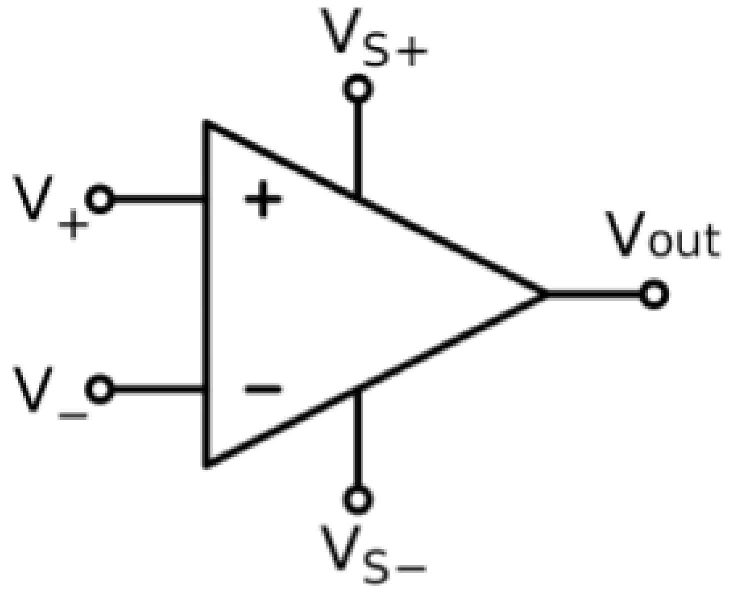
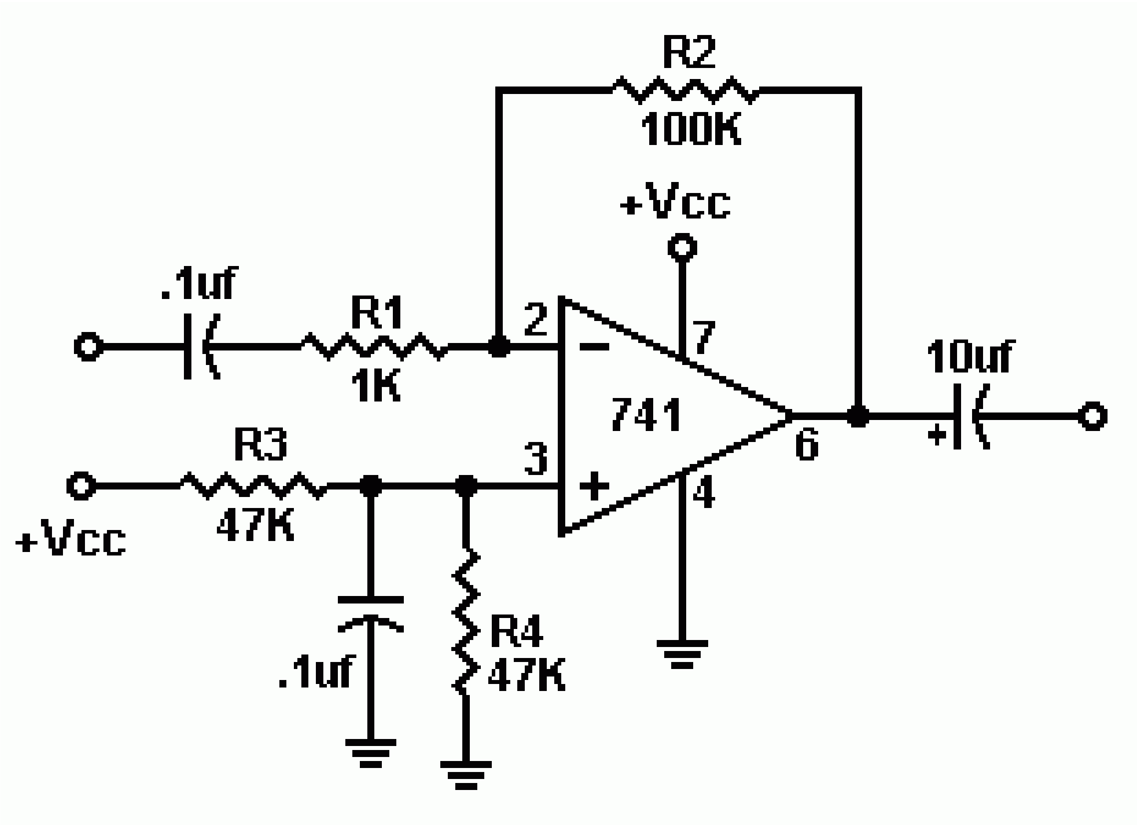
Introduction to op-amps



