Lecture 06

Phototransistors

OpAmps

Agenda

00. Stuff – study groups, teensy
01. Phototransistors
02. Operational Amplifiers (Op Amps)

Stuff

- Do not post documents (e.g. lectures or homeworks) to sites like coursehero or chegg, violates Penn's copyright policy.
- Lectures – how is the pacing?
- Piazza queue during OH.
- Toucan Study hall not working
- TA led study groups – optional

Optional Study Groups

Luo, Rui	Chenxi Ji
Shi, Wentao	Chenxi Ji
Wan, Shenshen	Chenxi Ji
Wang, Zhenyu	Chenxi Ji
Chen, Yuqi	Chenxi Ji
Cao, Ruijie	Geli Yang
Li, Peihan	Geli Yang
Wang, Muxuan	Geli Yang
Zhao, Xinyuan	Geli Yang
Du, Yi	Geli Yang
Garza, Nicholas A	Greg Campbell
Gehrke, Rafael	Greg Campbell
Magee, Madison N	Greg Campbell
Alexandrou, Andreas	Jorge Echeverria
Grimaldi, Brian	Jorge Echeverria
Gomes, Paedyn	Jorge Echeverria
Roth, Alexander W	Kelly Babitz
Zarin, Rachel	Kelly Babitz
Aufzien, Jacob H	Kelly Babitz
Jurewicz, Ryan T	Kevin Chazotte
Merczynski-Hait, Andrew	Kevin Chazotte
Romanow, Bryan	Kevin Chazotte

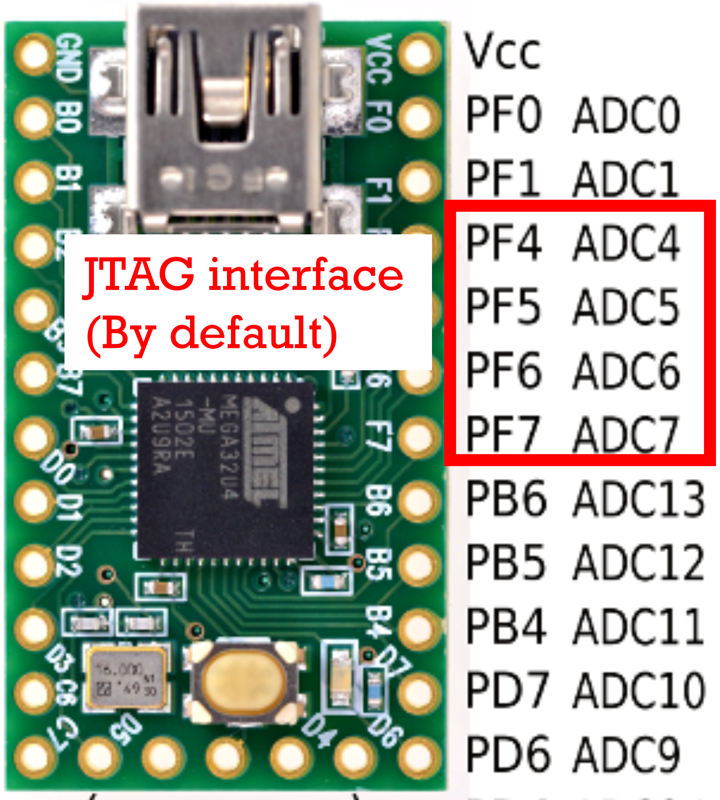
Delattre, Andre J	Lilian Stoesser
Gong, Zachary P	Lilian Stoesser
Messam, Brianna	Lilian Stoesser
Banerjee, Anirban	Malavika Manoj
Nagarajan, Shravan	Malavika Manoj
Shusharin, Pavel	Malavika Manoj
Kim, Joah	Martin Yang
Kulesza, Timothy	Martin Yang
Saven, Celestina	Martin Yang
Wang, Joanna Q	Martin Yang
Adesoye, Konyin	Shivam Dehinwal
Elms, Mason P	Shivam Dehinwal
Tippana, Sahachar	Shivam Dehinwal
Woc, Michael	Shivam Dehinwal
Fedrick, Shaun	Tony Qiu
Li, Jason	Tony Qiu
Ren, Joshua C	Tony Qiu
Fox, Christopher T	Walker Gosrich
Sarda, Sheil	Walker Gosrich
Tamakloe, Ralph S	Walker Gosrich

Random Teensy Things

- Using Pins F4-F7 are special (need to disable JTAG for ADC or GPIO)

```
teensy_disableJTAG();
```

- Better to avoid `float` if possible on the Atmega. It is about 100x's slower than `int` operations and takes up a lot of memory.

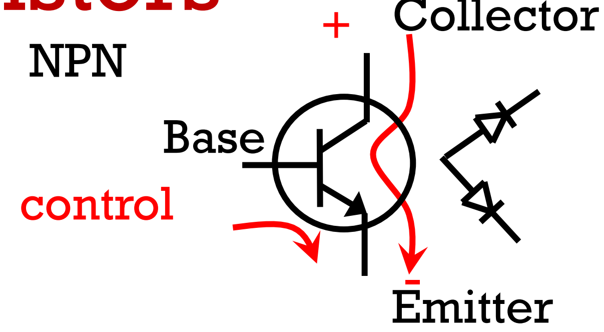


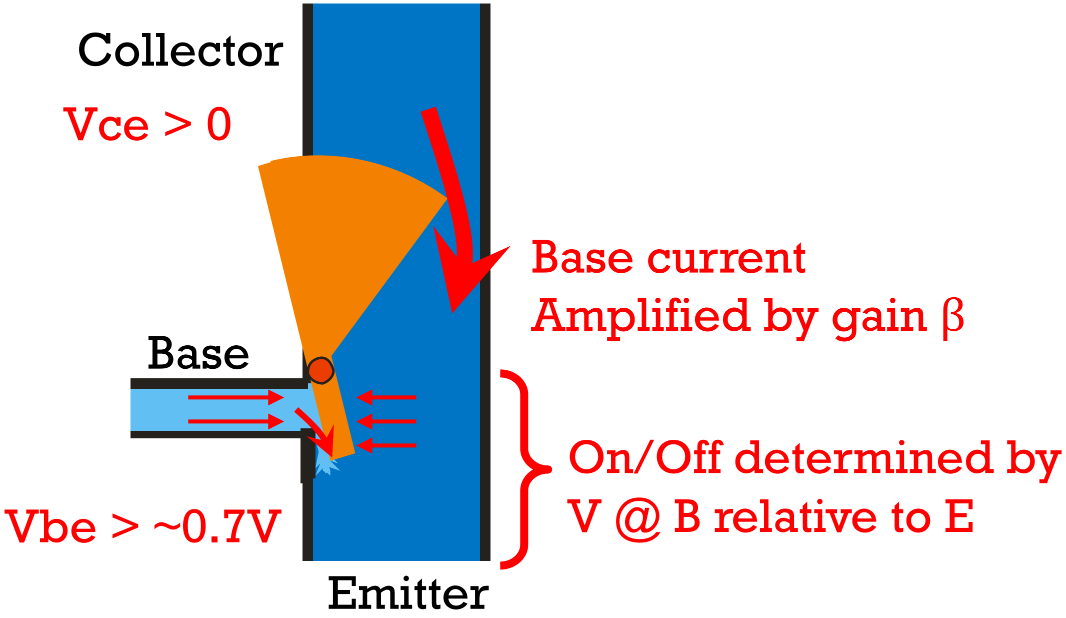
01

Phototransistor

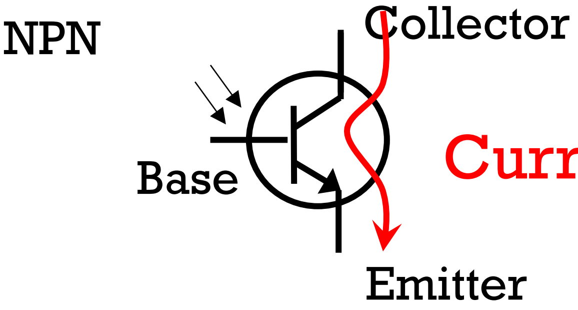
Bipolar Junction Transistors

BJT Transistors

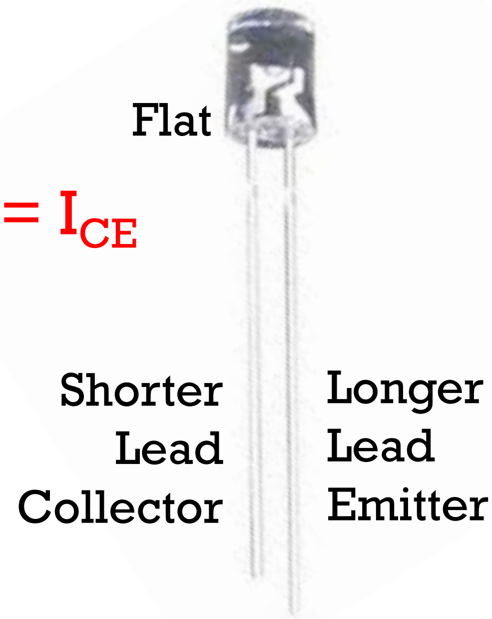


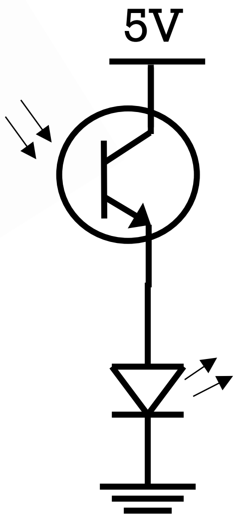


Phototransistors



Current = I_{CE}

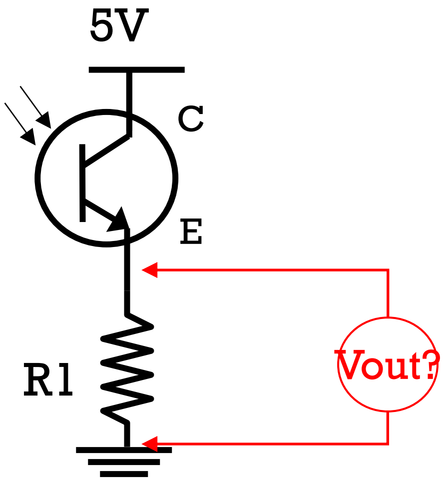


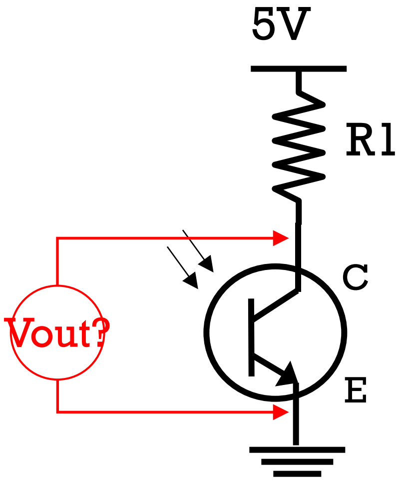


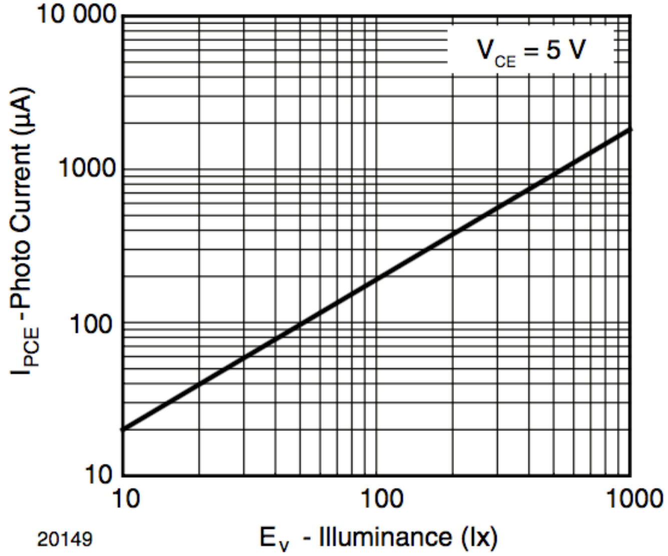
- Just two leads (no base)
  - Looks just like a diode…
- Light into base causes current to flow.
- If V_C is larger than V_E, (typically > 0.4V) then more light means more more current I_{CE}

What happens if circuit is exposed
a bright room?

