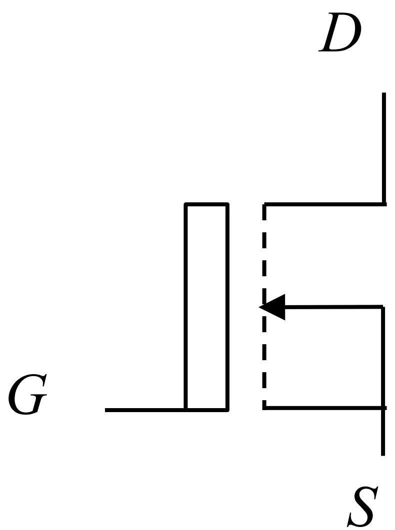
MOSFET Transistors

- Some other important values/considerations

V_{GS} : Gate-source voltage

$V_{GS(\text{th})}$: Threshold gate-source voltage. If $V_{GS} < V_{GS(\text{th})}$ transistor is in OFF state. If V_{GS} is significantly higher than $V_{GS(\text{th})}$, transistor is in ON (saturation) state.

V_{DS} : Drain-source voltage



Thus, like BJT, MOSFET acts as a solid-state switch. Switching times are usually in the nanosecond range.

MOSFET Transistors

Part #	On Resistance $R_{DS\ (on)}$	Max Current Drain $I_{D\ (max)}$	Power Dissipation P_D	Gate Threshold Voltage $V_{GS(th)}$	Drain-to-Source Breakdown Voltage V_{dss}	Type
2N4351	<= 300 Ω	100 mA	375 mW	1-5 V	>= 25 V	Logic-level MOSFET
NTE2980	0.2-0.28 Ω	6.7 A	25 W	1-2 V	>= 60 V	Normal MOSFET
IRFZ14	0.2 Ω	10 A	43 W	2-4 V	>= 60 V	Power MOSFET

$R_{DS\ (on)}$: Resistance between drain and source terminals when MOSFET is fully on.

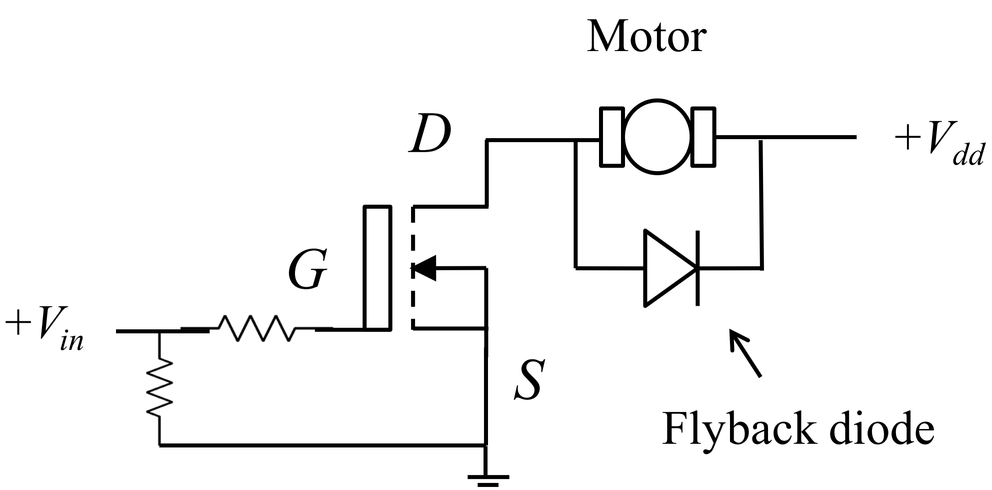
$I_{D\ (max)}$: Max current that can be passed between drain and source.

V_{dss} : Maximum voltage between drain and source when transistor is off. If voltage between *D* and *S* exceeds this value when in OFF state, current will start to flow.

MOSFET Transistors

- MOSFETs commonly used for switching to drive motors or LEDs

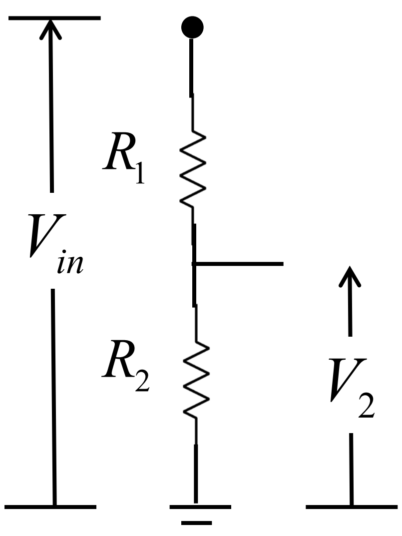
MOSFET Circuit for Driving a Motor



- When V_{in} is below threshold voltage, transistor is OFF and no current flows through motor
- When V_{in} is well above threshold voltage, transistor is ON and current flows through motor
- Flyback diode protects MOSFET from large voltage buildup when transistor is switched from on to off
- Resistor used to ground gate terminal when $V_{in} = 0$ to turn transistor completely off