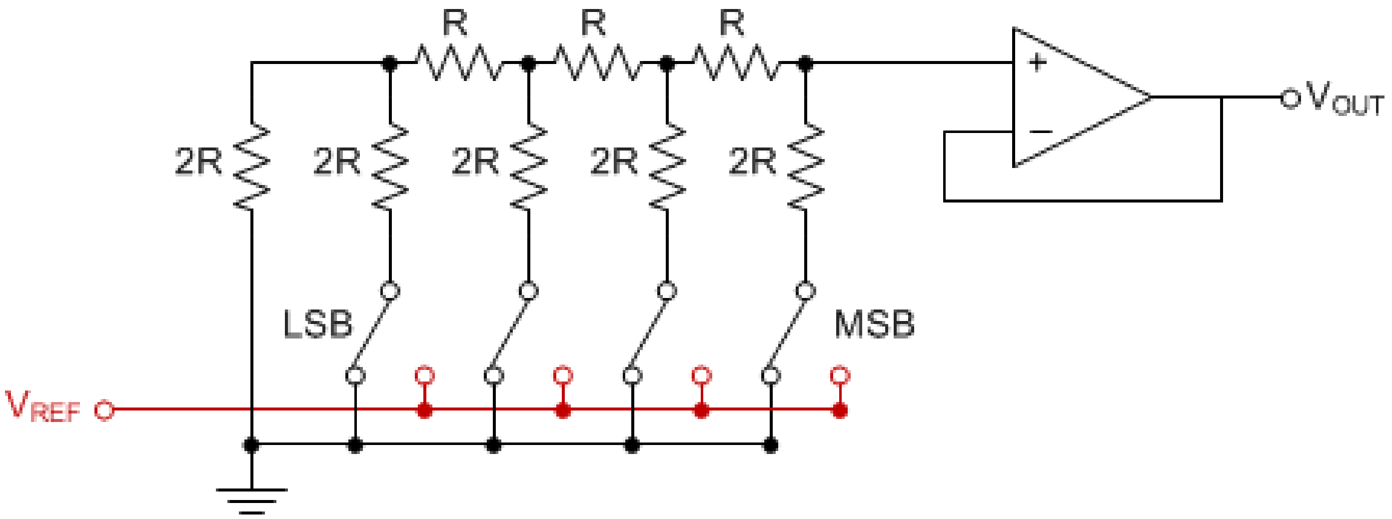
Uses of op-amps

- Amplifiers



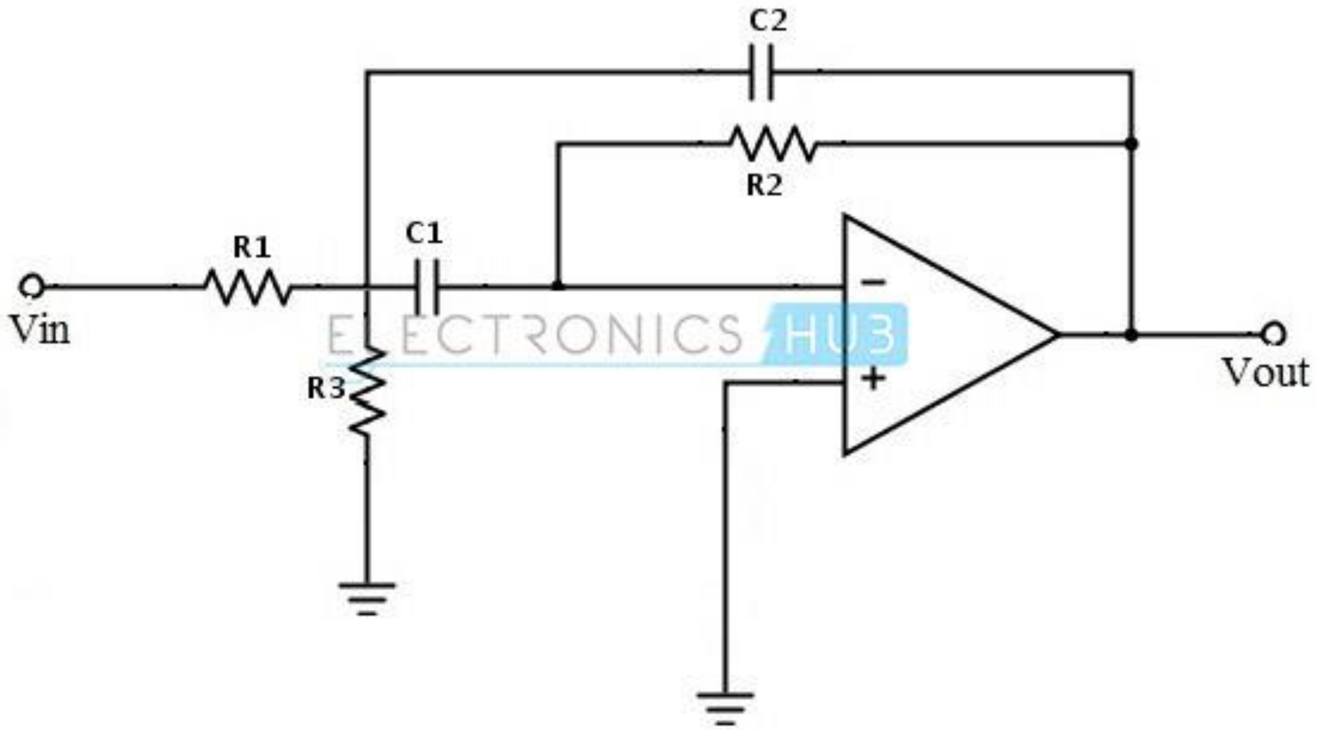
Uses of op-amps

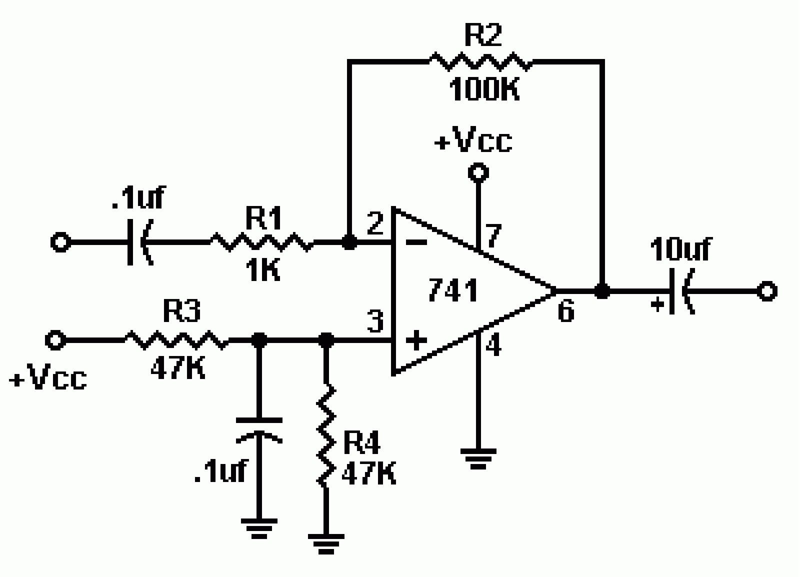
- Amplifiers
- Buffers



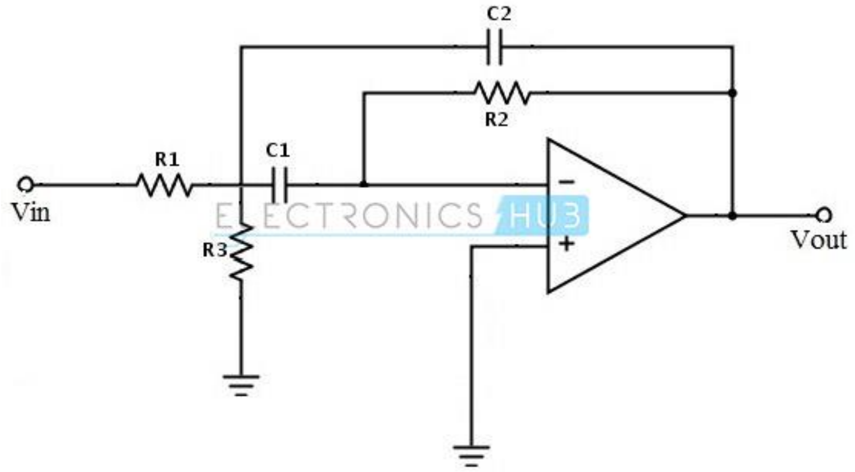
Uses of op-amps

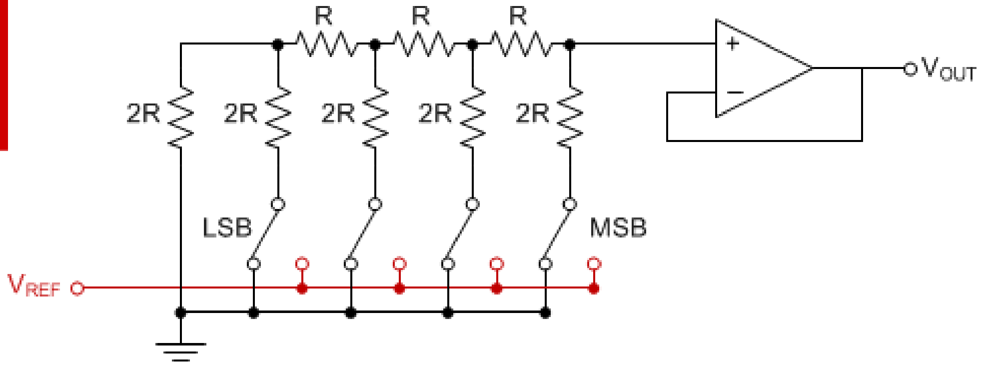
- Amplifiers
- Buffers
- Filters



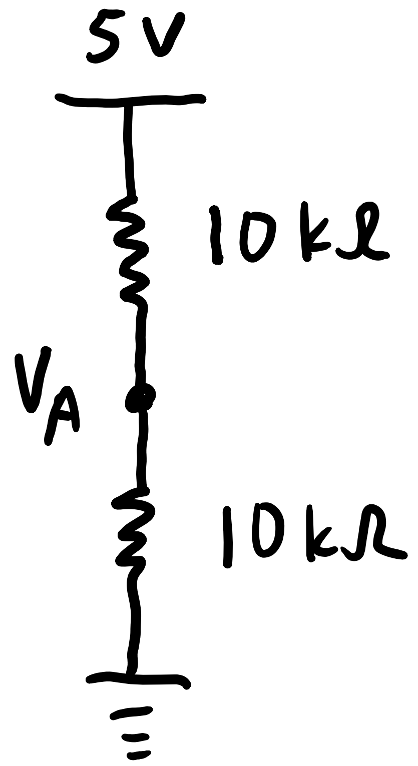

R2
100K
+Vcc
.1uf
R1
1K
2
7
741
10uf
6
R3
47K
3
4
+Vcc
R4
47K
.1uf


KEEP
CALM
AND
DON'T
PANIC

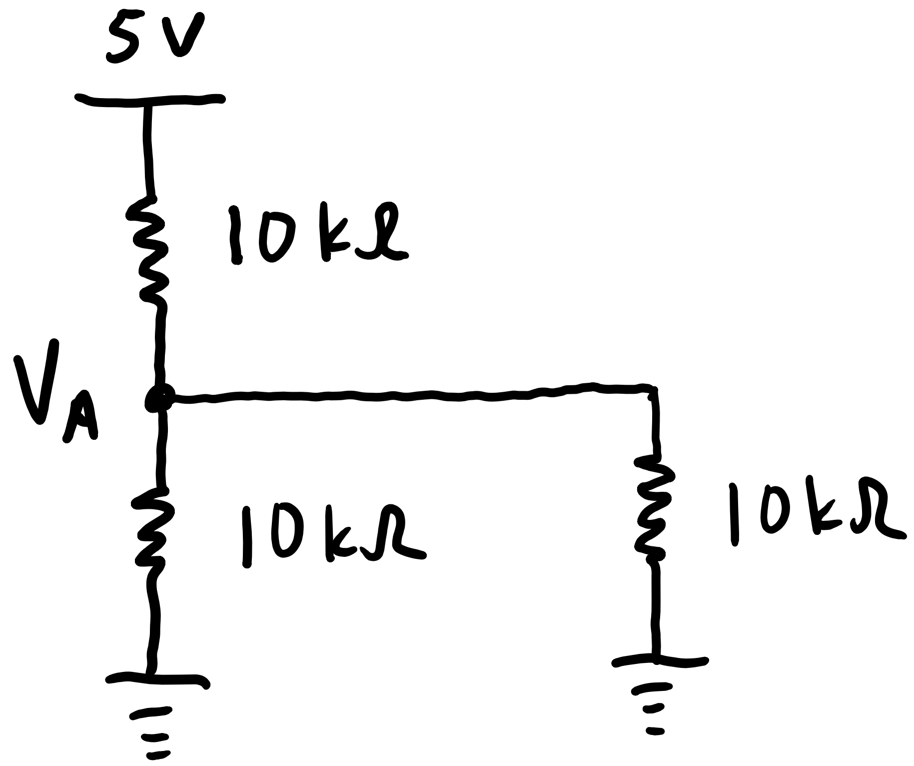

C2
R2
R1
C1
Vin
Vout
R3
ELECTRONICS HUB


R
R
R
2R
2R
2R
2R
2R
VOUT
LSB
MSB
VREF

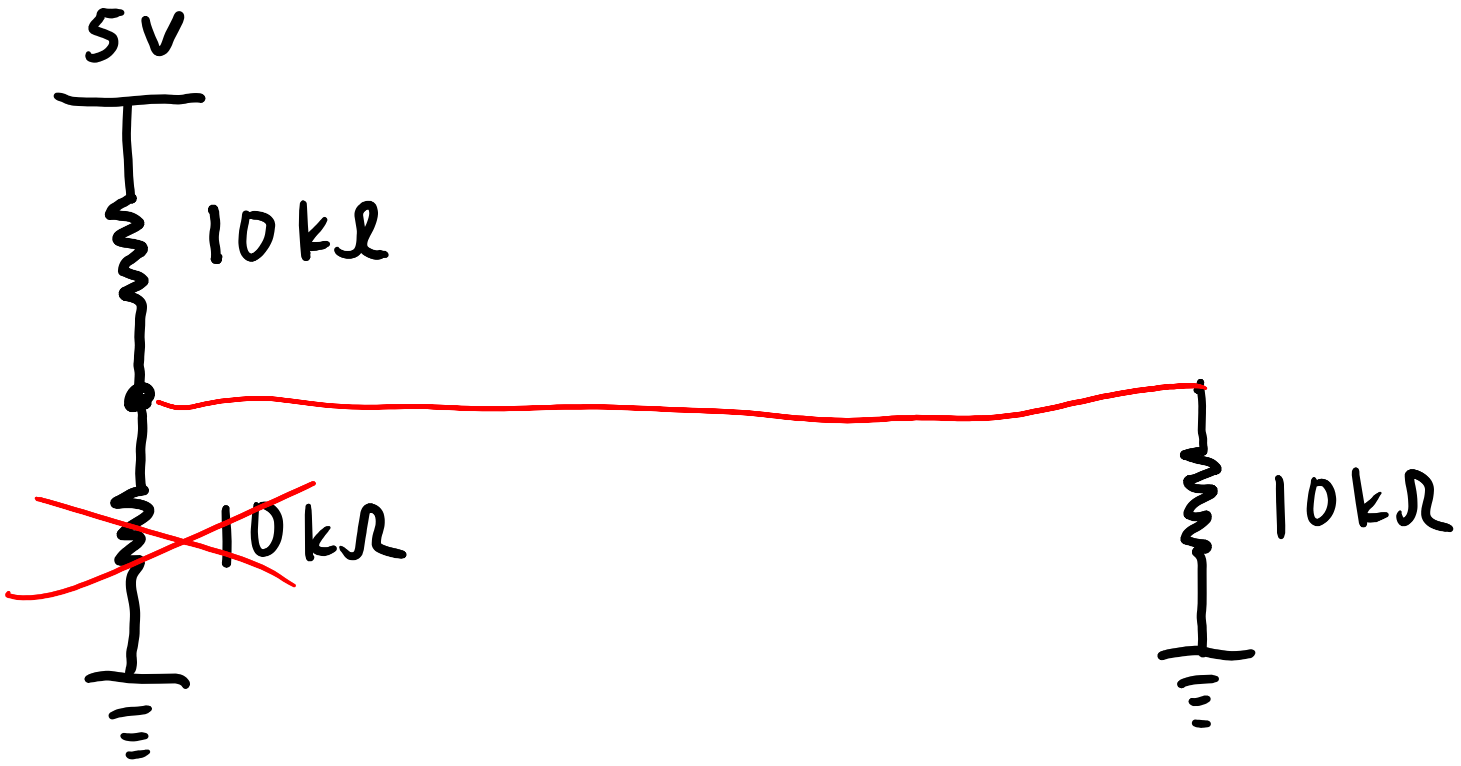
Quick review: What is V_A?



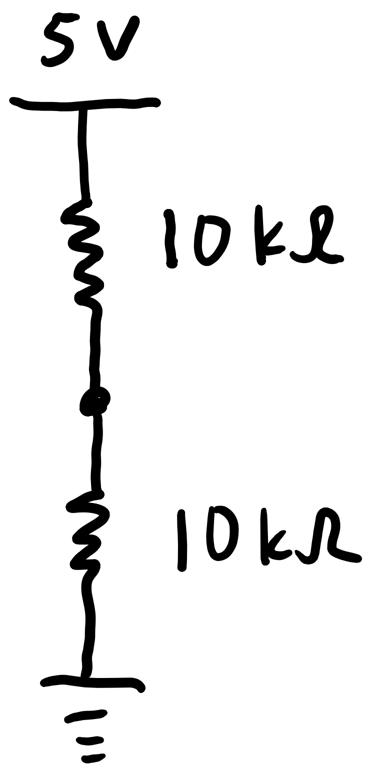
Now what is V_A?

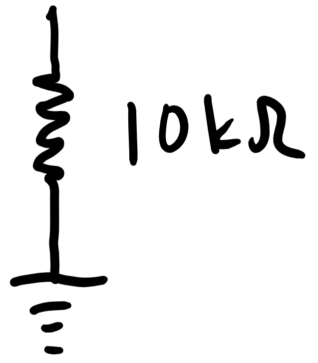


But what if we want to drive a load with 2.5V?

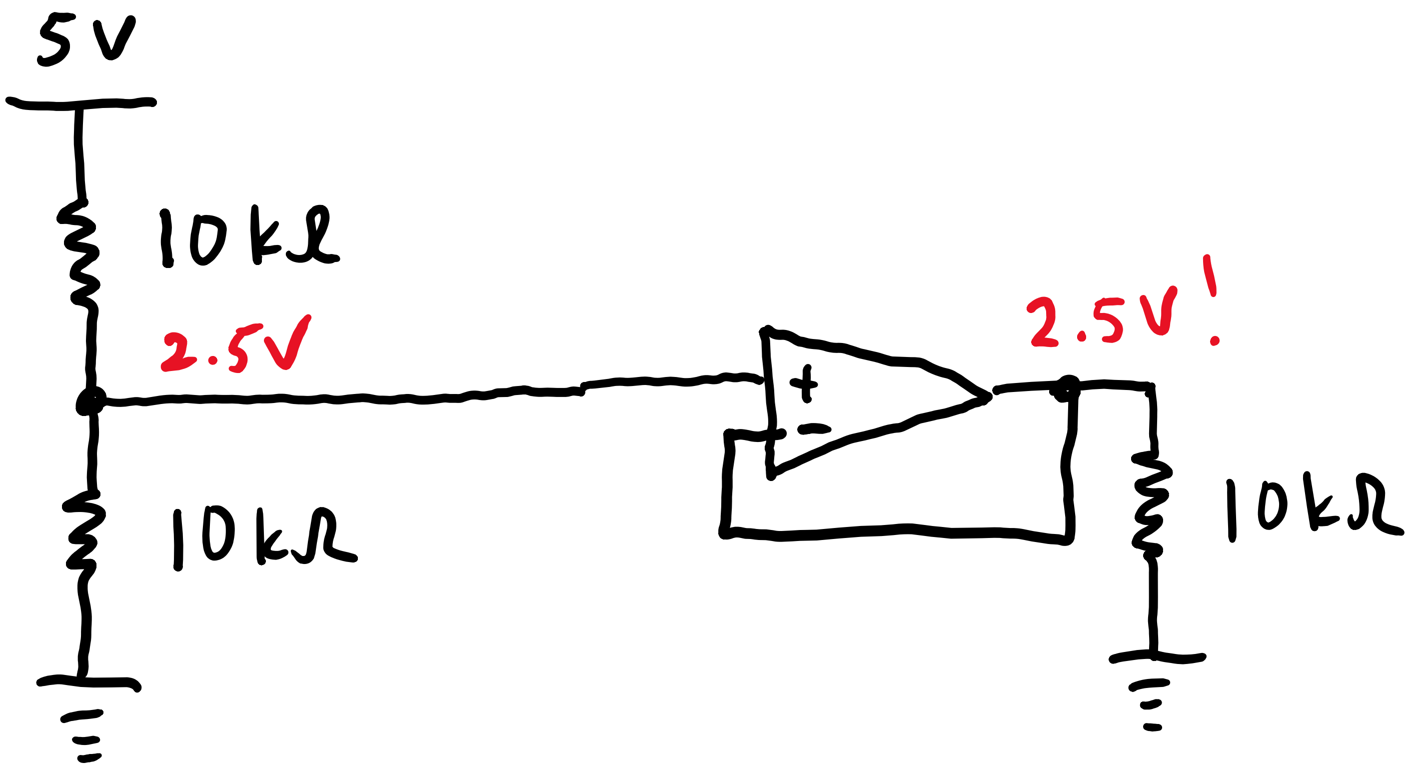


But what if we want to drive a load with 2.5V?

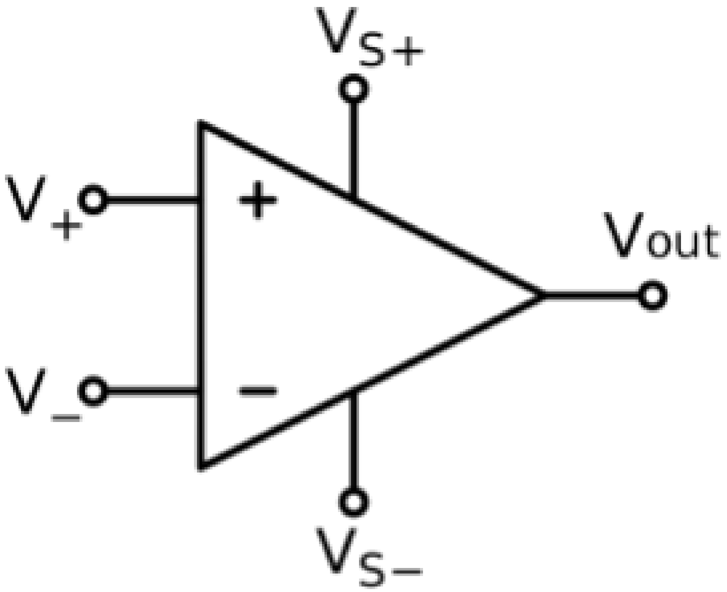




Let's use an op-amp!



Op-amp fundamentals: open loop

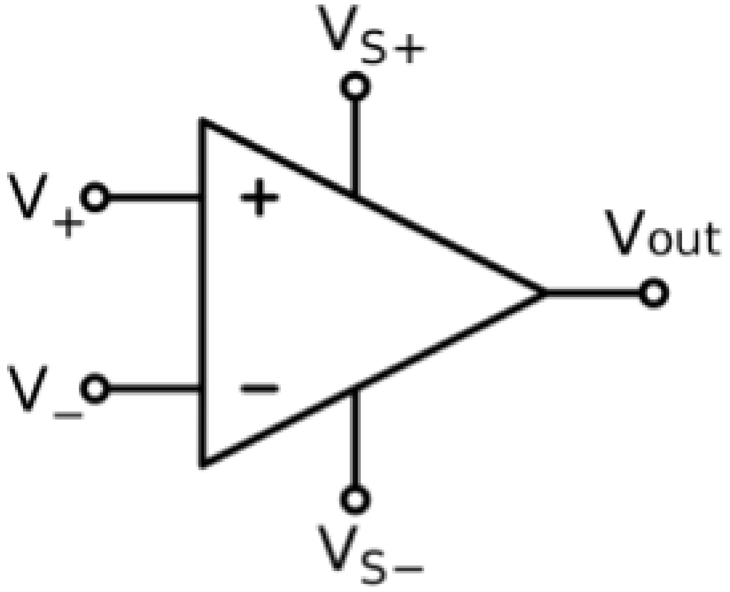


$$V_{out} = G\,[V_+ \; - \; V_-]$$

In technical terms, the gain, *G*, is *really, really big*.

For an *ideal* op-amp, G is infinite!

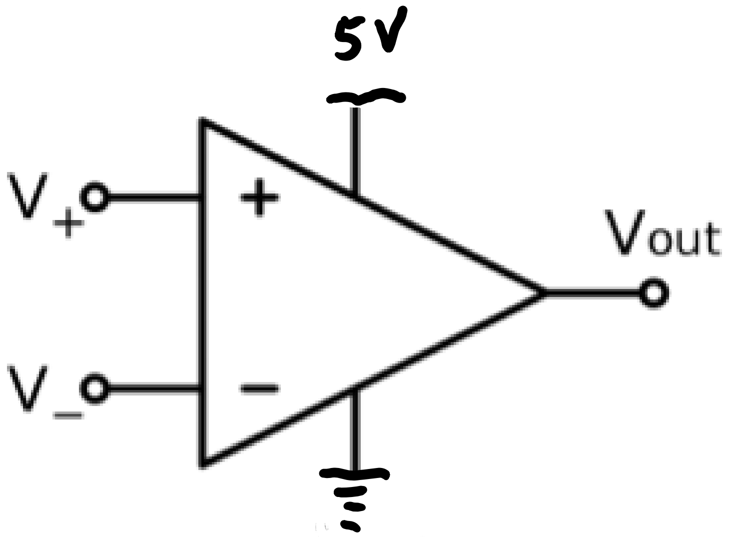
Op-amp fundamentals: open loop



$$V_{out} \approx \begin{cases} V_{s+} & \text{if} \quad V_+ > V_- \\ V_{s-} & \text{if} \quad V_+ < V_- \end{cases}$$

G is infinite, but we can't have infinite voltages. In practice, the output voltage is limited by the *rails*.