Phototransistors: How to use?



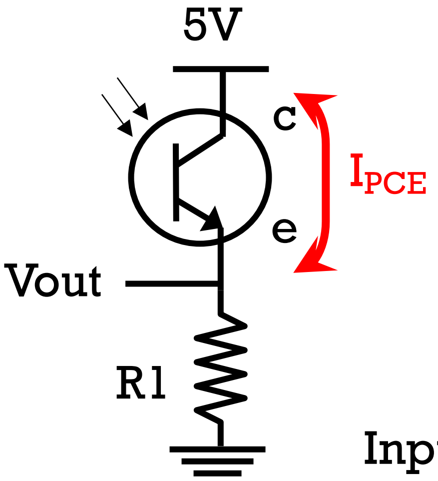




Q1: In Chat: Does Vout go up or down with more light?

Q1a: In Chat: What happens if we make R1 larger?

Sensitivity



Case	R1	100Ω	1000Ω	10Ω
Light 1	I_{PCE}	2mA	2mA	2mA
	V_{out}	0.2V	2V	0.02V
Light 2	I_{PCE}	3mA	3mA	3mA
	V_{out}	0.3V	3V	0.03V
Input range ΔI_{PCE}		1mA	1mA	1mA
Output range ΔV_{OUT}		0.1V	1V	0.01V

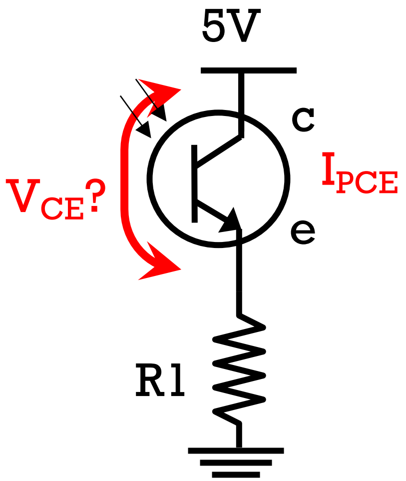
Not sensitive!

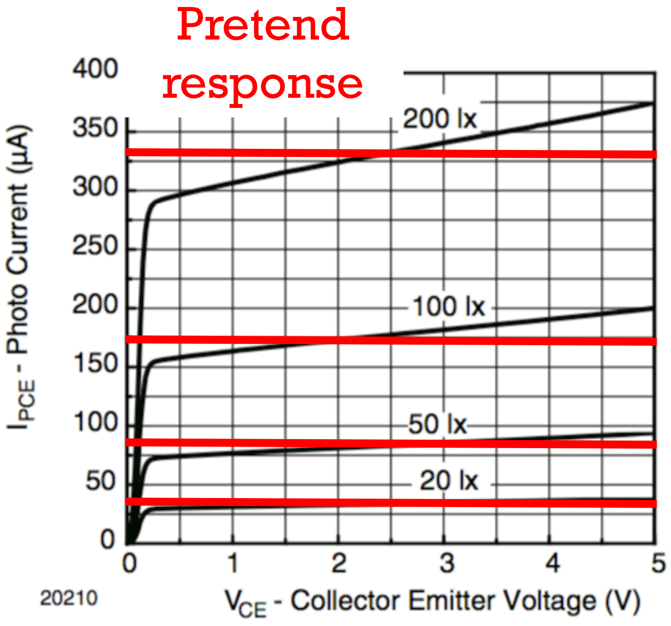
How much more gain is there from ^ this case to ^ this case

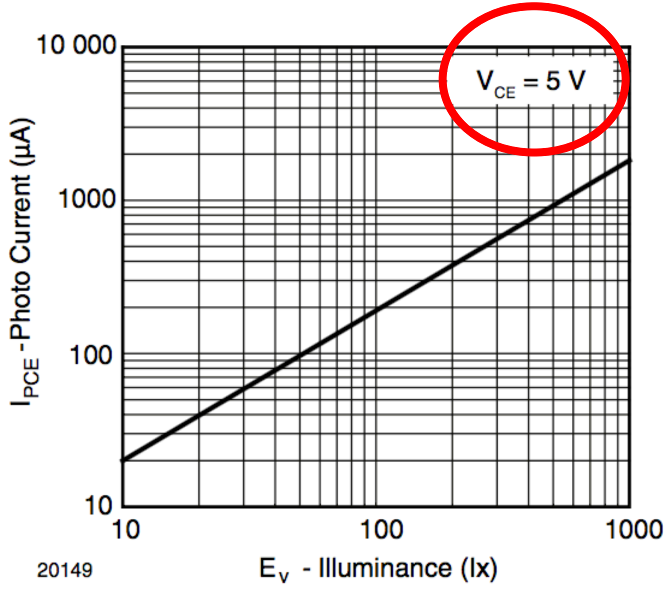
Phototransistors: How to use?

If we pretend the photo response is independent of Vce, for a given light condition how does doubling R1 change the current through R1?

Q2: In Chat: If we pretend the photo response is independent of Vce, for a given light condition how does doubling R1 change the voltage across R1?

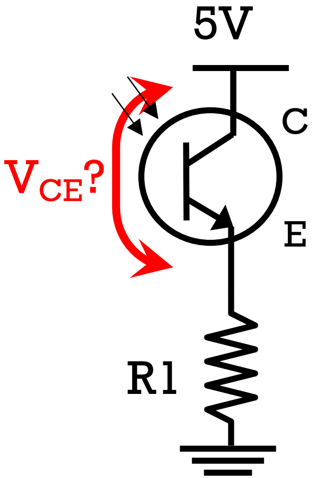


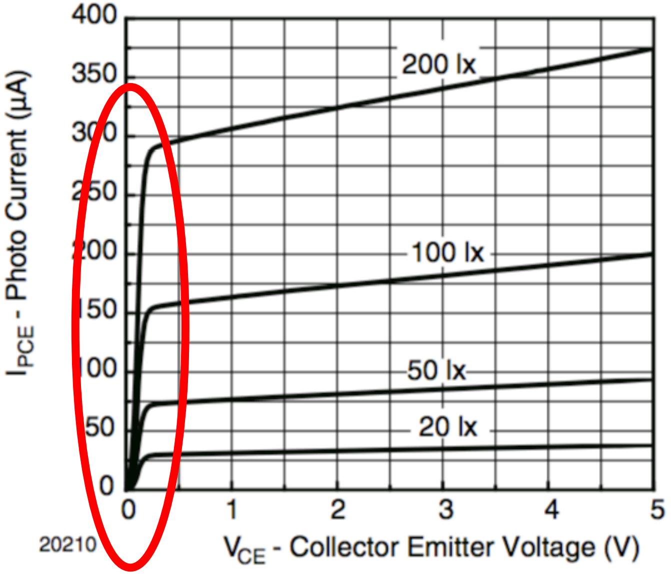


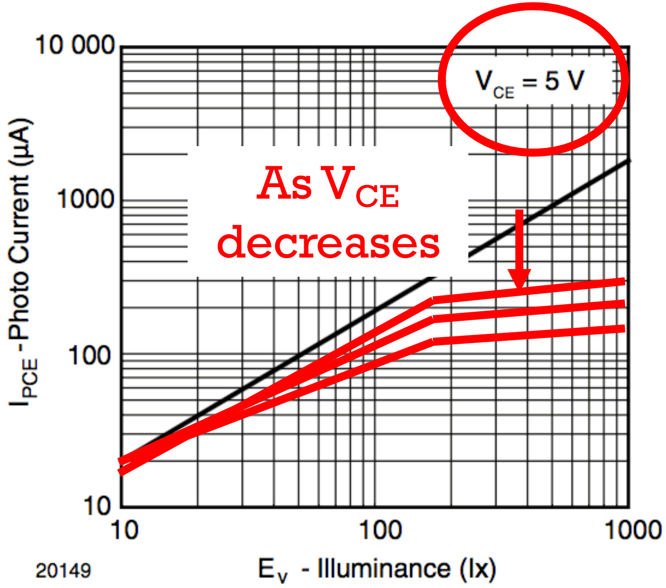


Phototransistors: How to use?

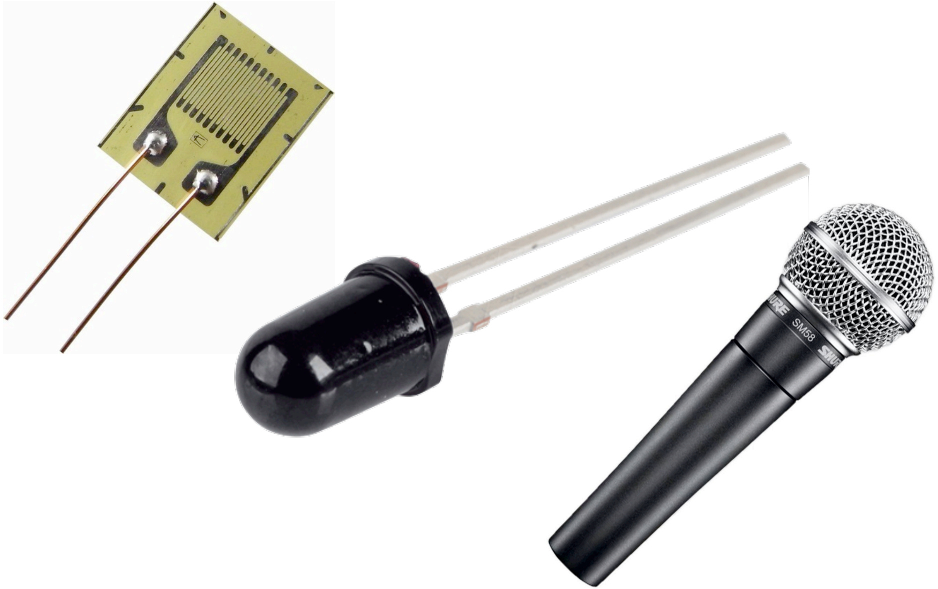
What happens if R1 is really large?







