University of California at Irvine
MAE106 Mechanical Systems Laboratory: Lecture 2
Review of Electrical Circuits

In this class, we are interested in learning how to design robotic and mechatronic systems, and in making measurements of the behavior of mechanical systems to better understand them and mathematically model them. To control a robot, or to make measurements of a mechanical system, we will use electric circuits. This lecture gives an overview of some of the electrical circuits we will use.

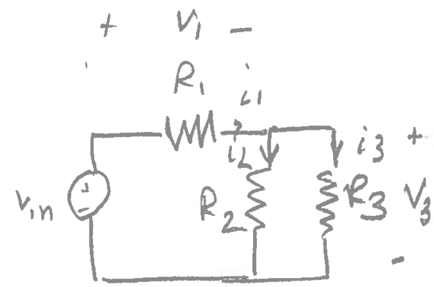
Current and voltage:
Current: think of it as the flow of charge through a circuit element (such as a wire or resistor) [Units: amps=coulombs/sec]

Voltage: think of it as the electrical pressure that can cause charge carriers to flow [Units: volts = electric potential energy (Joules) per unit of charge (coulomb)]

Current is always measured through something at a point; voltage is always measured between two points

For this class, “ground” is an arbitrarily defined point on a circuit to which we reference all voltages.

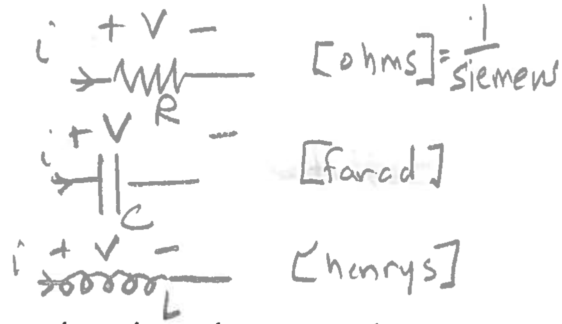
Toolbox for circuit analysis



- Kirchoff’s Current Law: $\sum_{node} \text{current in} = \sum_{node} \text{current out}$ $\quad i_1 = i_2 + i_3$
- Kirchoff’s Voltage Law: $\sum_{loop} \text{voltage} = 0 \quad -V_{in} + V_1 + V_3 = 0$
- Power (Important for “sizing” circuit elements such as resistors and calculating battery drain):
  $P = Vi$
- Triad of linear circuit elements:

R = resistor (eg. pot)
C = Capacitor (eg. filter)
L = inductor (eg motor model)

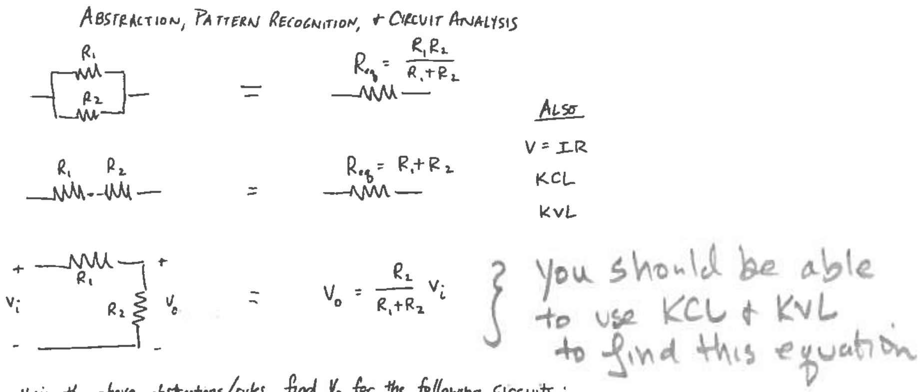
	i	$\frac{di}{dt}$
V	R	L
$\frac{dv}{dt}$	C	