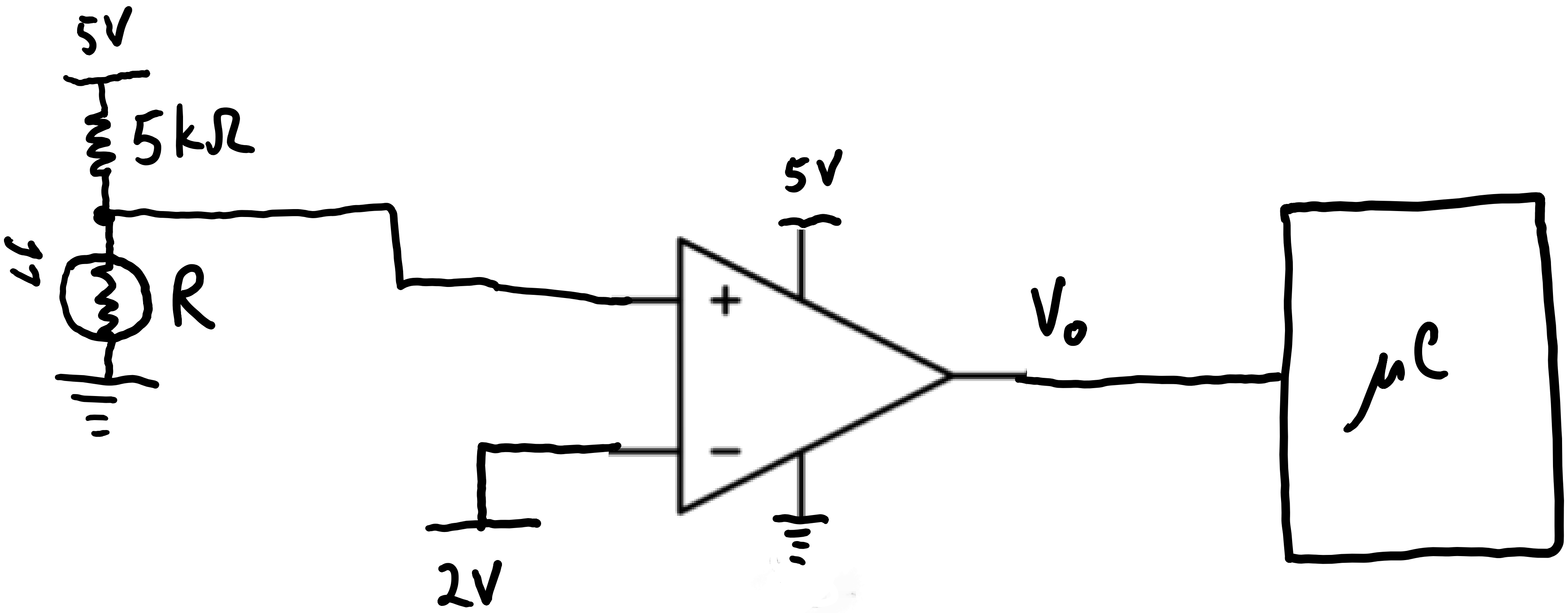
Op-amp as a comparator



$$V_{out} \approx \begin{cases} 5V & \text{if} \quad V_+ > V_- \\ 0V & \text{if} \quad V_+ < V_- \end{cases}$$

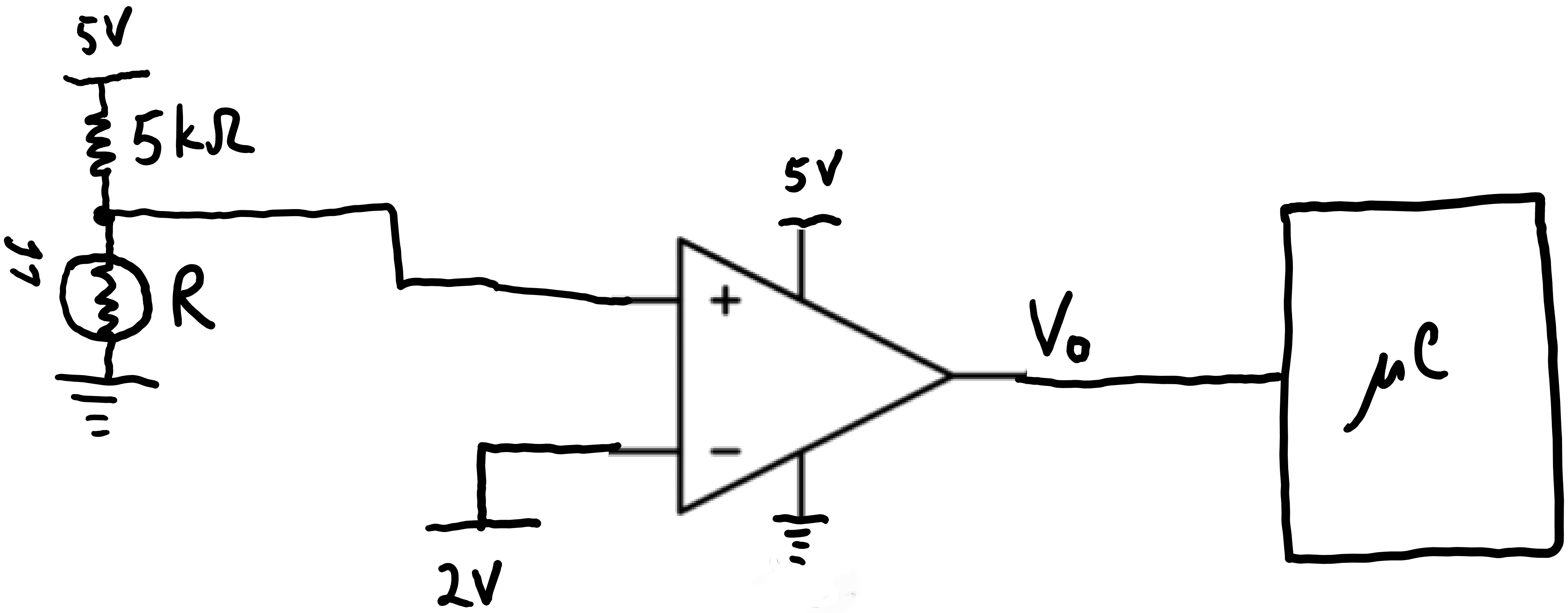
When used in an open-loop, the op-amp acts as a *comparator*.

For example, an op-amp as a light switch



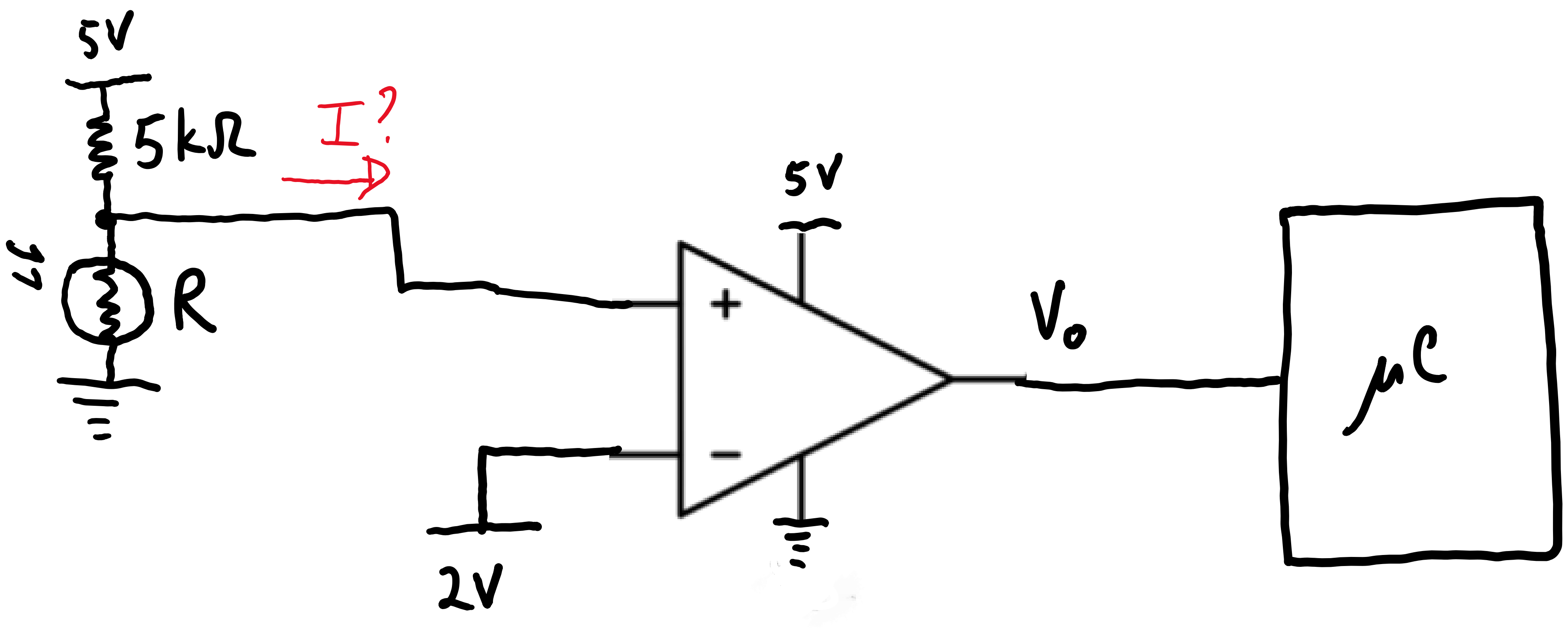
What values of R will produce a HIGH output and what will produce LOW?

For example, an op-amp as a light switch



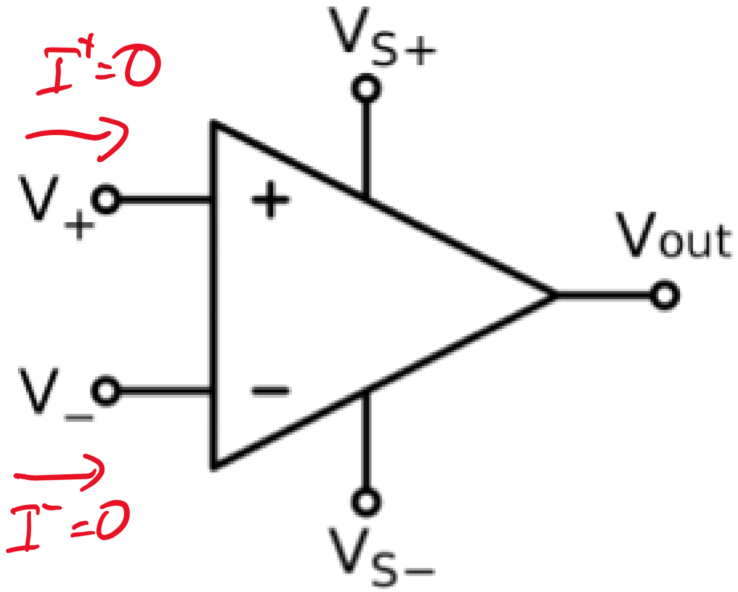
When R = 0 Ohm, what is V_o?
What about when R = 5 k Ohm?
Where does the output switch?

For example, an op-amp as a light switch



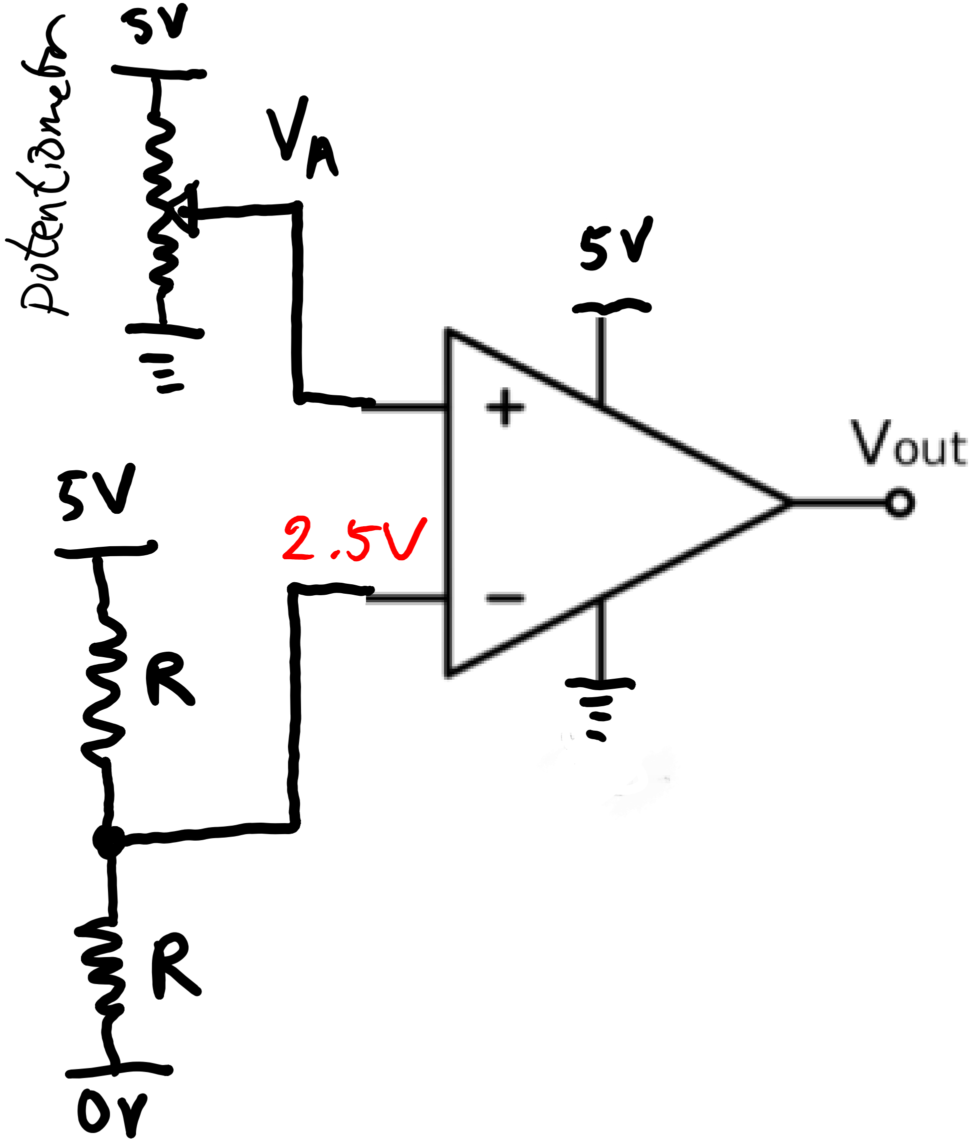
Waitaminute, waitaminute. Don’t we have to assume that no current flows out of the voltage divider?