Typically sensors need to be amplified

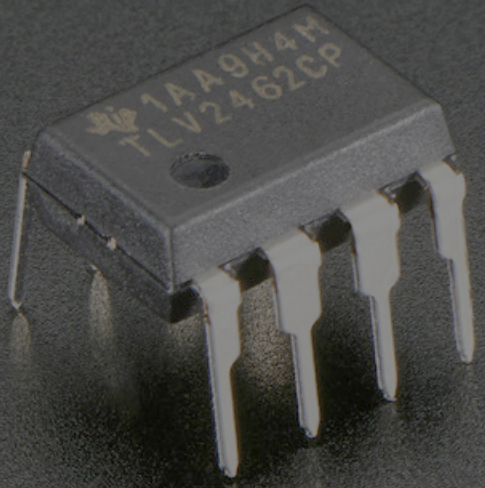


- Strain gauges
- Photodiodes
- Audio signals
- The amount of amplification is called GAIN
  - Gain = Output/Input
  - (Usually) gain = Vout/Vin

02

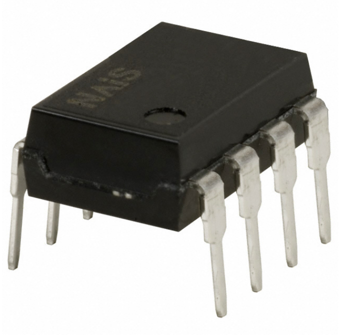
Op Amps

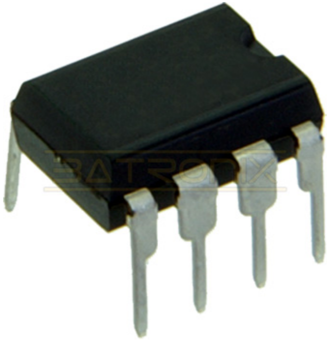
Operational Amplifier

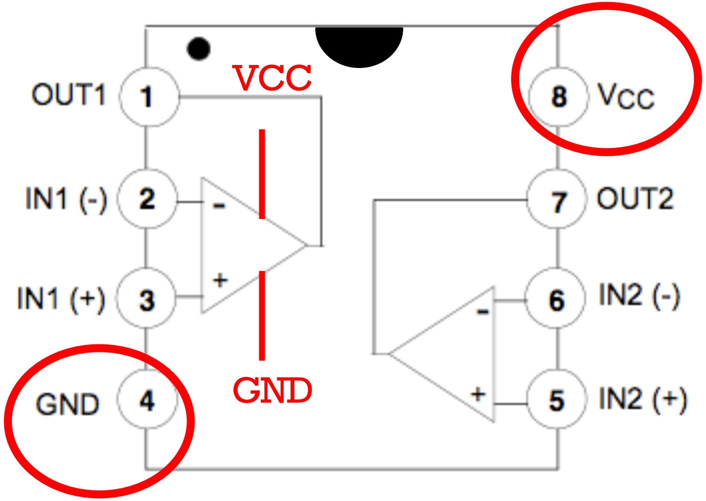


Op Amp

- LM358 in GMLab, generic, low cost, single supply dual opamp.



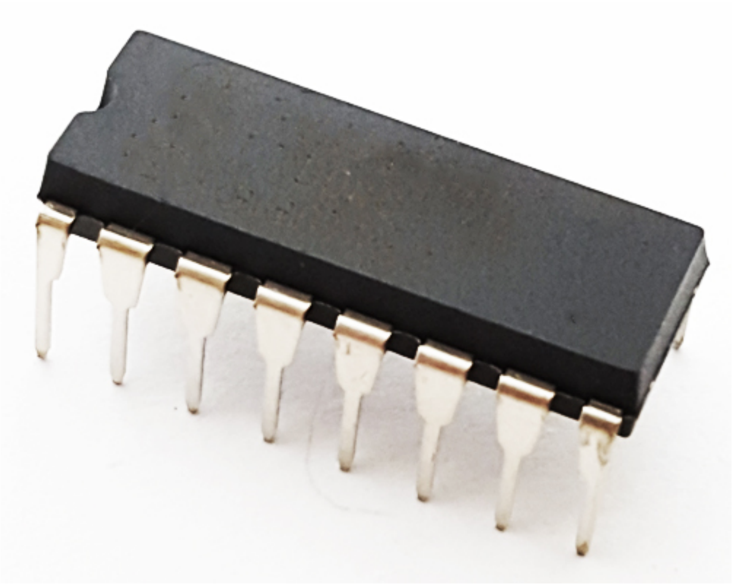


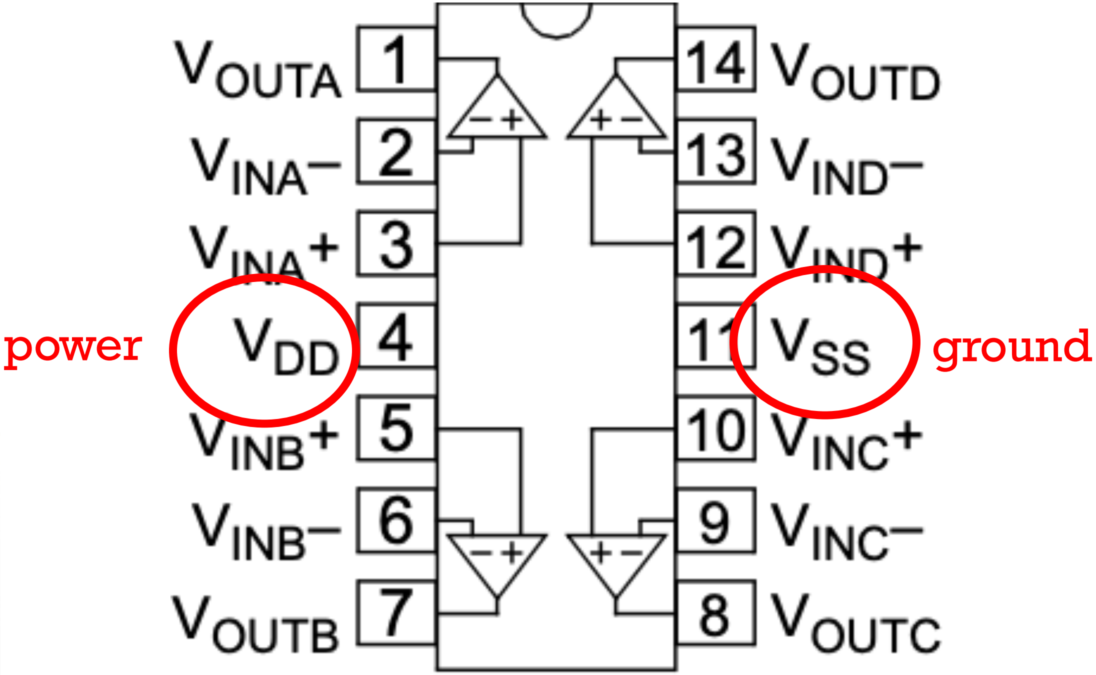


view from the top (pins going into the page)

Better opamp MCP6044 (in your kit)

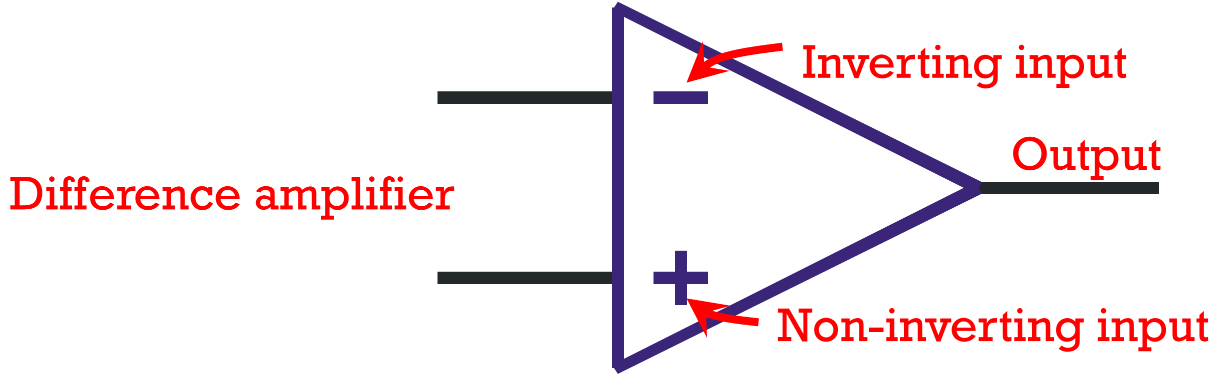
- Quad opamp (4 of them) A, B, C and D





view from the top (pins going into the page)

The Ideal Operational Amplifier

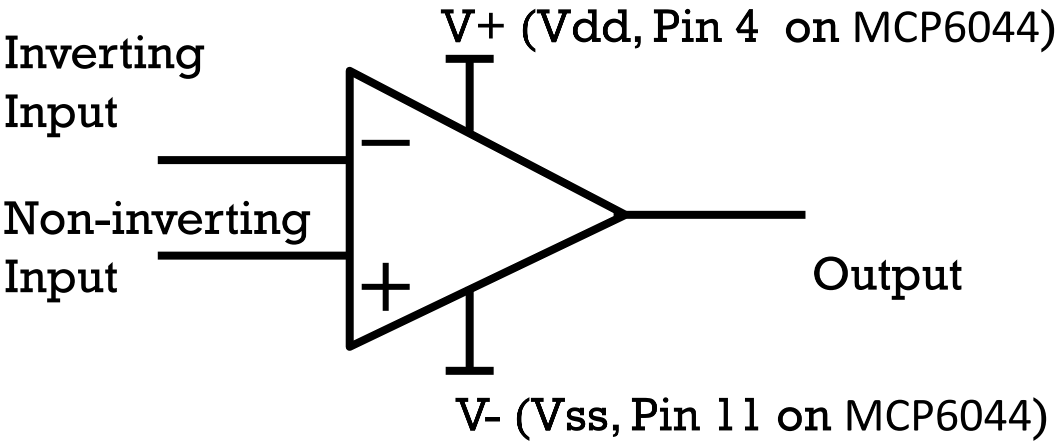


Inverting (V)		Noninverting (V)	Output (V)
Higher	>	Lower	Goes down
Lower	<	Higher	Goes up

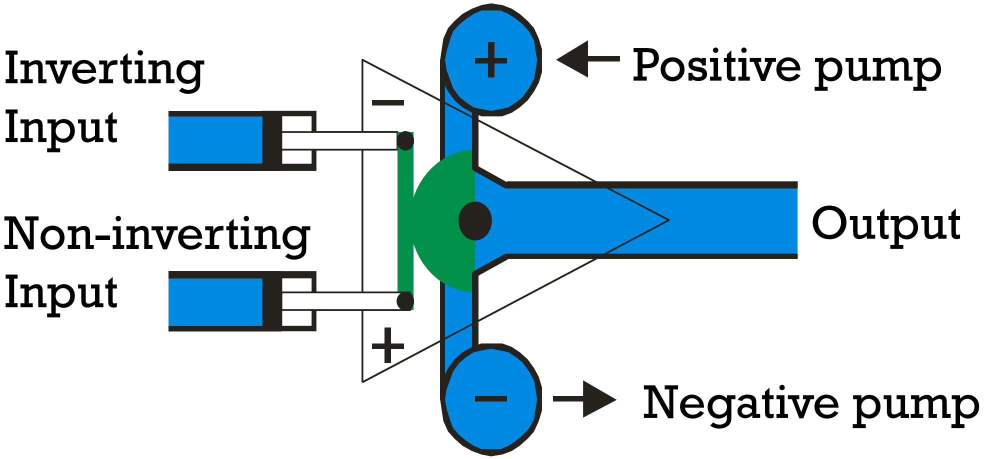
Gain is the ratio between difference and output
Gain is very high, consider it infinite.