Reducing Voltage Levels

- Recall voltage dividers
  - Can be used to step down voltages for low-power applications
  - *Should never use a voltage divider to supply power to a load*
  - Only for use in low-current applications with high values of R_1 and R_2 (in the 1 kΩ - 10 kΩ range)

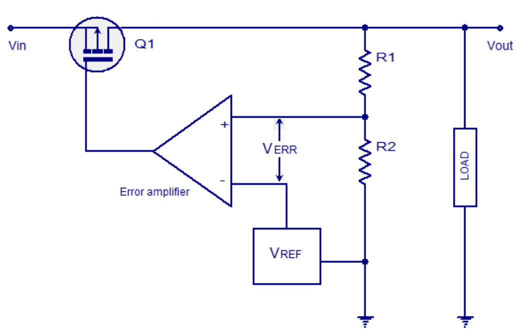


- While providing power, current will flow through R_1 and R_2
- This means resistors will dissipate power in the form of heat
- If any substantial current flows through voltage divider, it *generates excessive heat* and is *power inefficient*

Voltage Regulators

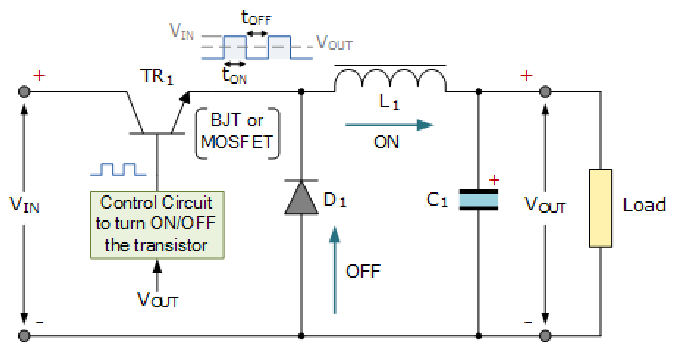
- Voltage regulators are semi-conductor devices that provide very efficient, stable mechanism for stepping down voltages
  - Will provide single output voltage (e.g., 5V) for a range of input voltages (e.g., 7-35V)

Linear Voltage Regulator



Uses differential amplifier and transistor to achieve stable output voltage

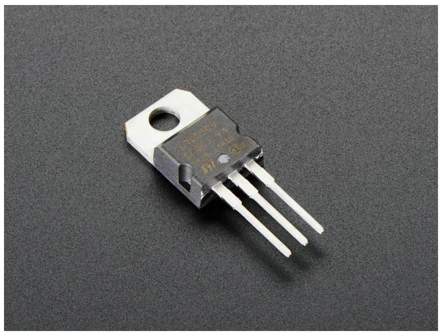
Switching Voltage Regulator



Switches gate / base of transistor at specific rate to achieve stable output voltage

Voltage Regulators

- Common linear voltage regulator: 7805



- Output voltage: 5 V
- Input voltage range: 7-35V
- Maximum current provided: 1.5A
- Dropout voltage: 2V
- Cost: $0.75

- All linear regulators have a <u>dropout voltage</u>
  - This describes how much higher input voltage must be than desired output voltage
- Heat dissipation is an issue – regulators must be attached to heat sink for high power applications

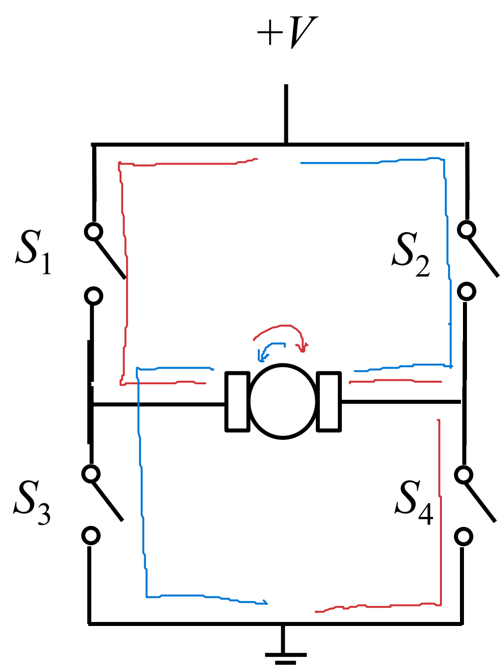
$$P = (V_I - V_O)I$$

Power dissipation equation for regulator

H-Bridge Drives

- Commonly used to drive motors in both directions
  - Typically used to drive brushless and brushed DC motors
  - Critical element in <u>servo</u> drives