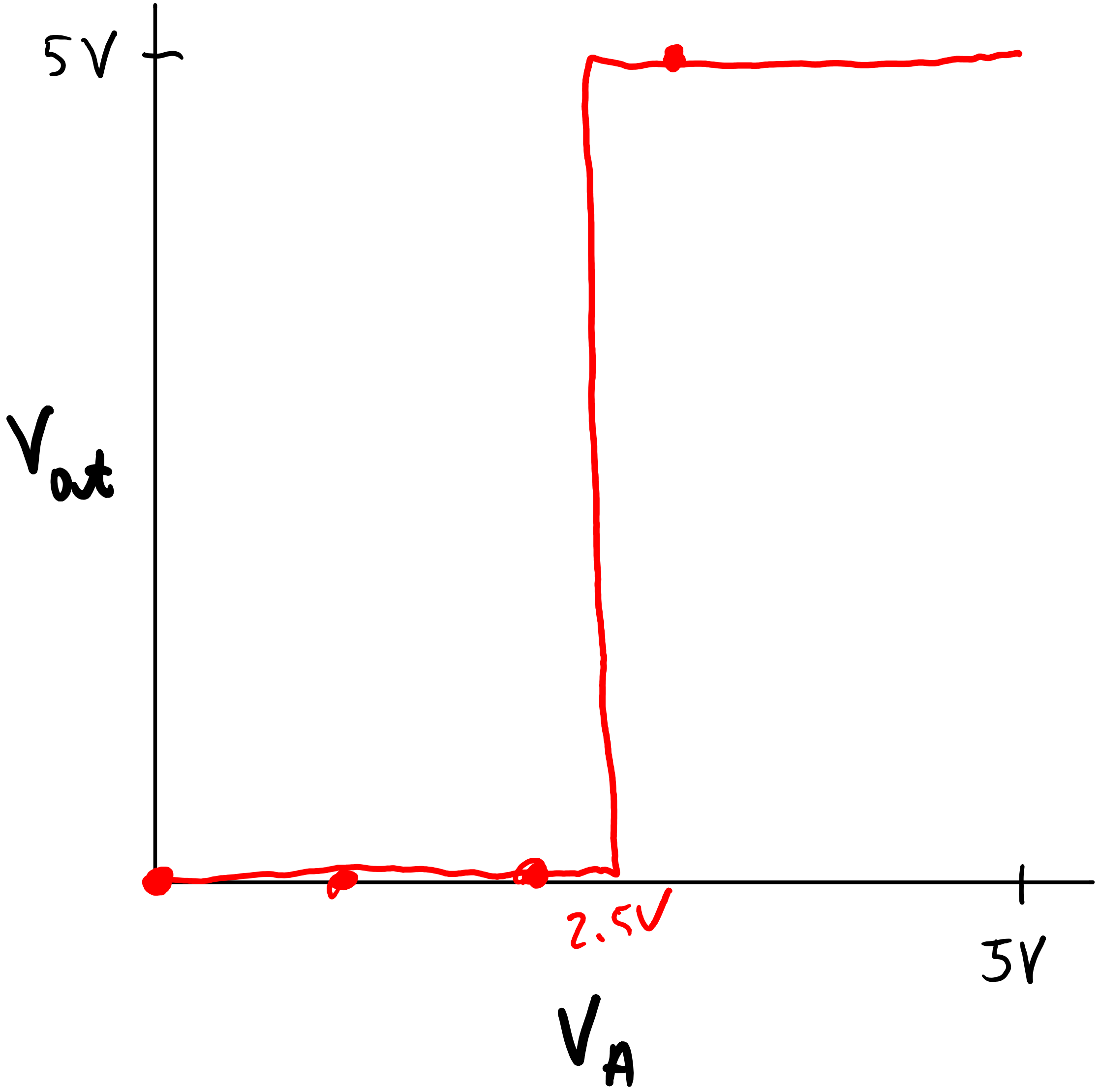
Golden Rule #1



For an ideal op-amp, we assume that **no current flows into or out of the V+ and V- terminals!**