1st Golden rule: Inputs draw no current

Opamp water analogy

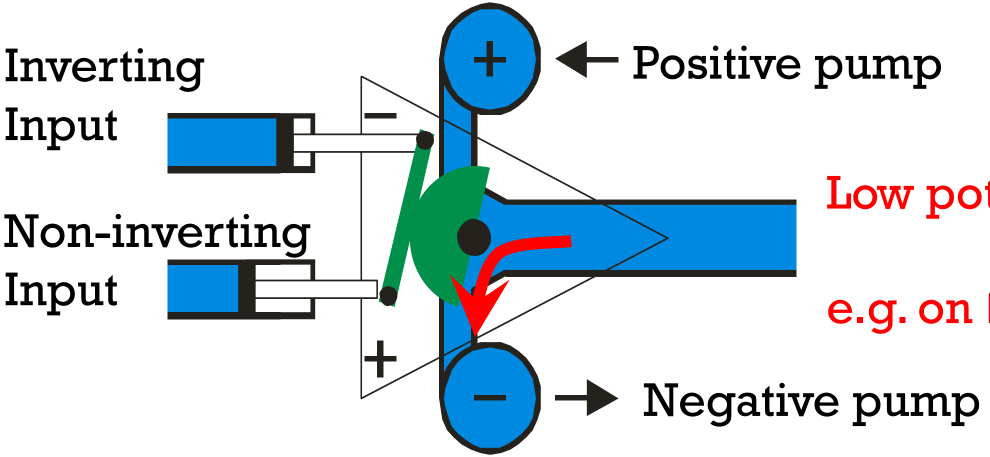


Opamp water analogy



Opamp water analogy

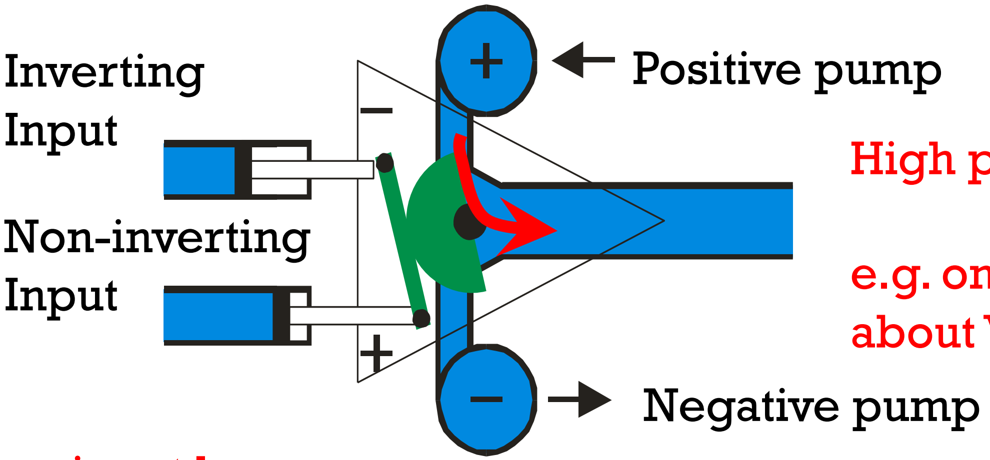
Inverting input
has higher
potential



Low potential output

e.g. on MCP6044 about 0.01V

Opamp water analogy

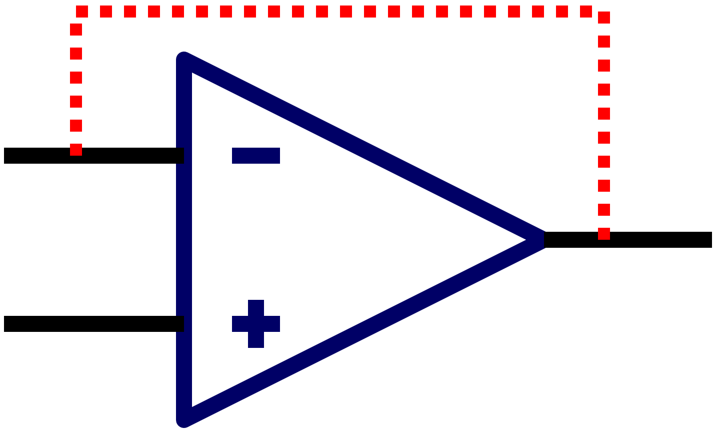


High potential out

e.g. on MCP6044
about Vdd - 0.01V

Non-inverting input has
higher potential

Negative Feedback



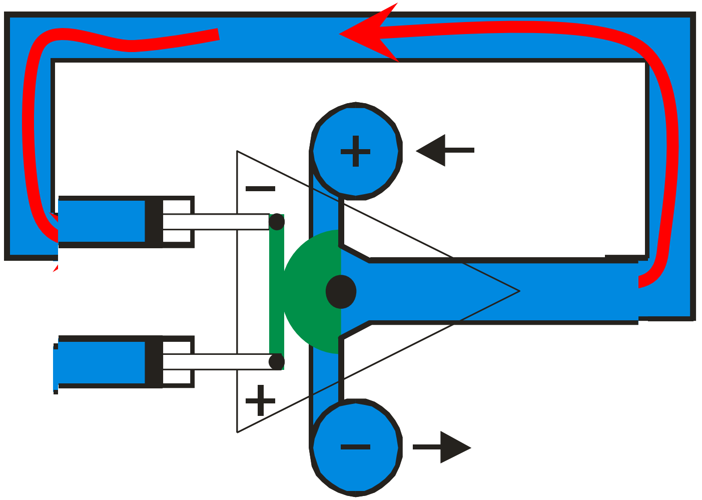
(-)V		(+)V	output?
higher	>	lower	Output drives (-) lower
lower	<	higher	Output drives (-) higher

Until (-) and (+) match

2nd golden rule: Inputs are at same potential (V)

If in negative feedback

Opamp water analogy (Negative Feedback)



If non-inverting input has higher potential with negative feedback, output drives the non-inverting input lower until it's equal.

Golden Rules of Ideal Opamps

1. Inputs draw no current
2. Inputs are at the same potential
   (when in feedback)

The Inverting Amplifier

$i1 - i2 - i3 = 0$

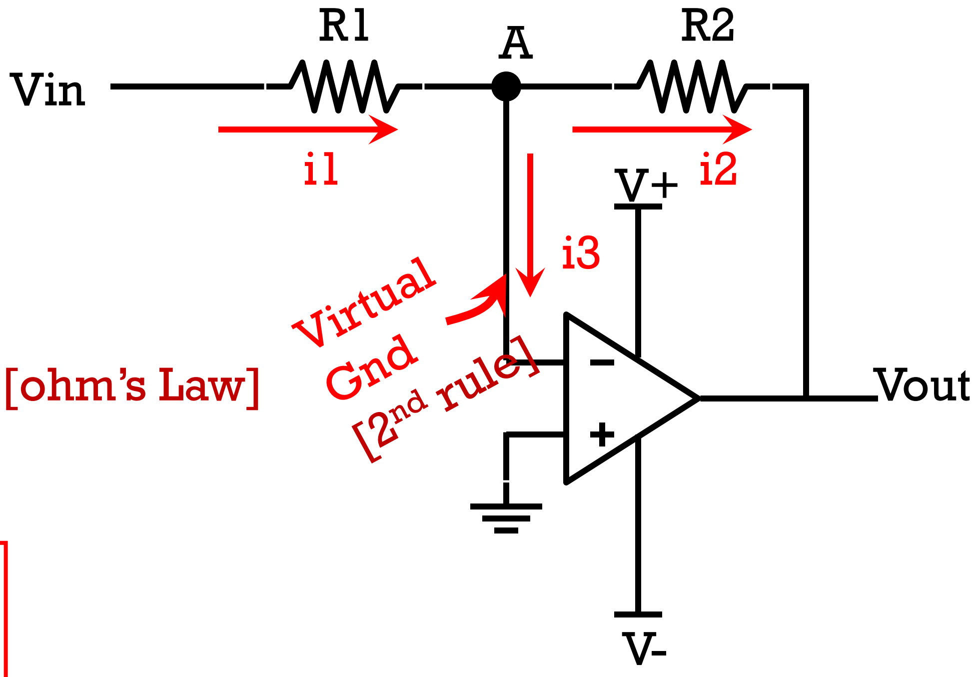
[Kirchoff's current law]

$i3 = 0$

[1st rule]

$i1 = i2$

$$\frac{Vin - V_A}{R1} = \frac{V_A - Vout}{R2}$$ [ohm's Law]



$$\boxed{\frac{Vout}{Vin} = \frac{-R2}{R1}}$$

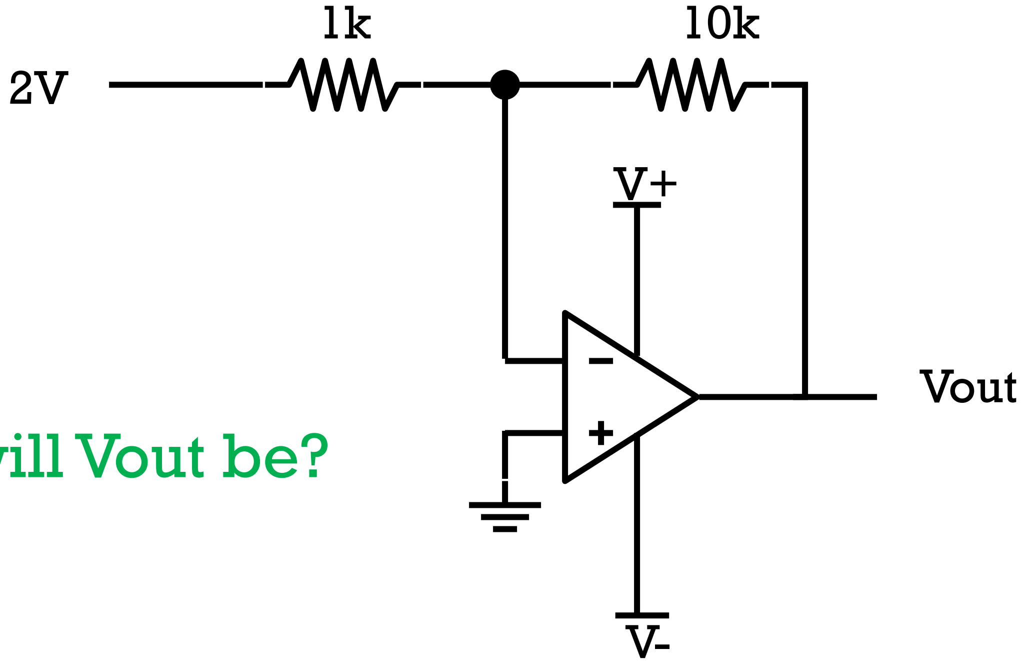
Gain

You can choose resistors to get desired gain

1st Golden rule: Inputs draw no current

2nd golden rule: Inputs are at same potential (V)

The Inverting Amplifier Exercise

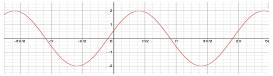


Q3: What will Vout be?