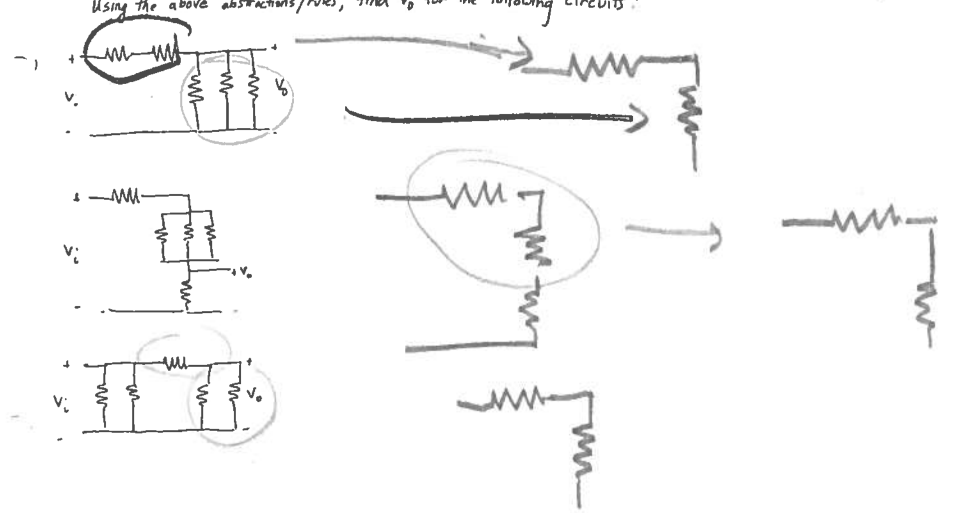


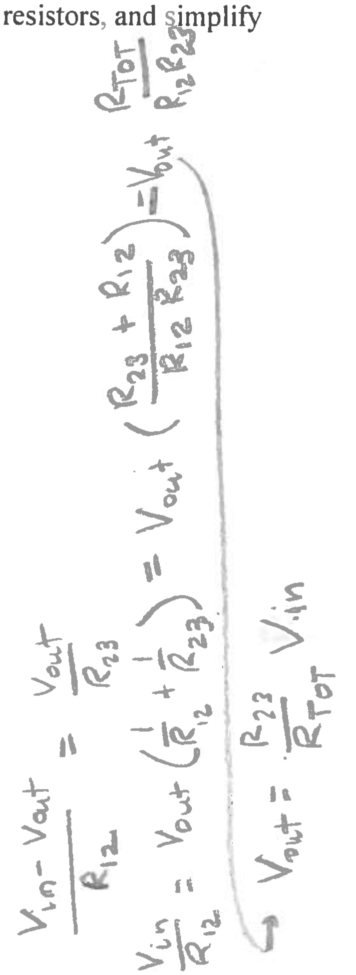
Note that because derivatives are involved, we can use these elements to create dynamics, and we can use that to our advantage in filtering signals.

Resistor Analysis:

To analyze circuits with resistors, it's useful to be able to recognize certain combinations of resistors, and simplify them into a simpler circuit or an equation.







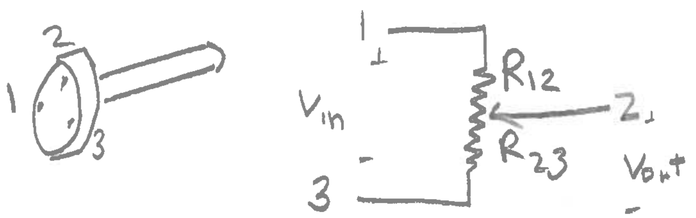
$$\frac{V_{in} - V_{out}}{R_{12}} = \frac{V_{out}}{R_{23}}$$

$$\frac{V_{in}}{R_{12}} = V_{out}\left(\frac{1}{R_{12}} + \frac{1}{R_{23}}\right) = V_{out}\left(\frac{R_{23} + R_{12}}{R_{12}R_{23}}\right) = V_{out}\frac{R_{TOT}}{R_{12}R_{23}}$$

$$V_{out} = \frac{R_{23}}{R_{TOT}} V_{in}$$

Important application of resistor analysis: Potentiometers

Typically used to provide a mechanically-adjustable voltage.
Useful, therefore, as a control knob, or as a rotation sensor.
Wired-up in a voltage divider configuration.
The relative value of the two internal resistors are changed by turning the pot shaft.



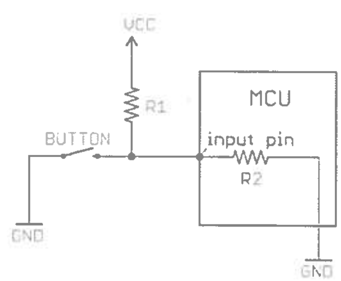
$R_{TOT} = R_{12} + R_{23} = 10K\Omega$, for example

KCL: $\frac{V_{in} - V_{out}}{R_{12}} = \frac{V_{out}}{R_{12}} \Rightarrow V_{out} = \frac{R_{23}}{R_{TOT}}$

Another important use of resistors: "Pull-up" or "pull-down" resistors

"Let's say you have a micro-control unit with one pin configured as an input. If there is nothing connected to the pin and your program reads the state of the pin, will it be high (pulled to VCC) or low (pulled to ground)? It is difficult to tell. This phenomena is referred to as *floating*. To prevent this unknown state, a pull-up or pull-down resistor will ensure that the pin is in either a high or low state, while also using a low amount of current."