Comparator example



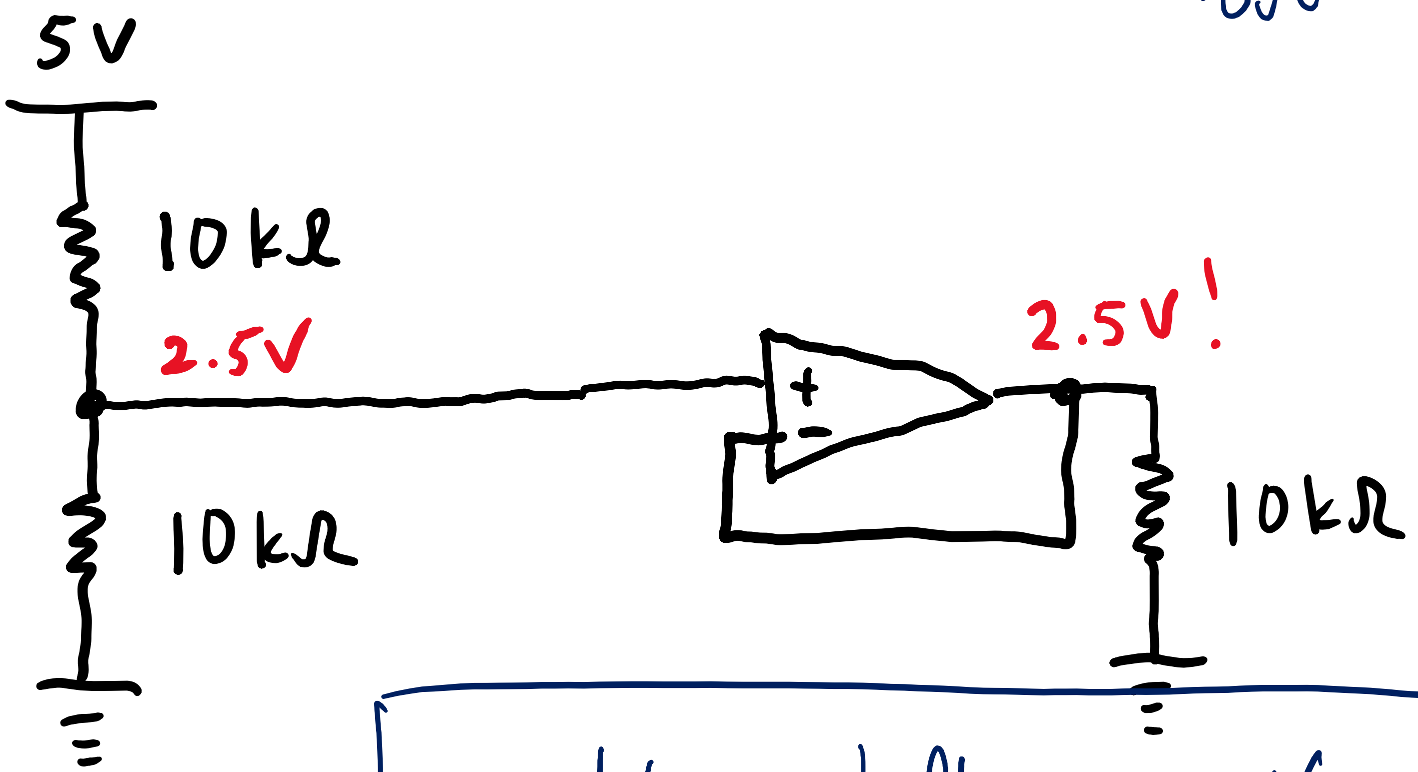


Returning to the earlier problem

$$V_{out} = V_{in}\left[1 + \frac{R_f}{R_i}\right]$$

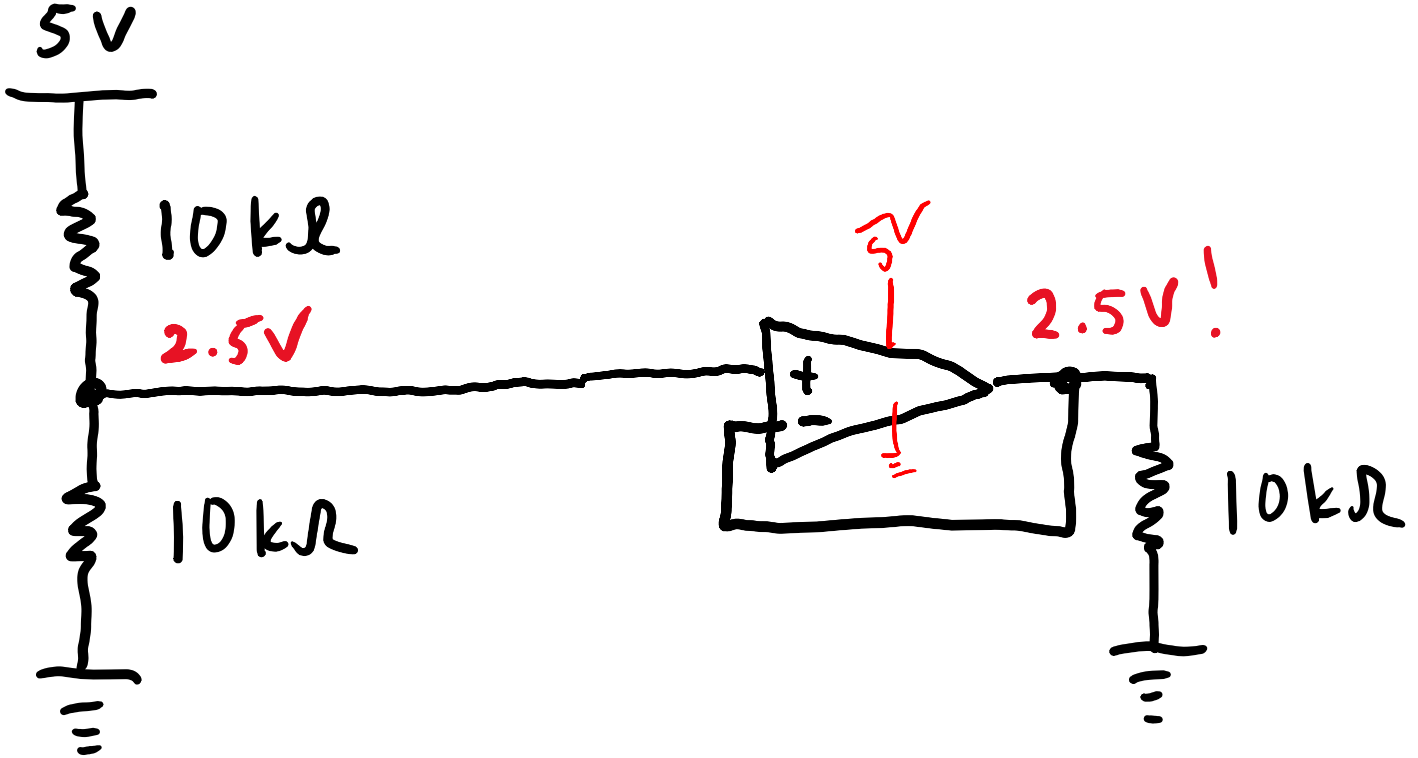
$R_f = 0$

$R_i = \infty$



$\boxed{\text{voltage buffer} \Rightarrow V_{out} = V_{in}}$

Op-amp as a voltage follower



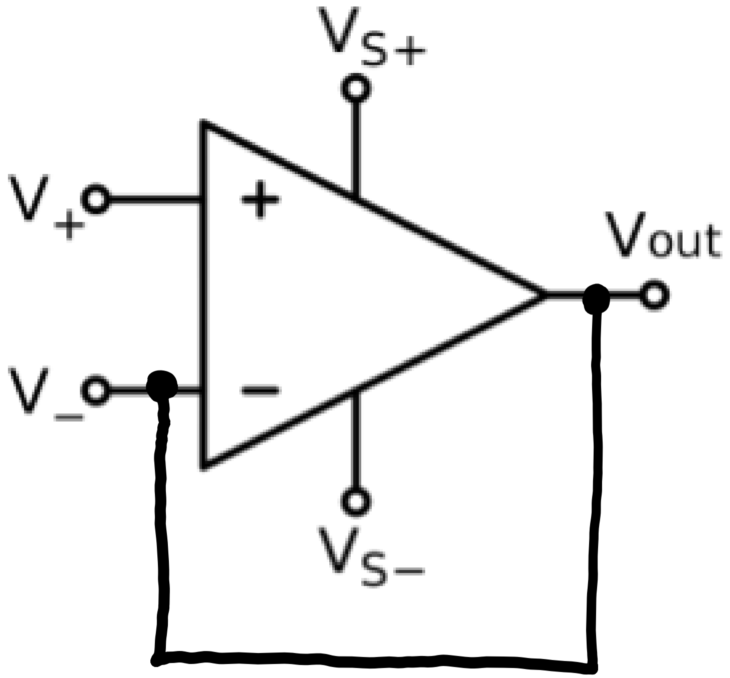
$$V_0 = G(V^+ - V^-)$$

$$= G(V^+ - V_0)$$

$$\Rightarrow V_0[1+G] = GV^+$$

$$V_0 = V^+ \frac{\overset{=\infty}{G}}{\underset{=1+\infty}{1+G}} = V^+$$

Golden Rule #2

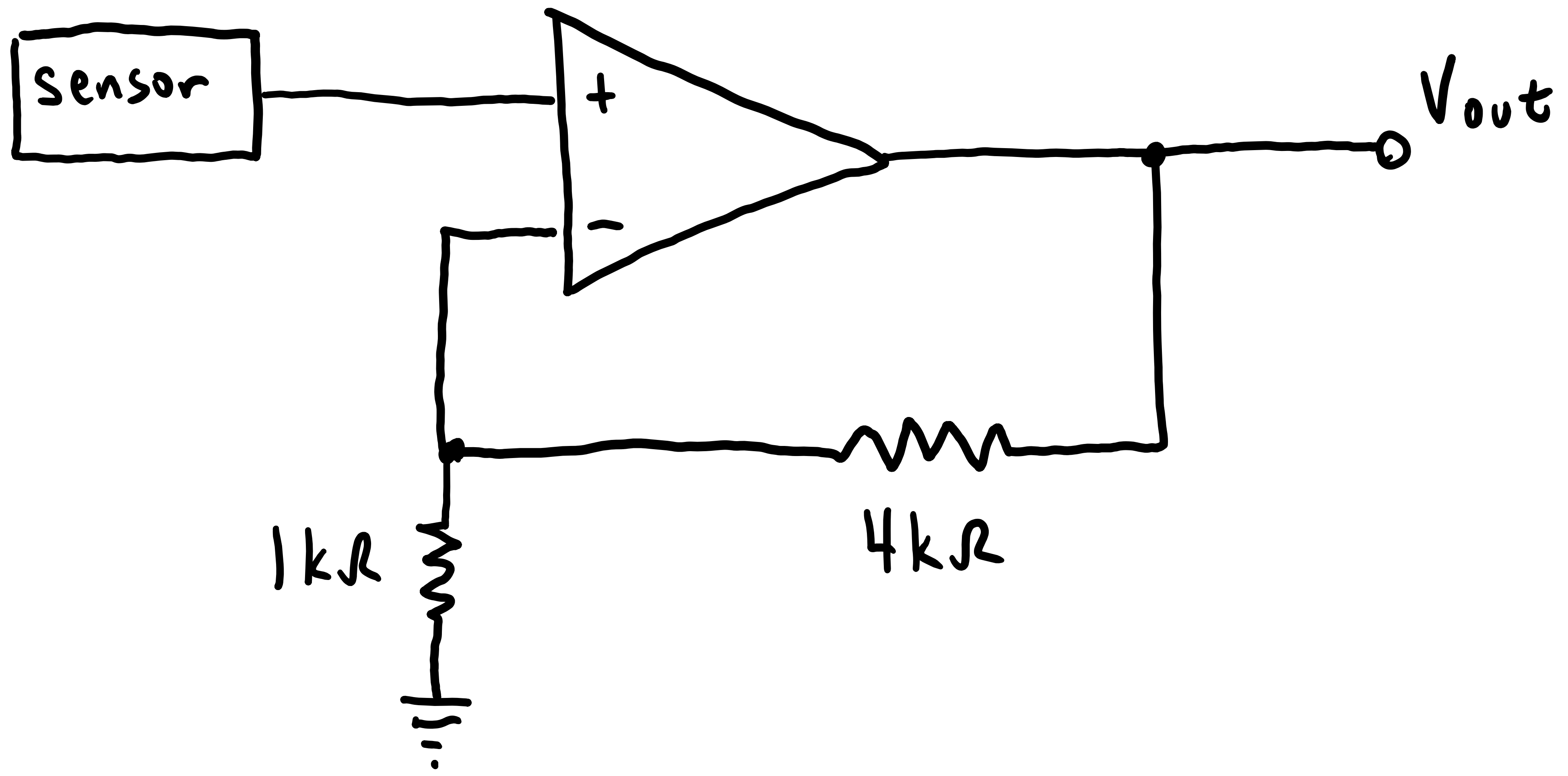


When wired in a <u>negative feedback loop</u>, the op-amp will "do whatever it takes" to make **V- equal to V+**.

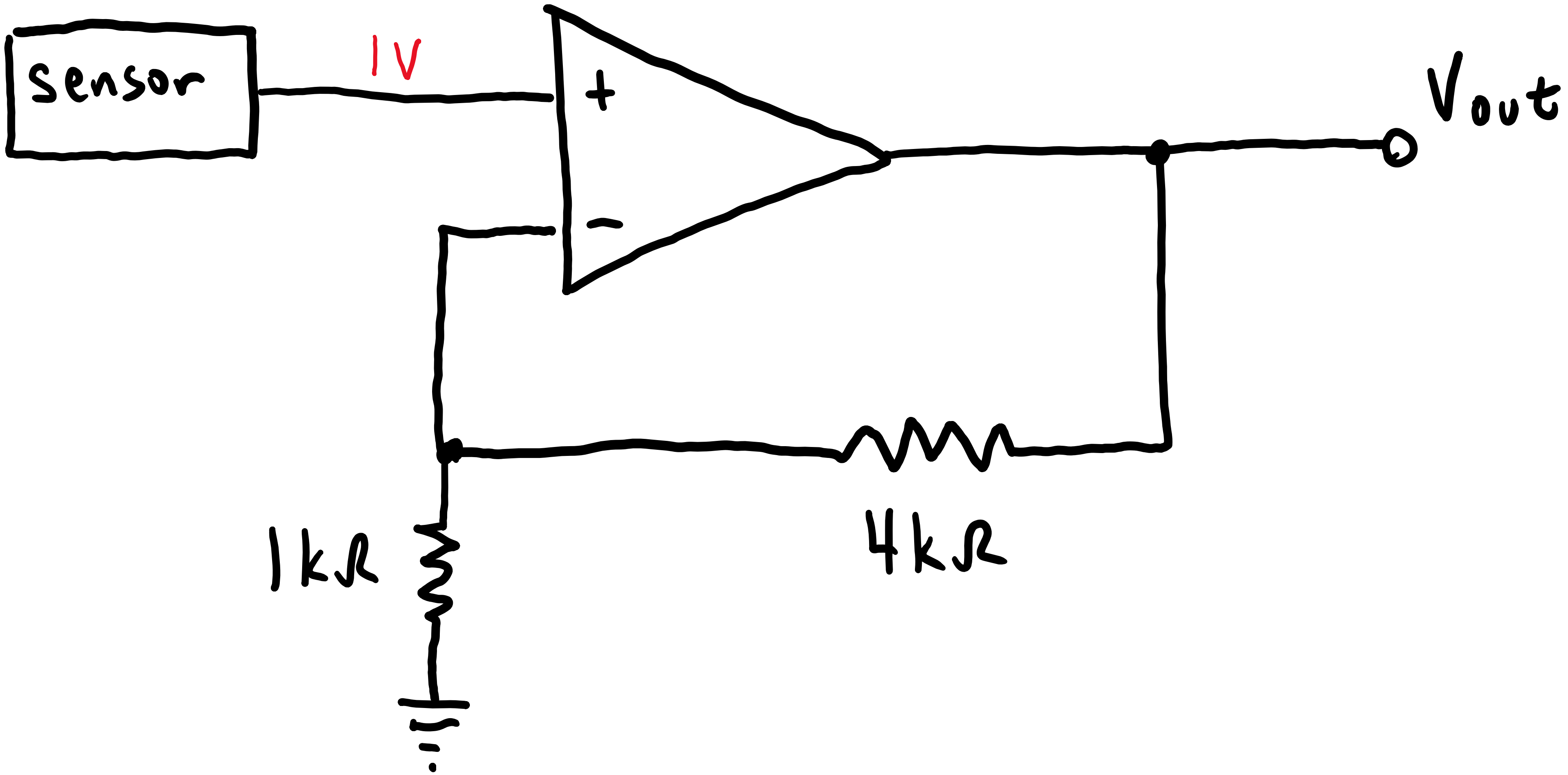
Say you have a light sensor that returns 0 V at 0 lux and 1 V at 100 lux. You want to increase the sensitivity such that it reads 5 V at 100 lux. That is, you want to increase the sensitivity from 10 mV / lux to 50 mV / lux.

What does a budding roboticist do?