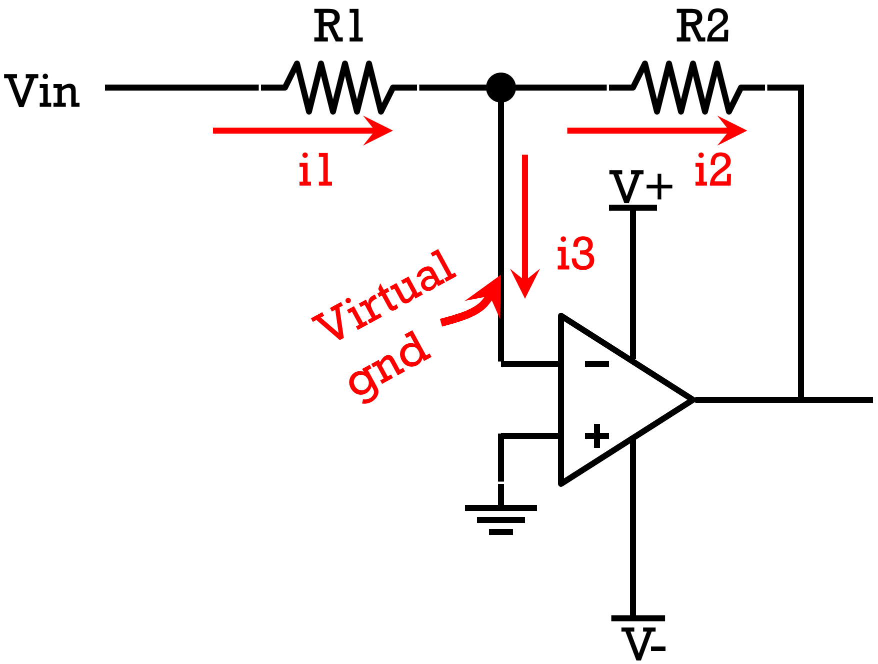
The Inverting Amplifier Exercise

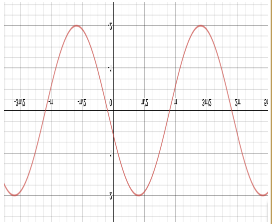
$i3 = 0$

$i1 = i2$



$$\frac{Vin - 0}{R1} = \frac{0 - Vout}{R2}$$



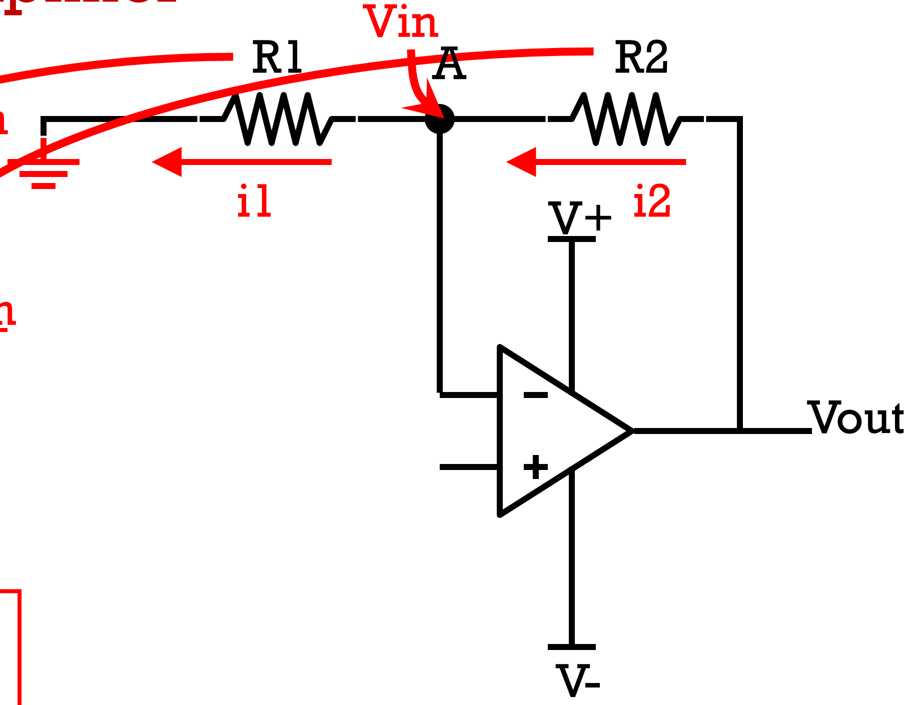


We have a sine wave peaks at +1V and -1V at Vin

Q4 In Chat: What values of R1 and R2 will give us an output flipped sine wave peaks at +5V and -5V?

The Non-Inverting Amplifier

[2nd rule]



[1st rule] $i1 = i2$

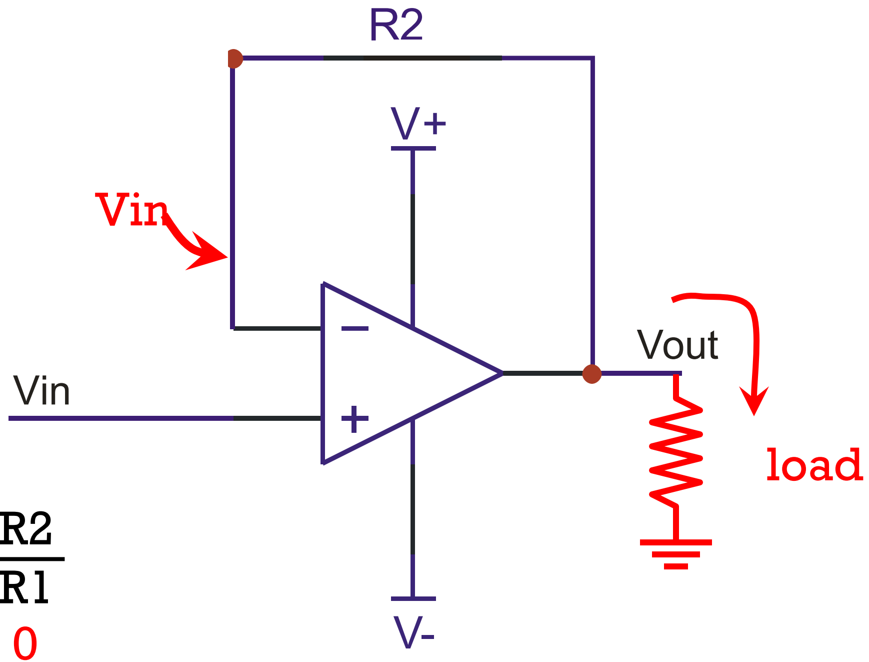
[ohm's Law] $$\frac{Vin - 0}{R1} = \frac{Vout - Vin}{R2}$$

$$\frac{Vin}{Vout - Vin} = \frac{R1}{R2}$$

$$\boxed{\frac{Vout}{Vin} = \underbrace{1 + \frac{R2}{R1}}_{\text{Gain}}}$$

The Non-Inverting Buffer

Vout = Vin



$$\frac{Vout}{Vin} = 1 + \frac{R2}{R1}$$

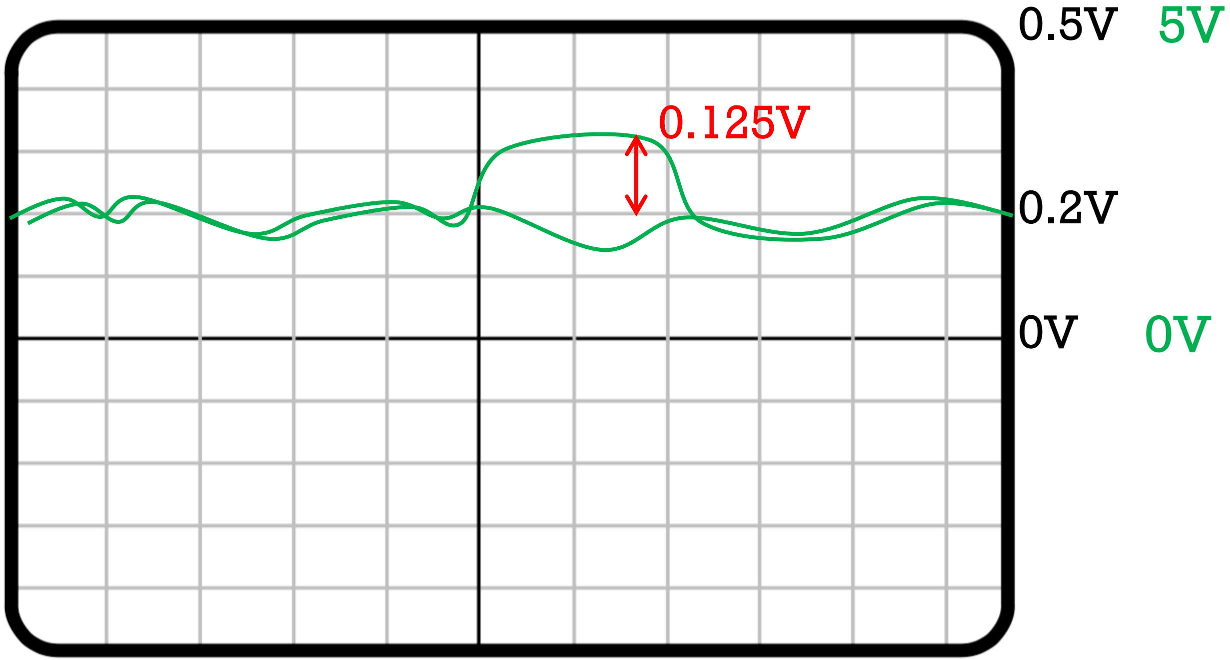
$$= 1 + \frac{0}{\infty}$$

Isolate input, from current stand point
(no (very little) current will flow from accessing Vin)

Amplifying photosensor signals.