See: https://learn.sparkfun.com/tutorials/pull-up-resistors/what-is-a-pull-up-resistor

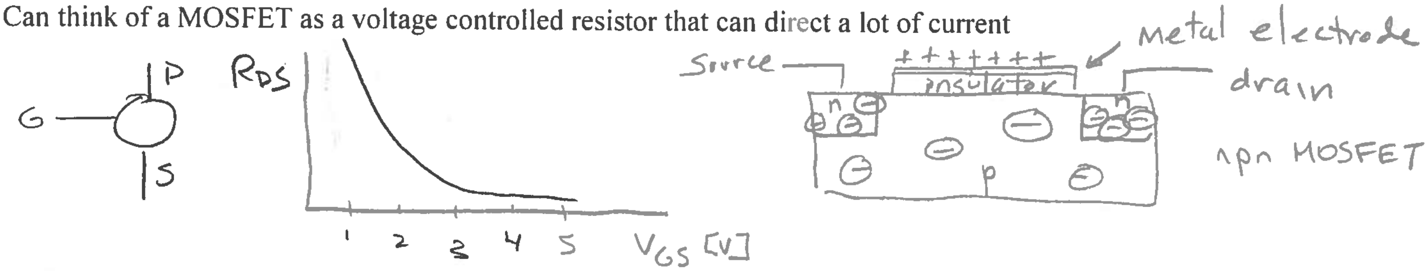


How do we use circuits to control power needed for mechanical devices like motors?

Often we want to control a device that requires a lot of power (e.g. a motor) with signals that have very low power (e.g. Arduino)
Small DC brushed motor: $V = 10$ volts $R = 2\,\Omega$ $i = \frac{V}{R} = 5$ amps (Arduino can put out 40 milliamps only!)
Typical Arduino max output current: 40 mamp

One common solution: Power transistor -- MOSFET

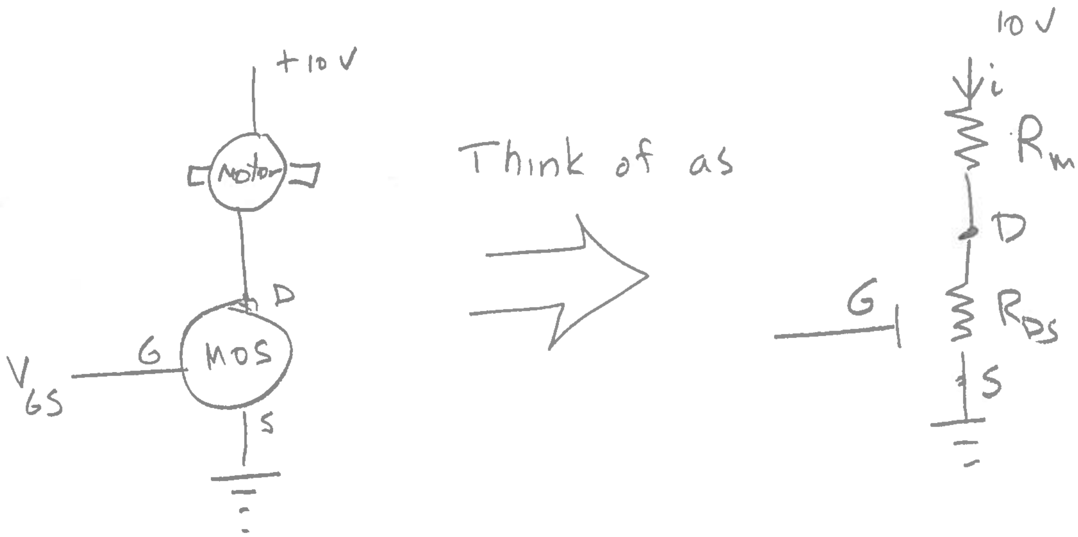
Can think of a MOSFET as a voltage controlled resistor that can direct a lot of current



Notes: Input resistance is very high (therefore effectively no current goes into gate)
Low-power MOSFETS are the "switches" used in computers (what is a switch?)
MOSFETS are very sensitive to static electricity – use a grounding strap when you handle them in lab