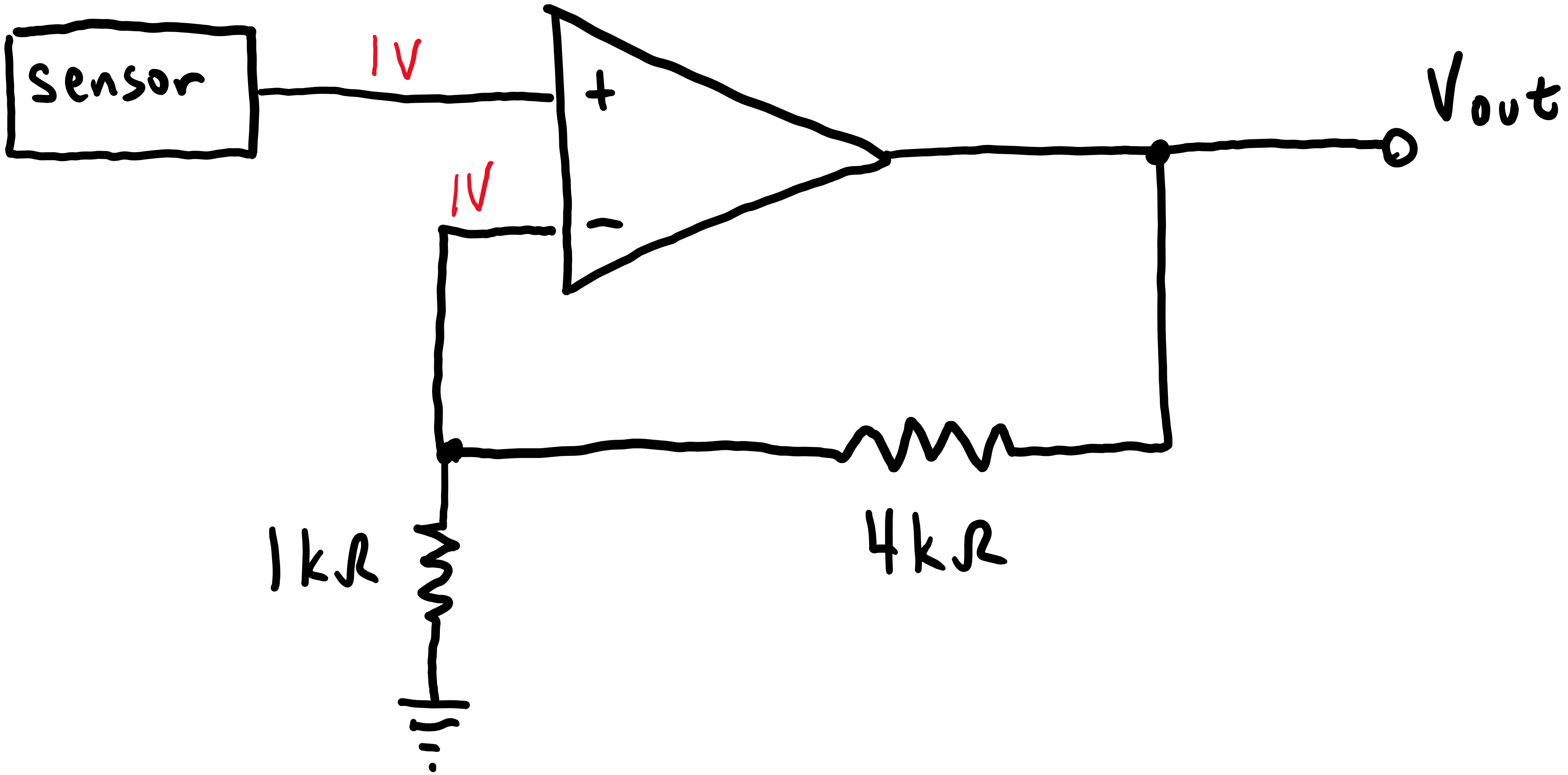
Let’s see what happens with this



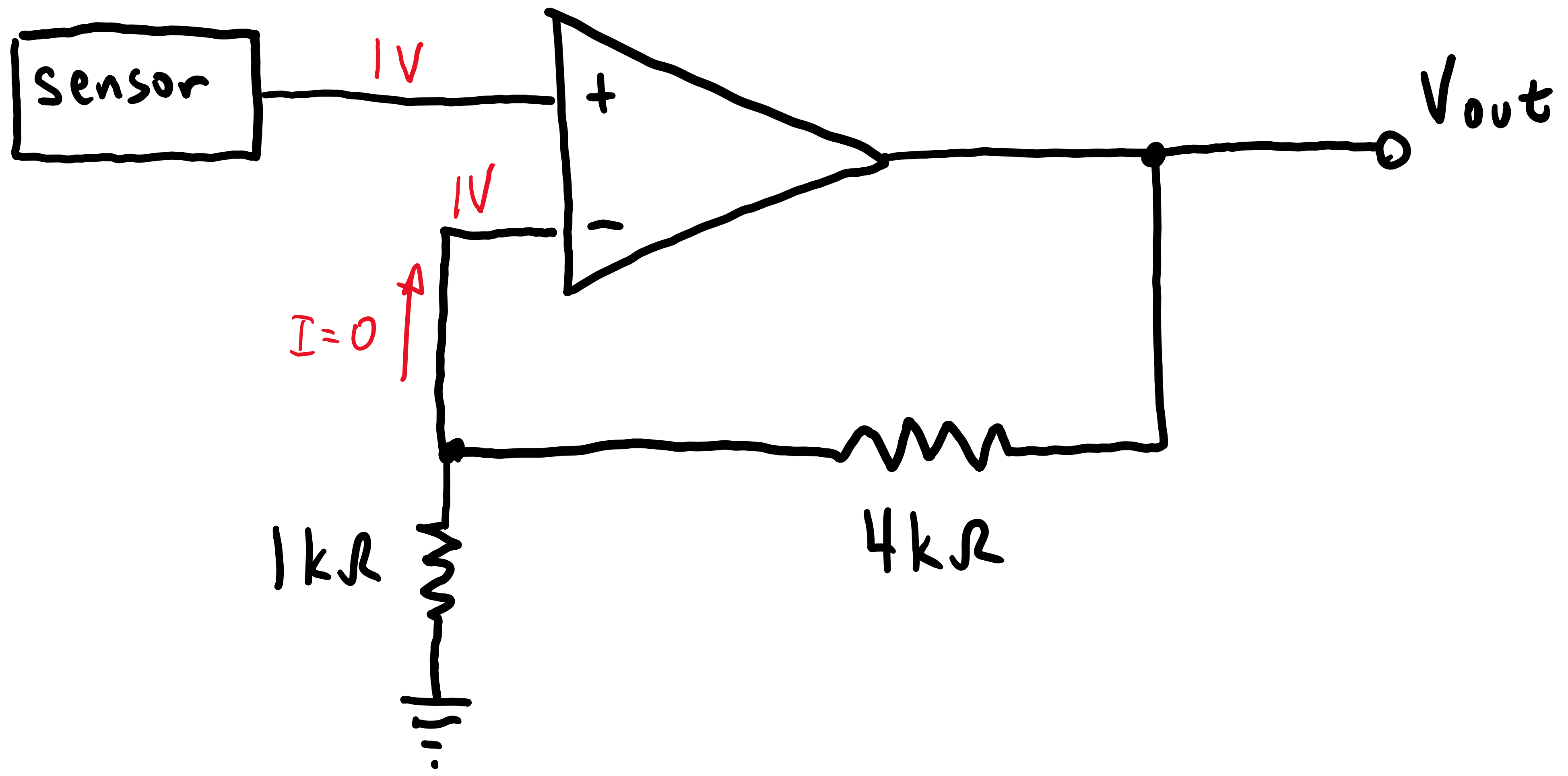
Let's see what happens with this



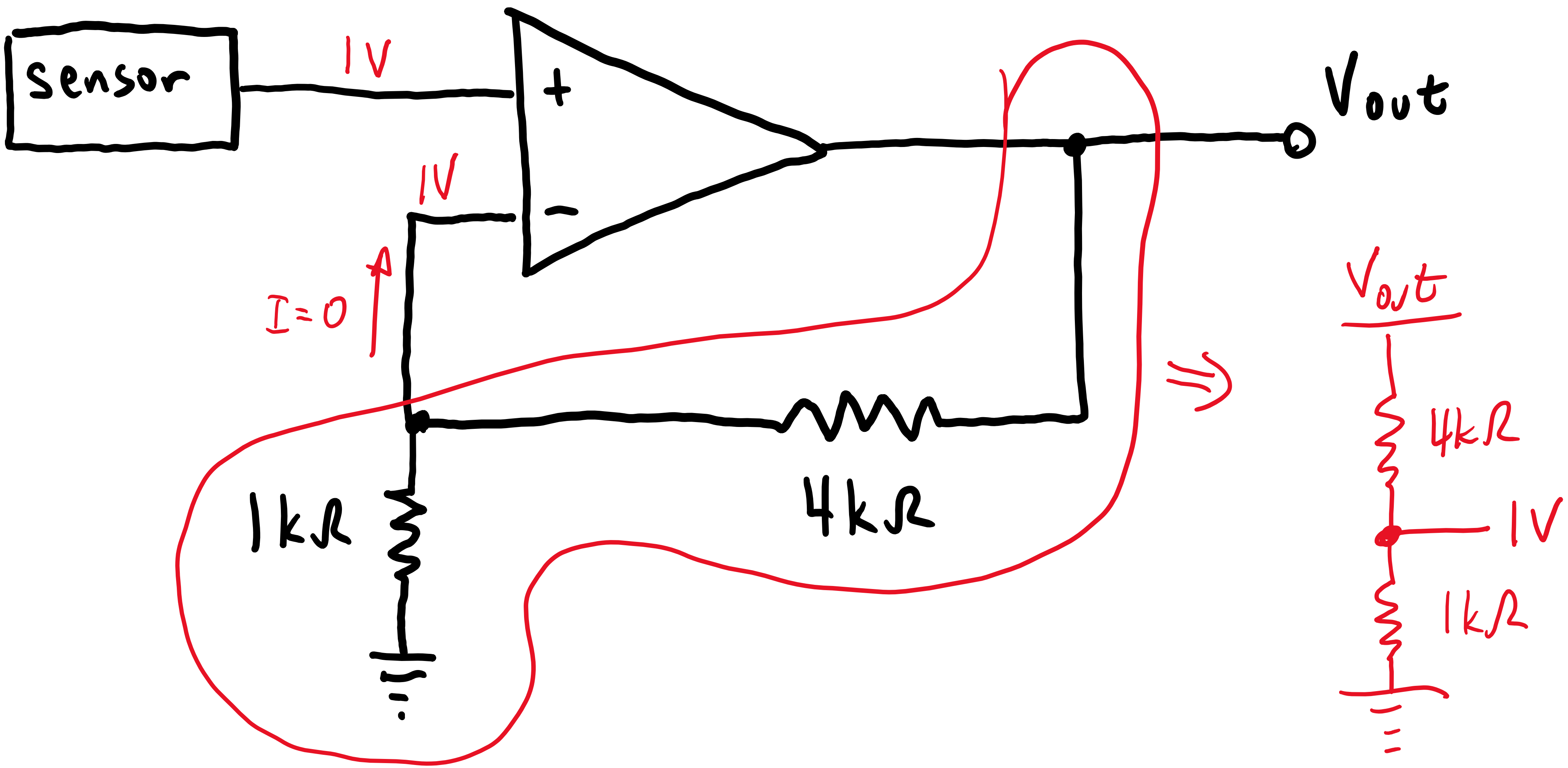
Let’s see what happens with this



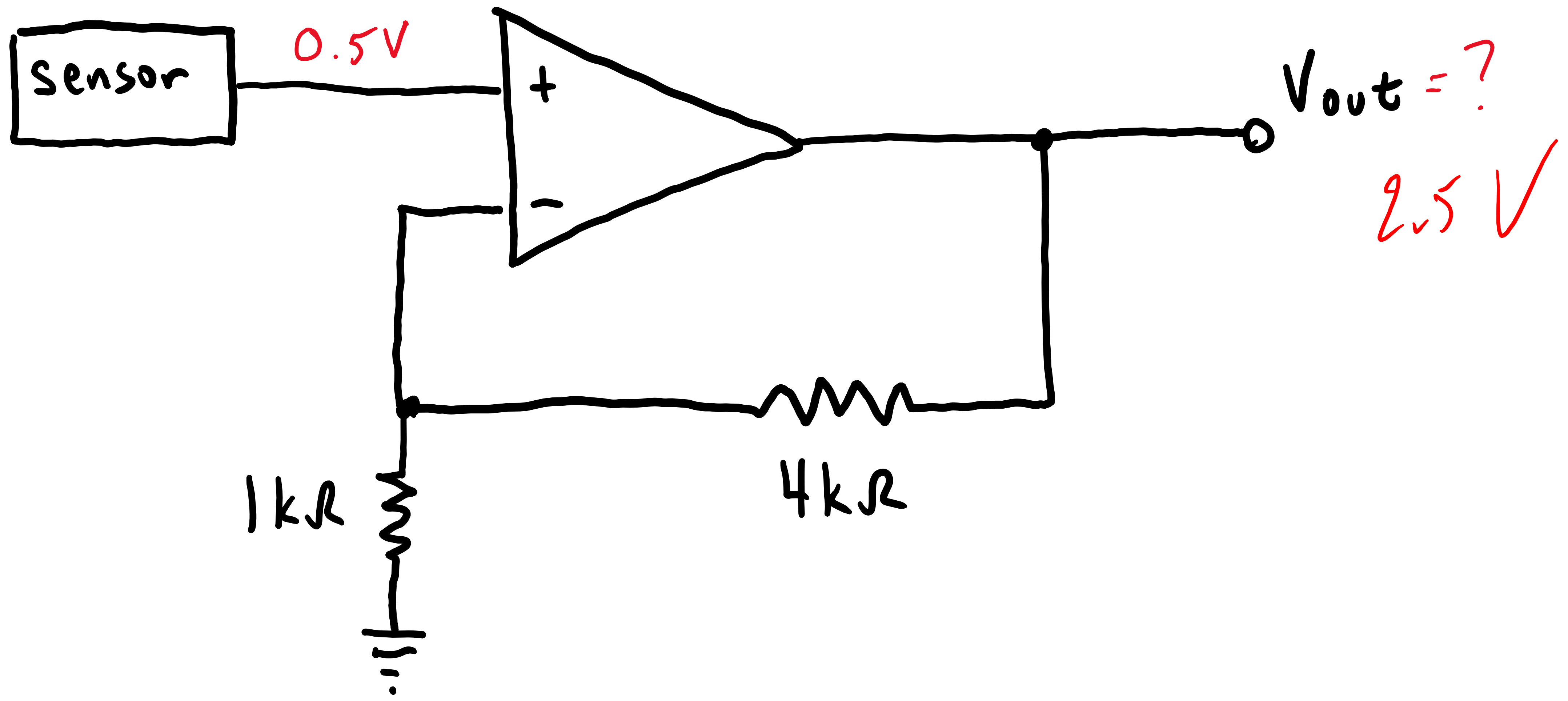
Let's see what happens with this

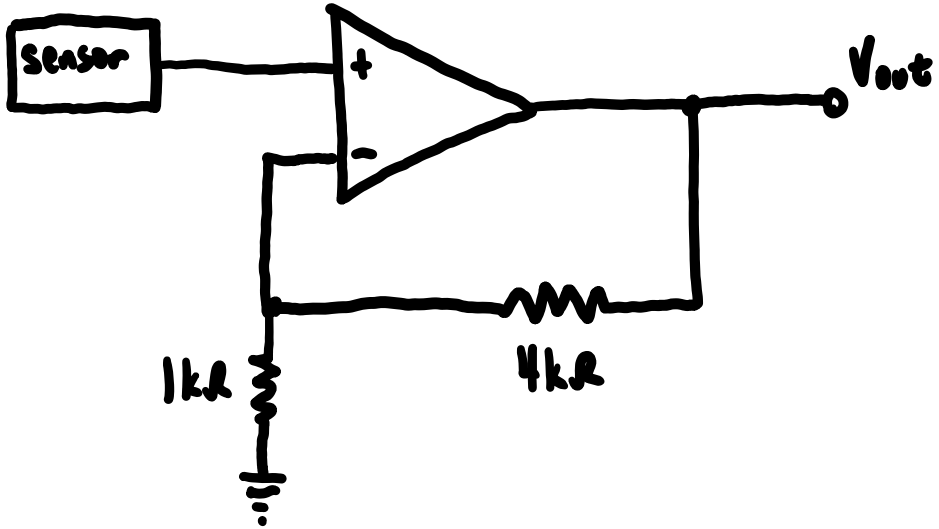


Let's see what happens with this

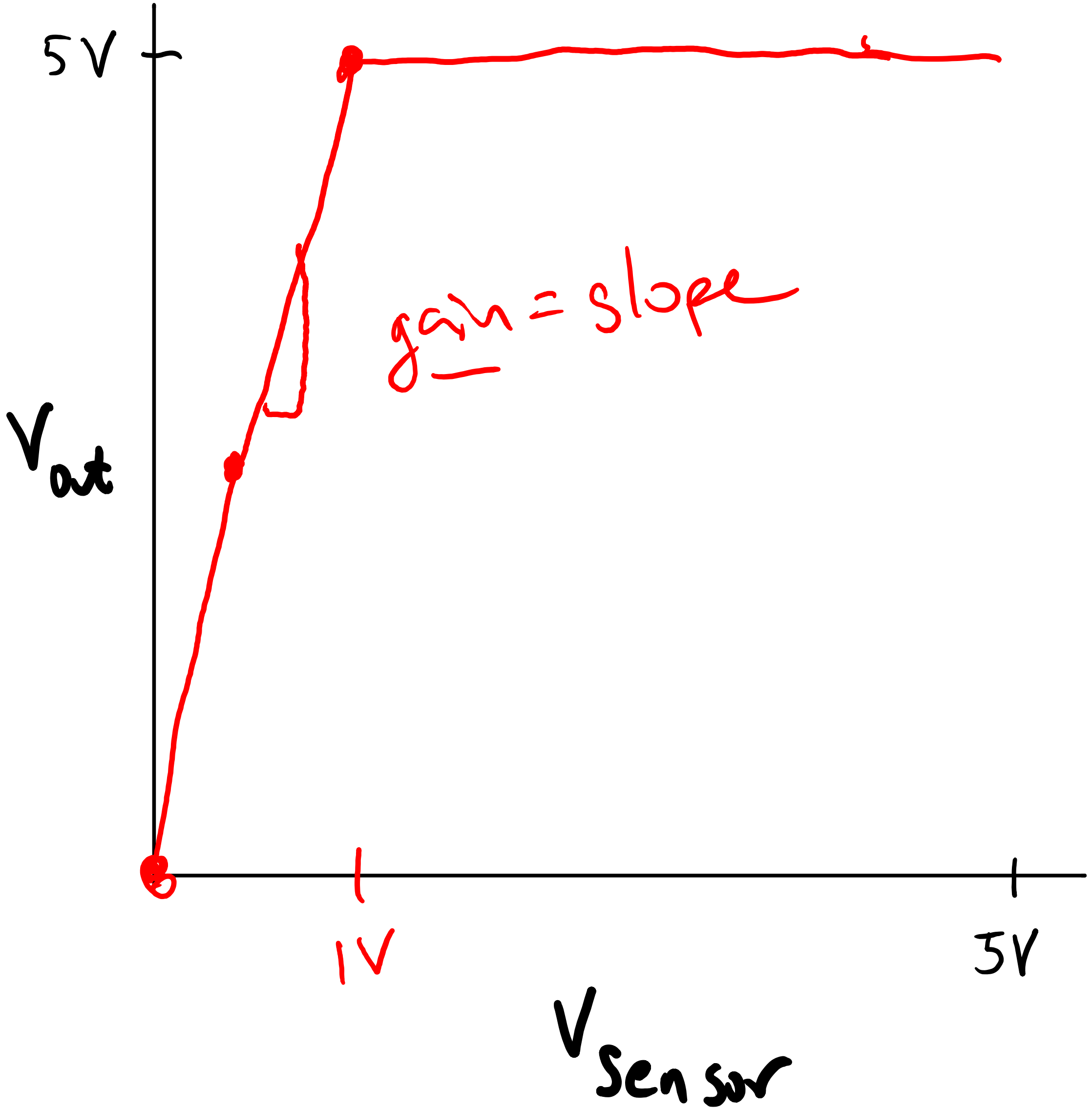


Your turn!



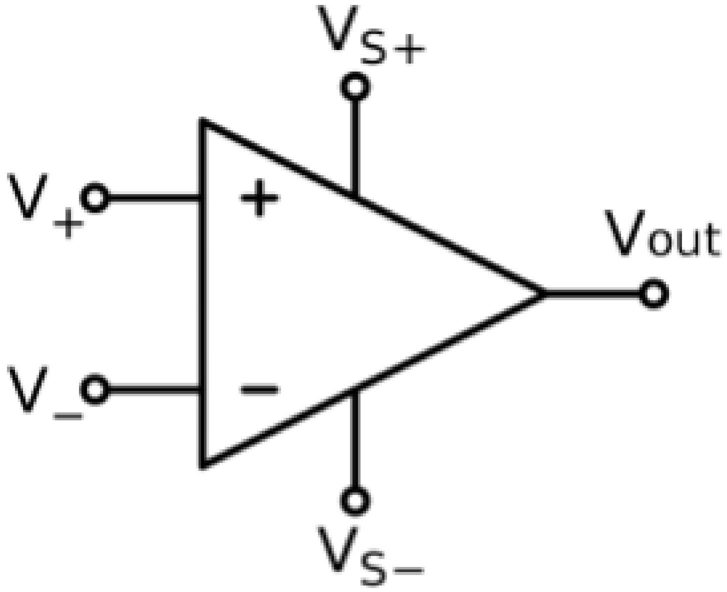


Sensor
+
−
Vout
1kΩ
4kΩ

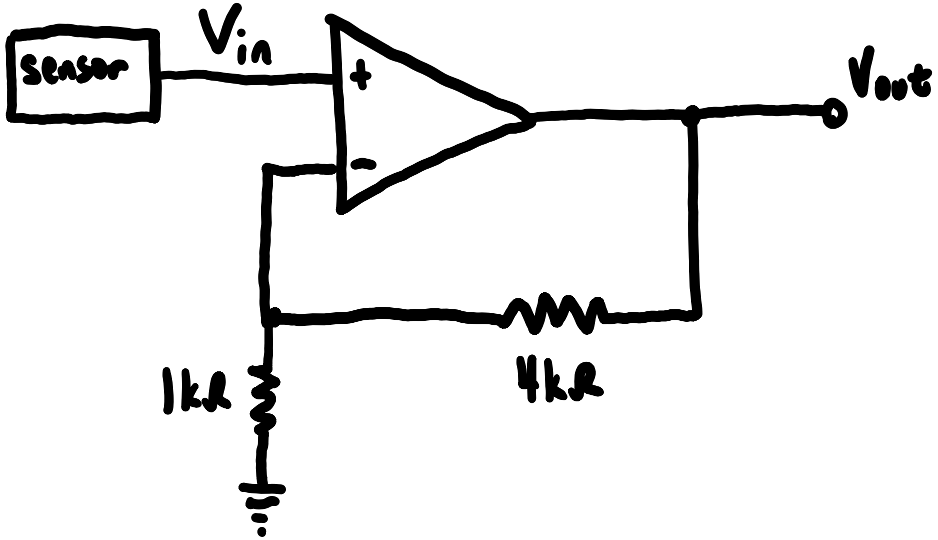


5V
Vout
gain = slope
1V
5V
Vsensor

What is “gain”?