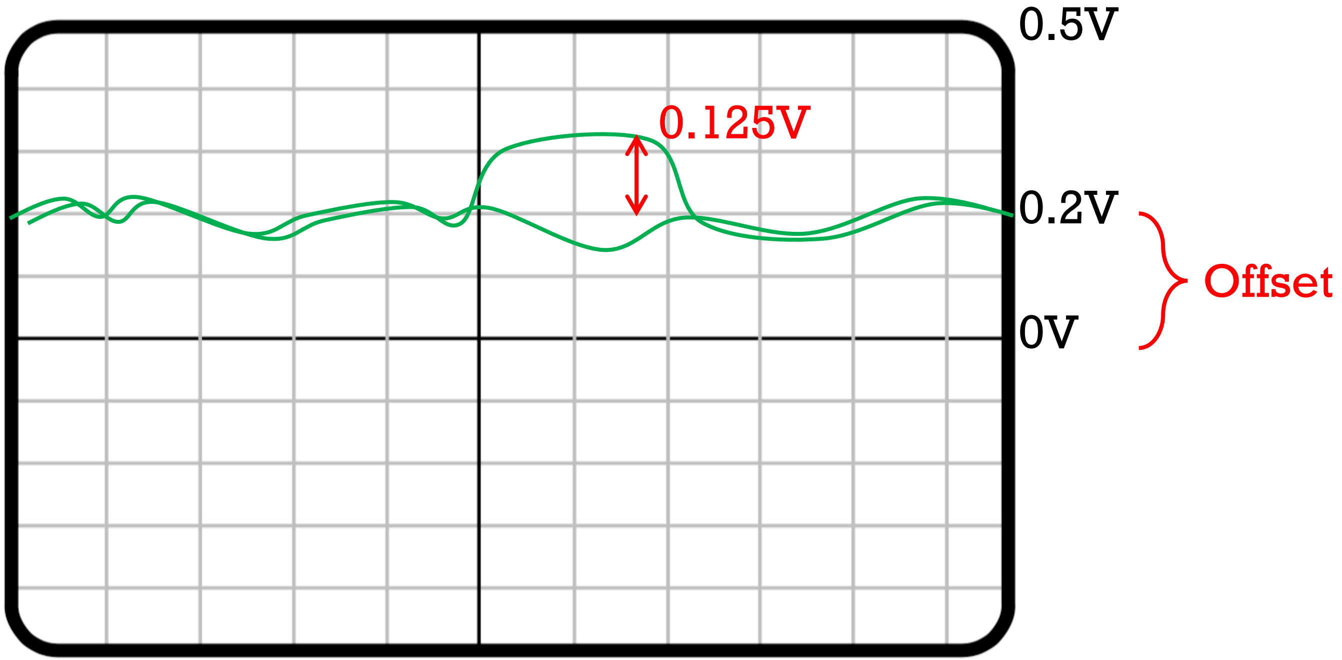
Q5: Draw and hold the scope trace when signal is amplified 40x and the scale of the scope changes to 5V.

Scope output of a photo sensor circuit (unamplified)

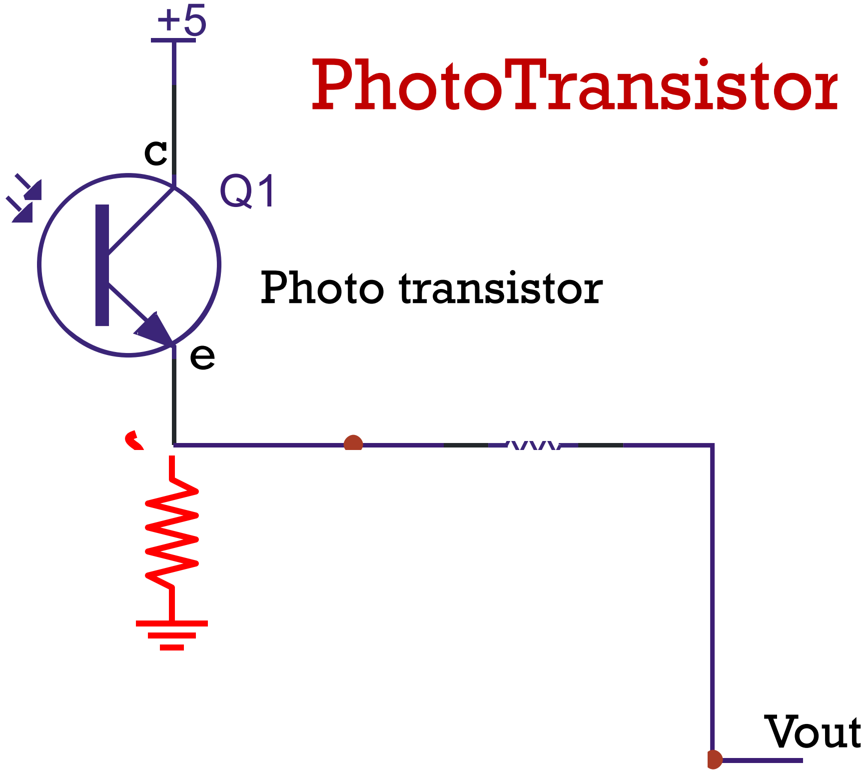


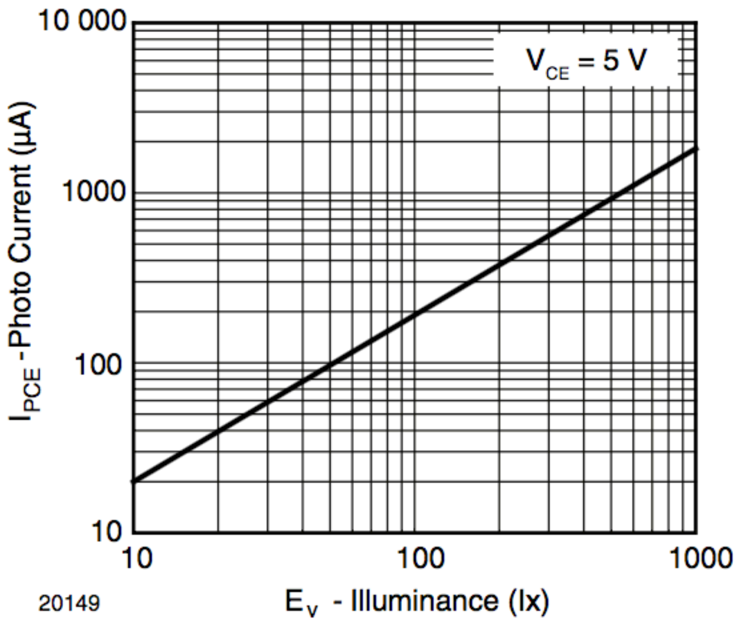
Signal Conditioning: Amplification

Must consider Gain and DC Offset



PhotoTransistor

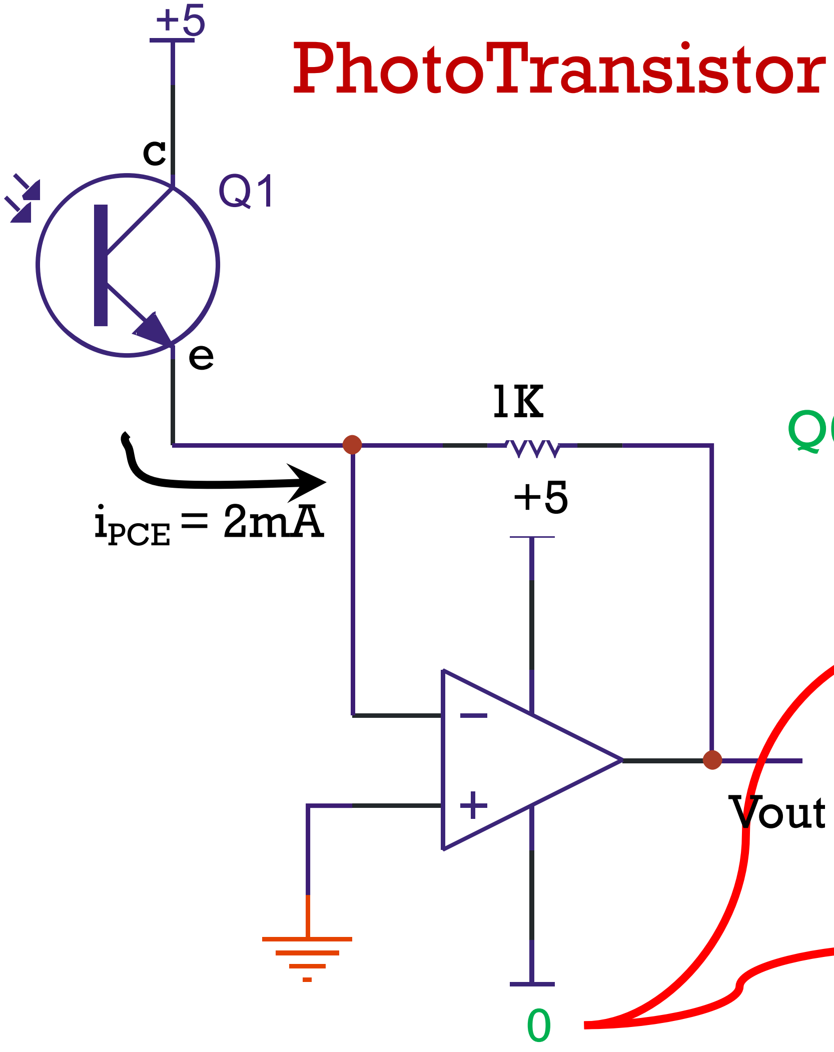




$\text{Vout} = -\, i_{PCE}\, R2$ [ohm's Law]

Transresistive configuration

PhotoTransistor



$Vout = -\,i_{PCE}\,R2$

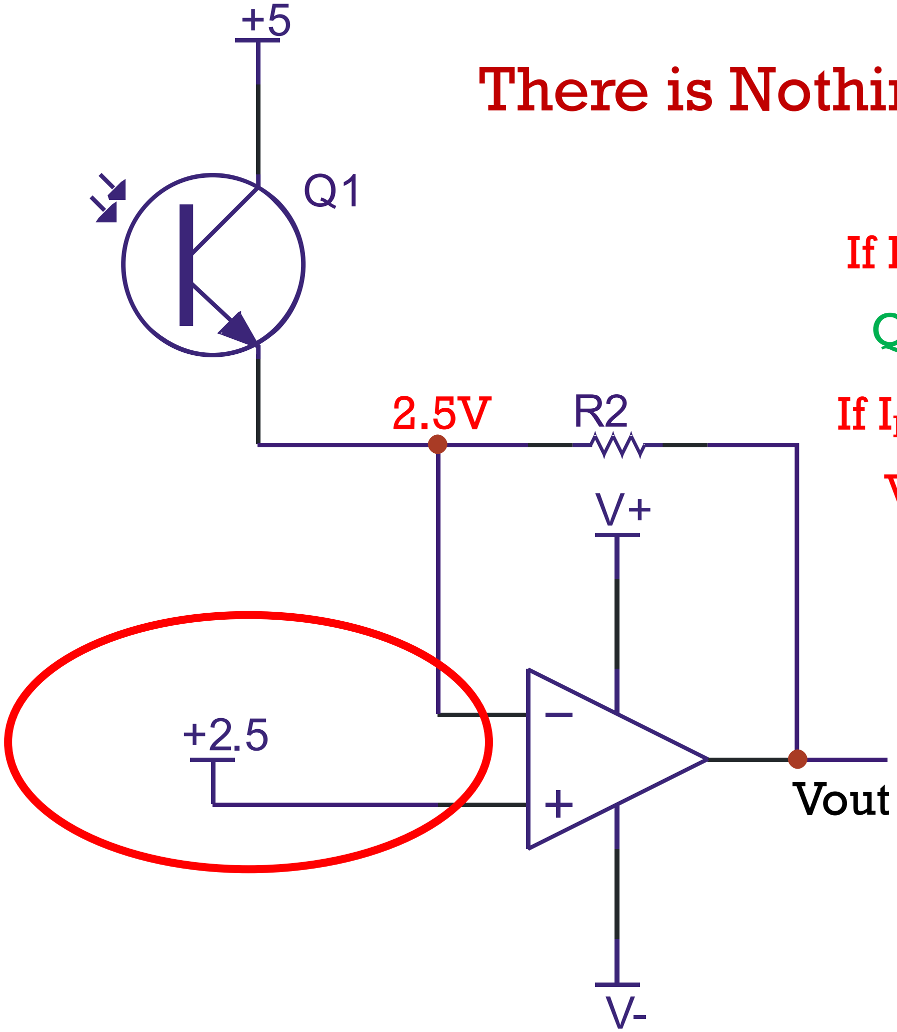
Q6: What is Vout in this case?