Example: use a power transistor to control a motor with a low-power computer output

Hints about motors:
A DC brushed motor spins at a speed proportional to the input voltage, if it is just turning an inertial load.
If you stop the motor, it will produce a torque proportional to the input current



If R_{DS} is big, no current flows

If R_{DS} is small (because V_{GS} is big), current flows

Thus by controlling V_{GS}, we can make the motor turn or not turn

V_{GS}: low power, ~0 current

turn or not turn: High current needed

Operational Amplifiers

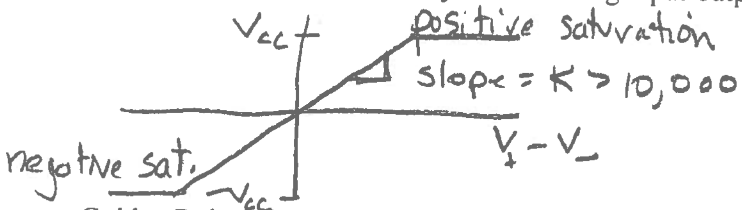
Uses

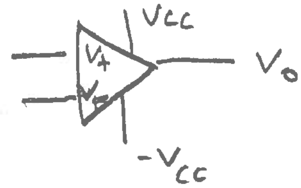
- A primary use is to amplify a small voltage from a sensor so it can be read into microcontroller
- Also can be used to build filters, feedback controllers, and computational circuits
- Can also be used to isolate different parts of circuits ("buffer" = "voltage follower")

What are they?

- High gain, differential, linear voltage amplifiers, made of > 20 transistors plus resistors and capacitors
- Two input terminals, one output, two power supply lines (five pins total)
- Operate over a wide but defined range of supply voltages
- By design, they have a high input resistance and a low output resistance
- Often used with negative feedback configuration, giving us one of the "golden rules" below.

Without feedback, described by the following input-output function:





in linear region

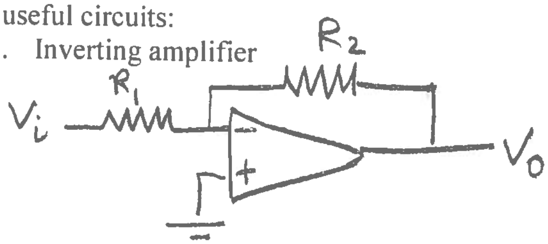
$V_0 = K(V_+ - V_-)$

Golden Rules of Op-amp Circuit design:

1. Input currents are zero (op amps are designed to have a high input resistance)
2. Input voltages are equal (if operating in linear region, and connected with negative feedback)

Four useful circuits:

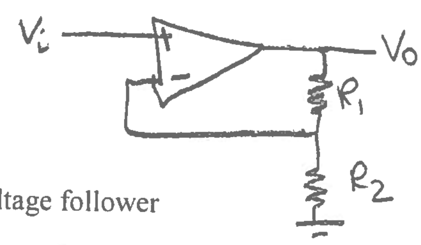
1. Inverting amplifier



what is V_o as a function of V_i?

KCL $\frac{V_i}{R_1} = \frac{0 - V_o}{R_2}$ $V_0 = \frac{-R_2}{R_1} V_i$

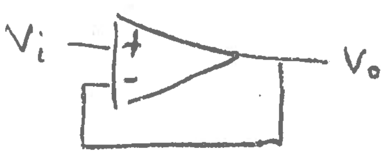
2. Non-inverting amplifier



$V_0 = \frac{R_1 + R_2}{R_2} V_i$

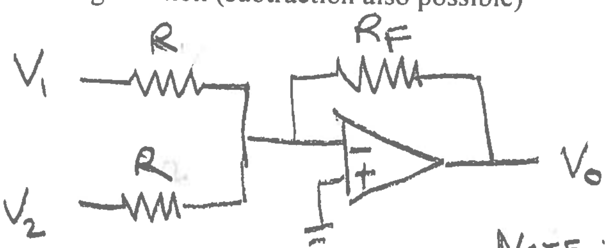
Both useful to amplify small sensor signals

3. Voltage follower



$V_o = V_i$ Why do this? High input impedance lets us connect circuit modules with altering their performance

4. Analog addition (subtraction also possible)



$V_o = \frac{-R_F}{R}(V_1 + V_2)$

NOTE: $|V_o| < |V_{cc}|$ and $i_{out} < i_{max}$ else op-amp saturates

NOTE: FOR ALL CIRCUITS, Feedback from output to input is always to V_- (negative feedback)