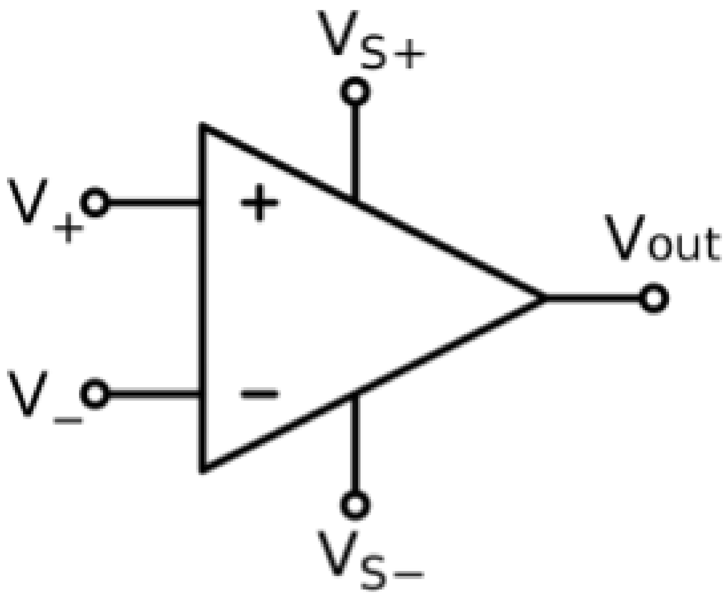


The gain of a ‘bare’ op-amp is very large...

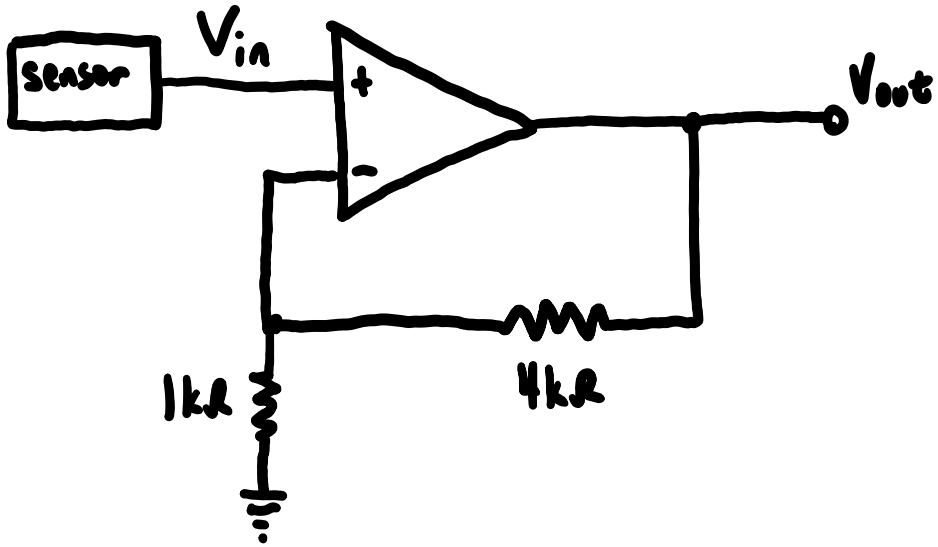


...but the usefulness of an op-amp comes from putting it a circuit.

What is “gain”?



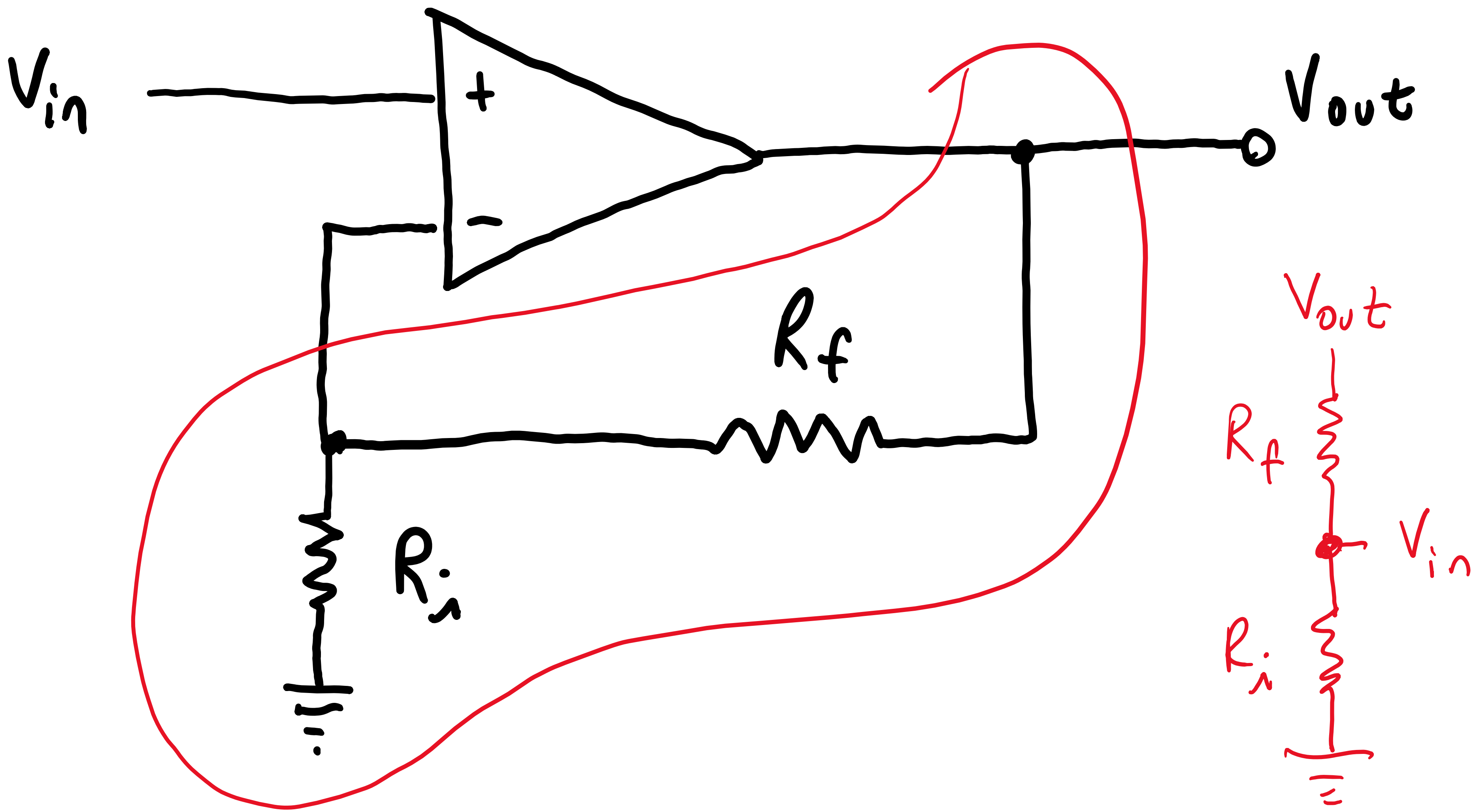
So the gain of an op-amp is just for reference.



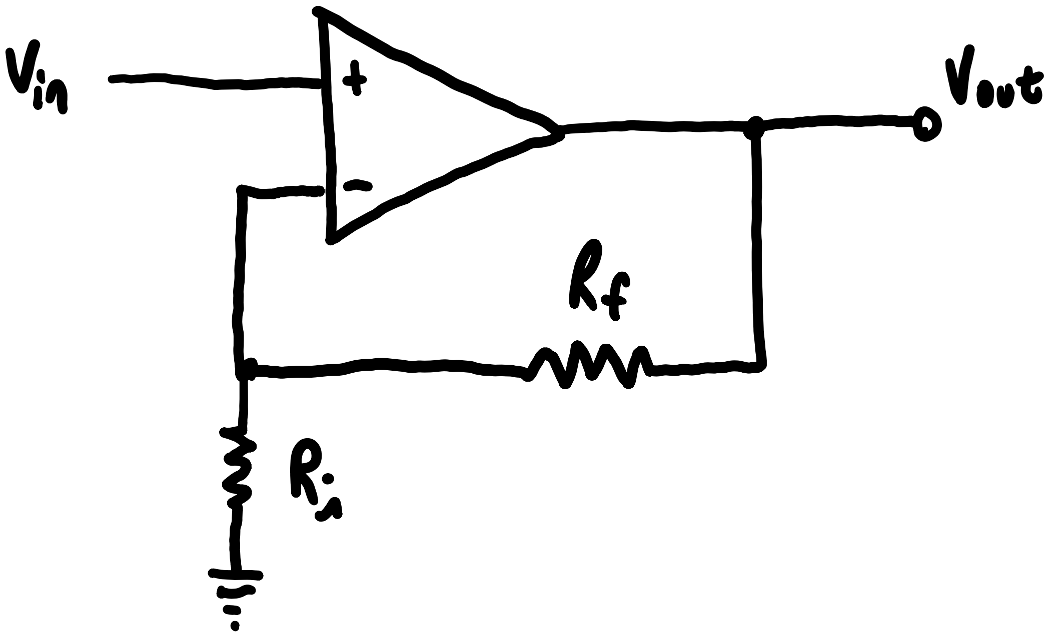
In practice, you need to be able to find the *relationship between input and output voltages*. The slope of that relationship is the gain of the circuit.

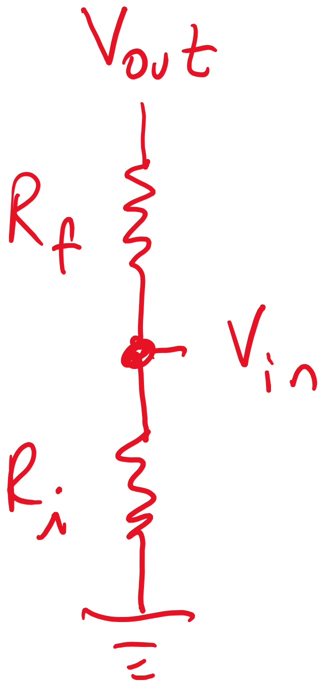
$$\text{gain} = \frac{dV_{out}}{dV_{in}}$$