With dual supply:
Vout = -2V

Q7: How about now?

With single supply
Should be Vout = -2, but
Vout = 0

There is Nothing Magic about Ground

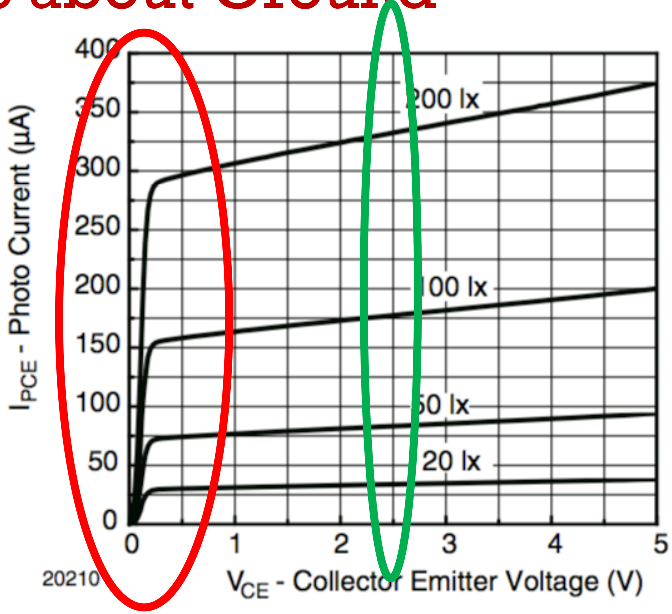


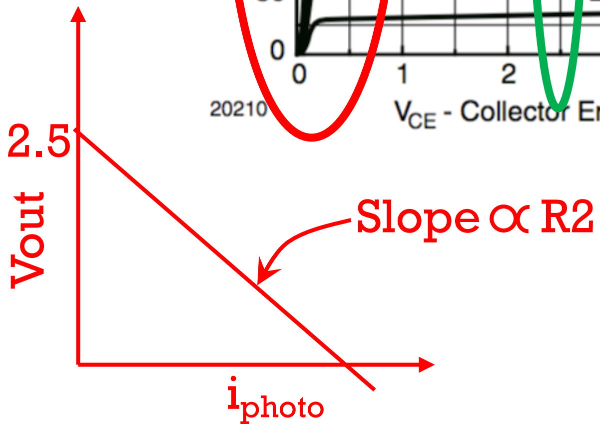
If $I_{PCE} = 0$ mA

Q8: Vout = ?

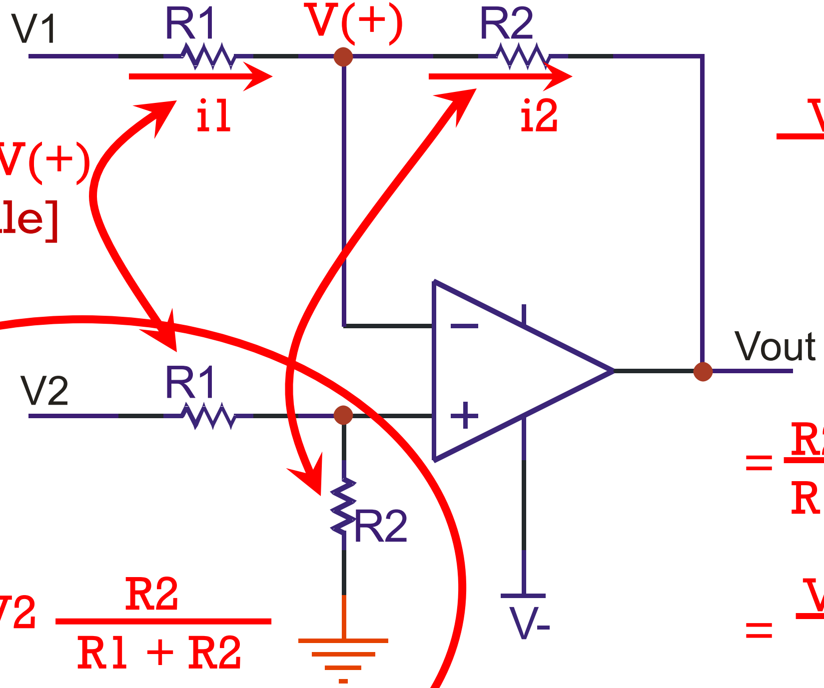
If $I_{PCE} > 0$

Vout < 2.5V





Another Application



$$V(-) = V(+)$$

[2^{nd} Rule]

$$V(+) = V2\,\frac{R2}{R1 + R2}$$

[voltage divider]

$$i1 = i2$$

[1^{st} Rule]

$$\frac{V1 - V(+)}{R1} = \frac{V(+) - Vout}{R2} \quad \text{[Ohm's law]}$$

$$-Vout = \frac{R2}{R1}\left(V1 - V(+)\right) - V(+)$$

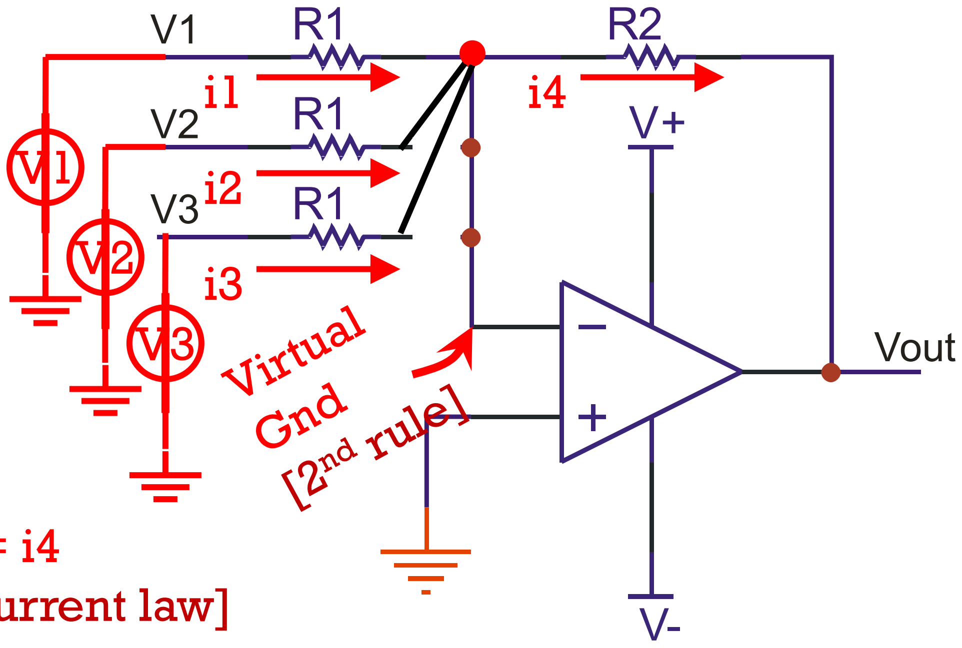
$$= \frac{R2}{R1}\left(V1 - V2\,\frac{R2}{R1 + R2}\right) - V2\,\frac{R2}{R1 + R2}$$

$$= \frac{V1R1 + V1R2 - V2R2 - V2R1}{R1 + R2}$$

$$\boxed{(V2 - V1)\frac{R2}{R1} = Vout}$$

(Subtraction) with multiplier

Still Another Application



i1 + i2 + i3 = i4
[Kirchoff's current law]

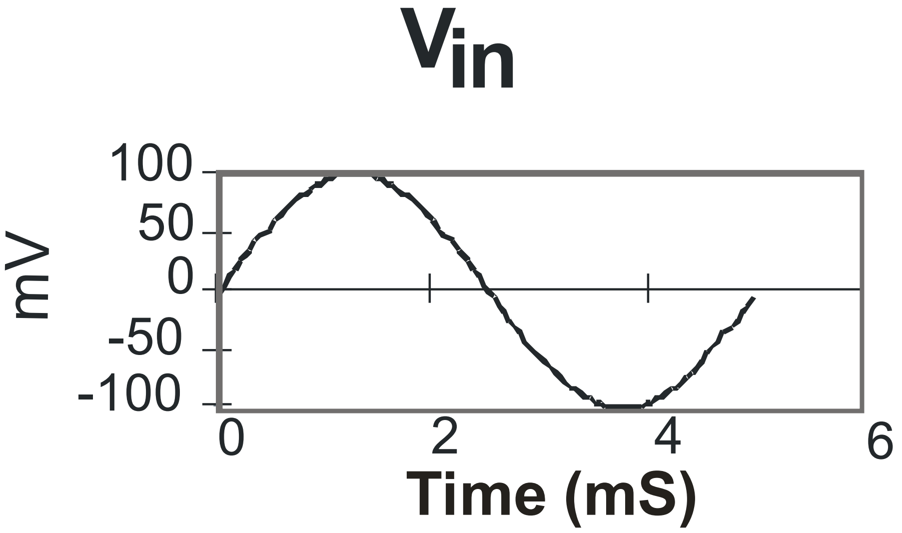
$$\frac{V1}{R1} + \frac{V2}{R1} + \frac{V3}{R1} = \frac{-Vout}{R2}$$