Typical Hobby Servo



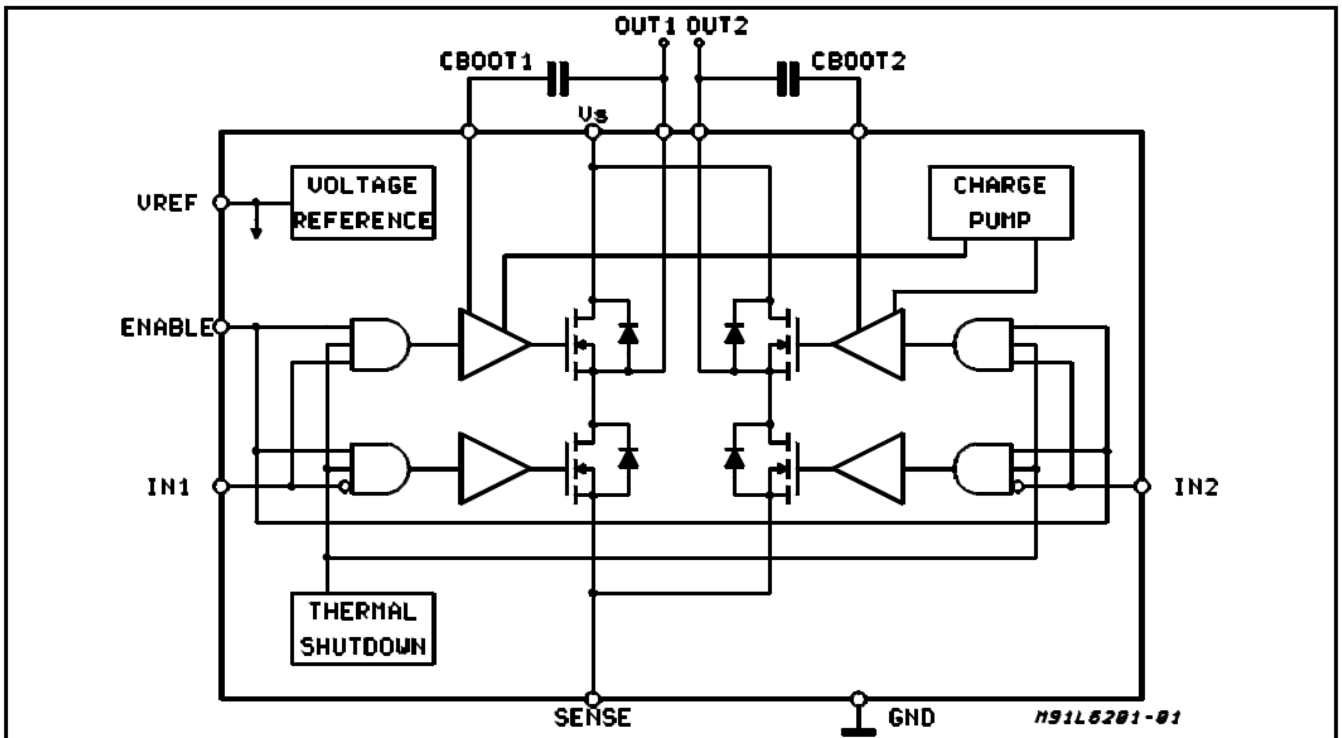
<u>Simple H-Bridge Schematic</u>

- When switches S_1 and S_3 4 are open and S_2 and S_4 3 are closed, motor turns one direction

- When switches S_1 and S_3 4 are closed and S_2 and S_4 3 are open, motor turns other direction

H-Bridge Drives

- H-Bridges are built from transistors, diodes, and logic gates
  - Yields very fast switching times



STMicro L6203 H-bridge

Note flyback diodes incorporated next to MOSFETs. Motor connects across two output terminals.

Example: Op-Amp Signal Conditioning

- Consider the signal conditioning op-amp circuit shown below, with an <u>ideal</u> diode in the feedback loop. Derive the input-output ratio V_O/V_i for the case when $V_O < 0$ and $V_i > 0$.

ideal diode : no voltage drop ?

$$R_{23} = \frac{R_2 \cdot R_3}{R_2 + R_3}$$

$$\frac{V_o}{V_i} = -\frac{R_2 \; R_3}{R_1 (R_2 + R_3)}$$