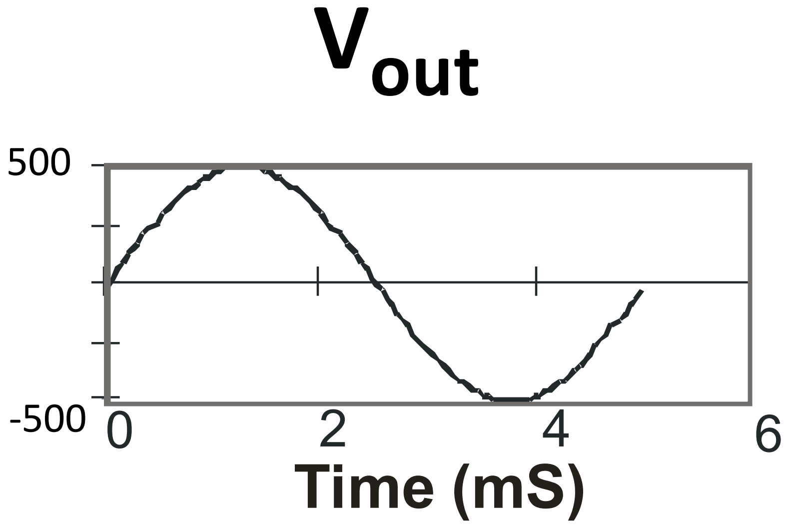
[Ohm's law]

$$\boxed{(V1 + V2 + V3)\,\frac{R2}{R1} = -Vout}$$

(Addition) with multiplier

Example problem:



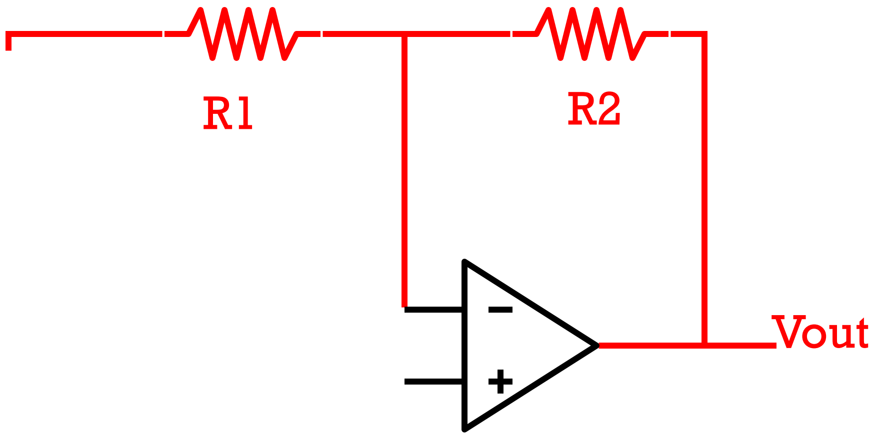


Vin is a sine wave with amplitude 200mV (peak-to-peak)

Q9: Design circuit such that:

Vout has a 1V (pk-pk) sine wave centered at 0V with same phase

Example Solution

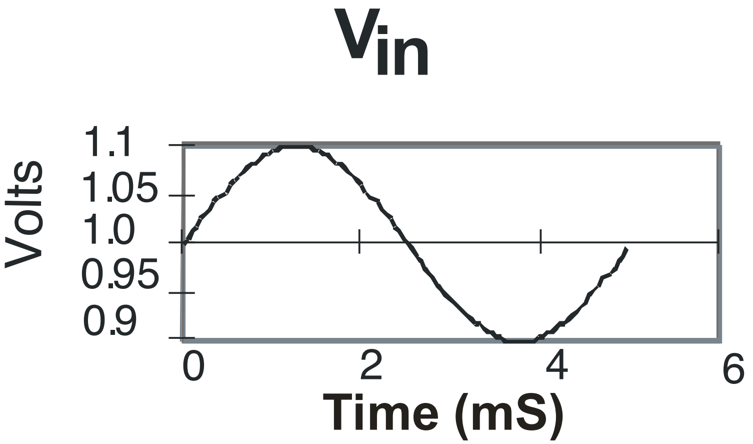


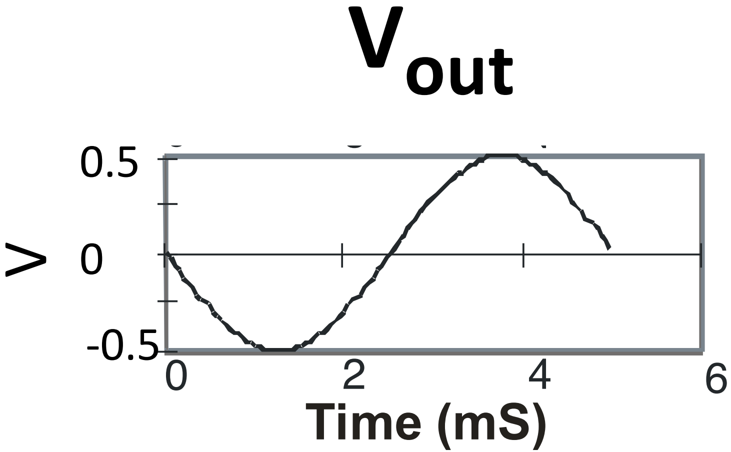
Example Solution

Op Amp Design Methodology

1. Decide inverting or not
2. Decide gain (Vout/Vin)
3. Find offset
   1. Create current equation for node at V(-)
   2. Use ohm's law to introduce R1, R2, Vout, Vin and Voffset
   3. Pick a known value for Vin and Vout.
   4. Solve for unknown Voffset.

Example with offset





Vin sine wave with amplitude 200mV (pk-pk) centered on 1V

Vout should be a 1V (pk-pk) sine centered at 0V, 180° out of phase

Example with offset Solution

1) Inverting

2) Gain $= -R2/R1$
We want gain of 5

Consider a point, when
Vin = 1.0V, then Vout = 0V

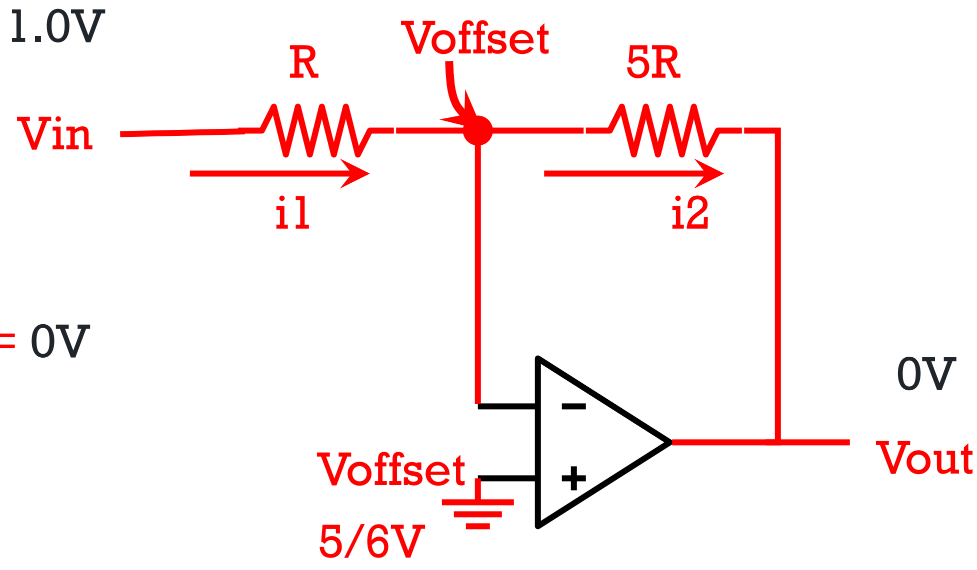
$$i1 = i2$$

$$i2 = \frac{Voffset - (0)}{5R}$$

$$i1 = \frac{1.0 - Voffset}{R}$$

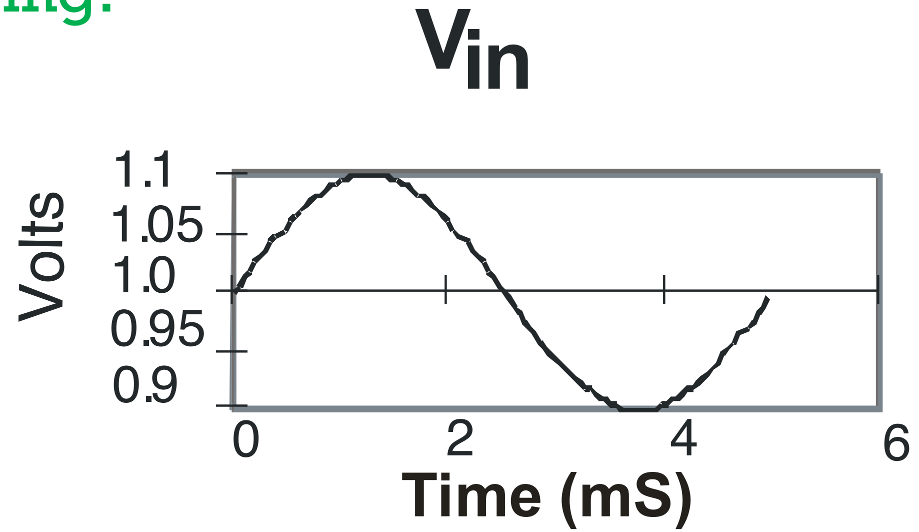
$$Voffset(6R) = 5R - 0(R)$$

$$Voffset = 5/6V$$



Q10: Is there a way to center Vout about 0V leaving Voffset at 0 if the input is high frequency?

Practice problem: Design an opamp circuit for the following:



Vin sine wave with amplitude 200mV (pk-pk) centered on 1V

Vout should be a 5V (pk-pk) sine centered on 2.5V and in phase.

Summary

- Phototransistors can be used with just a resistor
- OpAmp Golden Rules:
  1. Inputs draw no current
  2. Inputs are at the same potential (in feedback)
- Signal conditioning includes gain and offset.
- Alternating signals of specific frequencies among ambient signals easier if you AC couple (add a capacitor in line).

Office Hour Discussion

Is there anything you found particularly useful or broken during office hours?

Use Raise Hand function in Zoom

Answer in CHAT

Answer how you feel about each topic below with:

1. I don't understand this topic at all
2. I understand a little, but will need help
3. I understand half, but expect to get the rest later
4. I understand completely already

A. Op Amps

B. Timer Input Capture

C. Phototransistors

Debugging Code

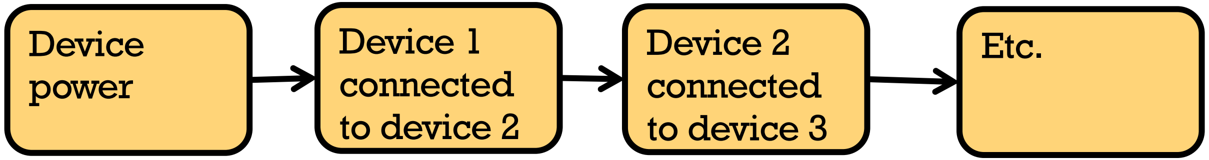
- If you feel you need help with C or programming in general.

  `https://www.onlinegdb.com/`

- Has an online debugger that lets you track the flow of code.
- Note: ATmega specific things won't work (PORTD, Timers etc.)
- Looking into setting it up so we can actually debug ATmega code (e.g. put includes and fake stubs so things can compile).

Debugging Electronics

- Hardware and Software piece - need to check both
- Break your system apart into pieces
  - viewed as linked via inputs and outputs
  - Ideally a chain of parts with 1 output from one part going to 1 input in the next part.



- Check known voltage at each part starting with power and ground.