Revisiting the non-inverting op-amp



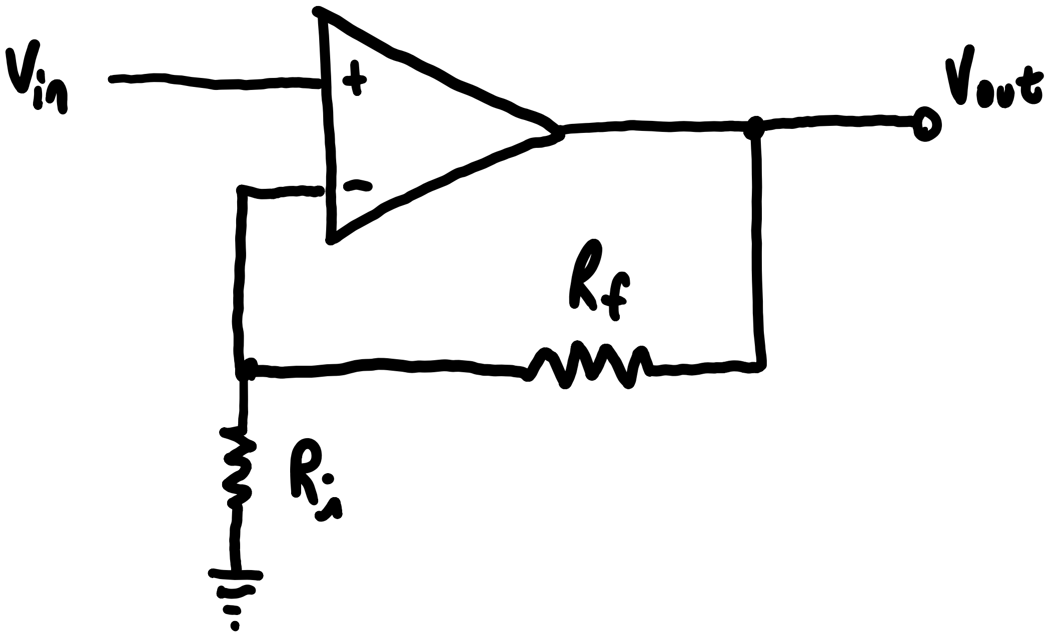
Non-inverting op-amp

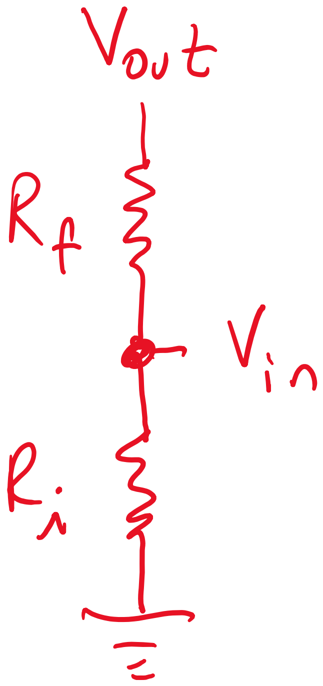




$$V_{in} = V_{out} \frac{R_i}{R_i + R_f}$$

Non-inverting op-amp

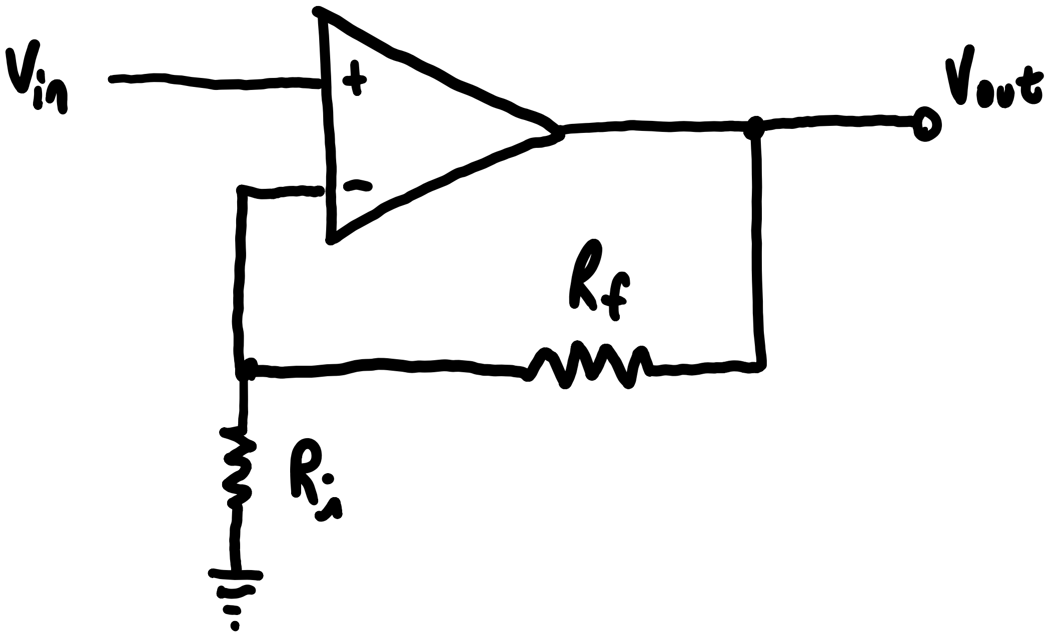


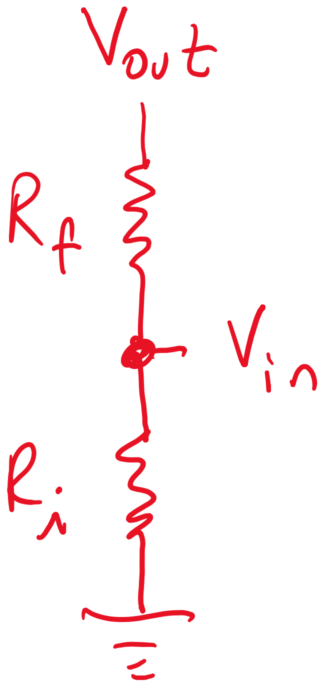


$$V_{in} = V_{out} \frac{R_i}{R_i + R_f}$$

$$V_{out} = V_{in} \frac{R_i + R_f}{R_i}$$

Non-inverting op-amp



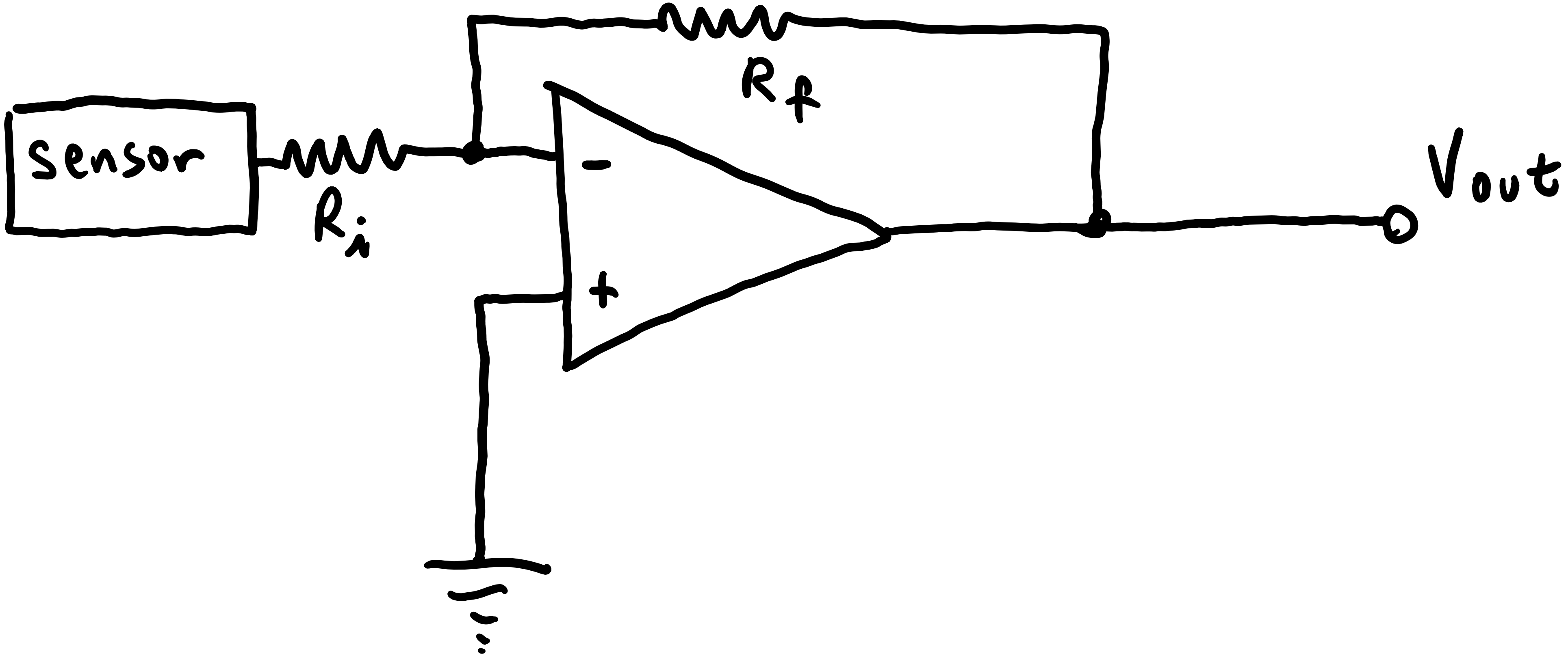


$$V_{in} = V_{out}\frac{R_i}{R_i + R_f}$$

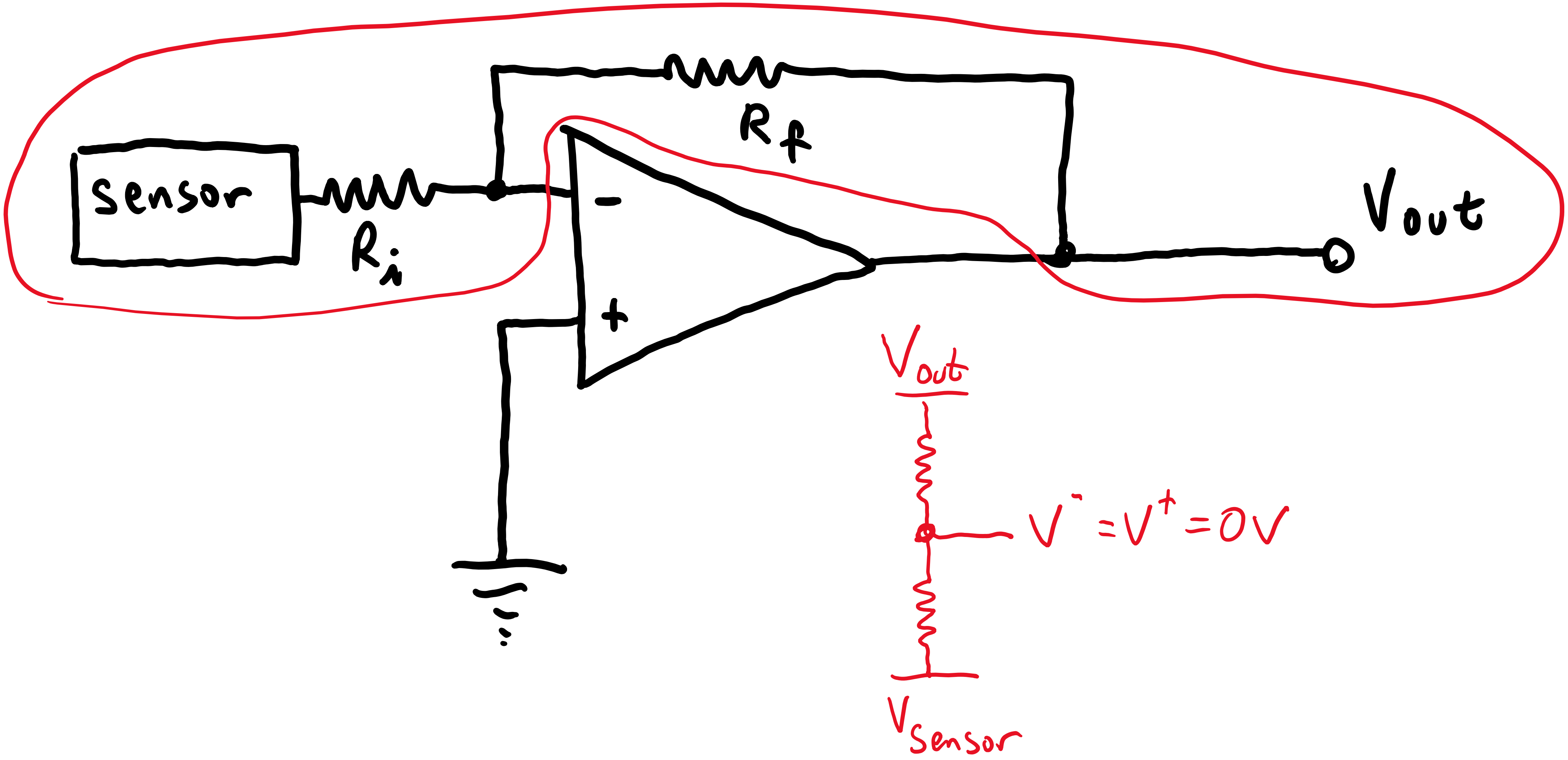
$$V_{out} = V_{in}\frac{R_i + R_f}{R_i}$$

$$V_{out} = V_{in}\underbrace{\left[1 + \frac{R_f}{R_i}\right]}_{\text{GAIN}}$$

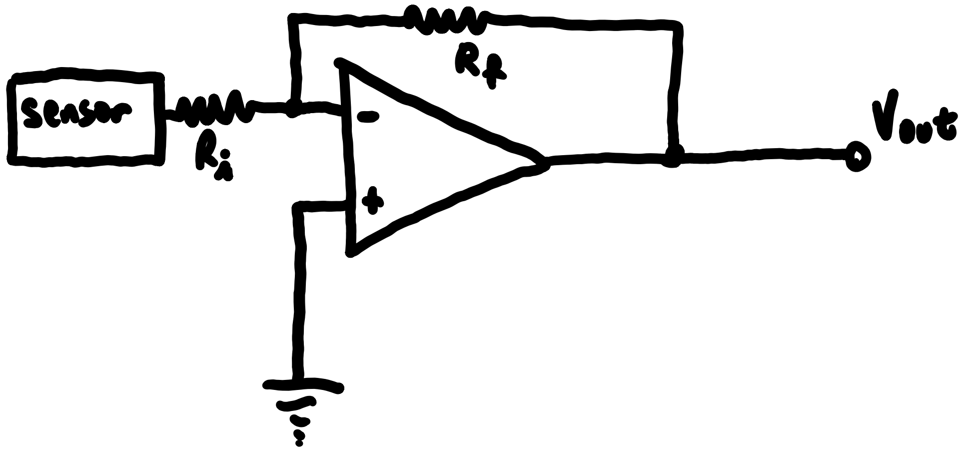
The inverting op-amp circuit

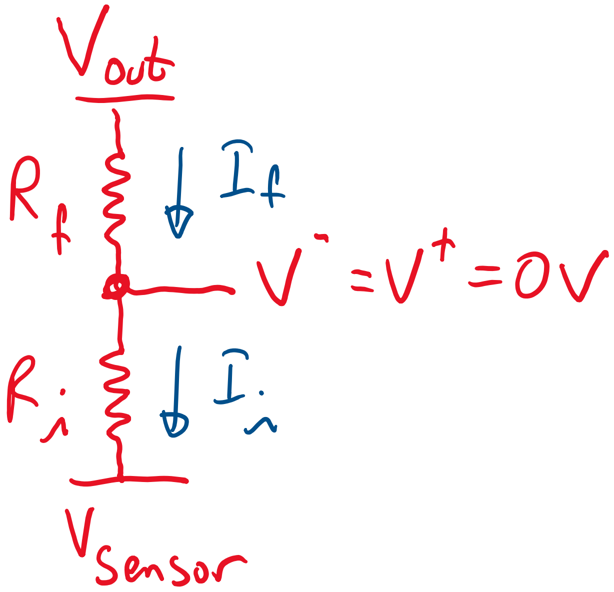


The inverting op-amp circuit



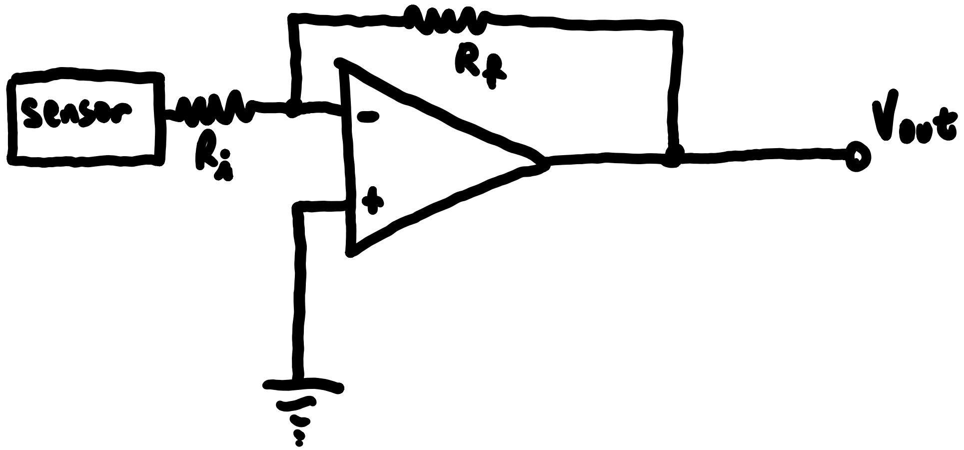
The inverting op-amp circuit

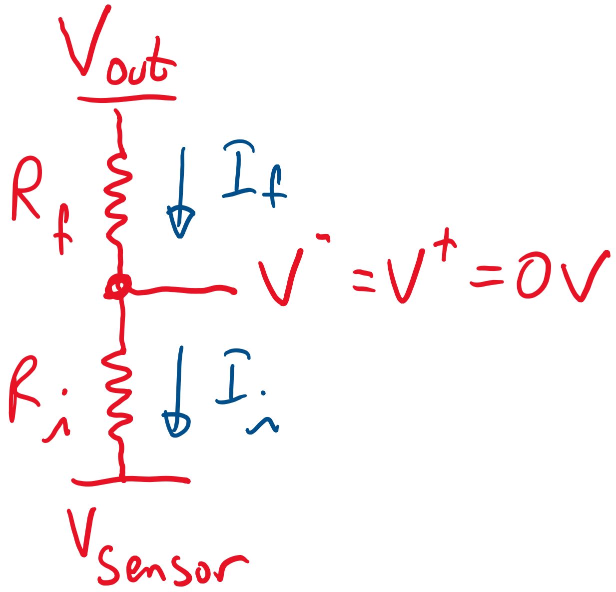




$$\frac{V_{out}}{R_f} = \frac{-V_{sensor}}{R_i} \Rightarrow$$

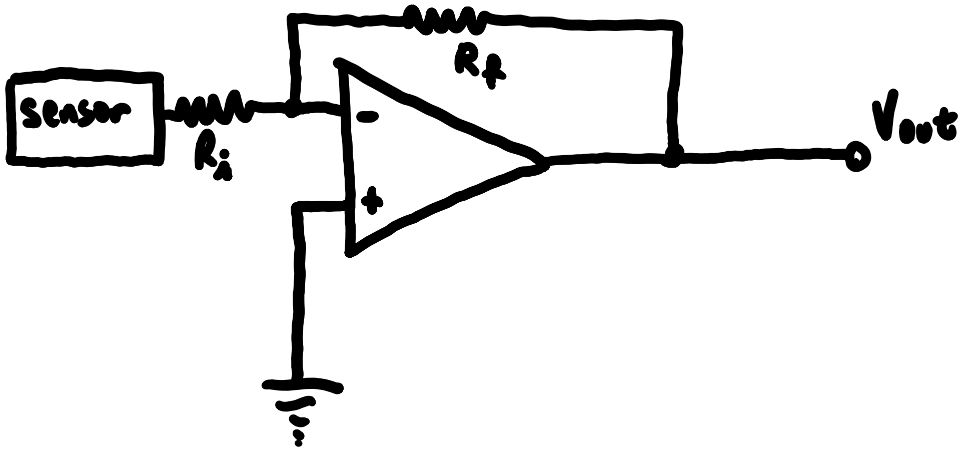
The inverting op-amp circuit

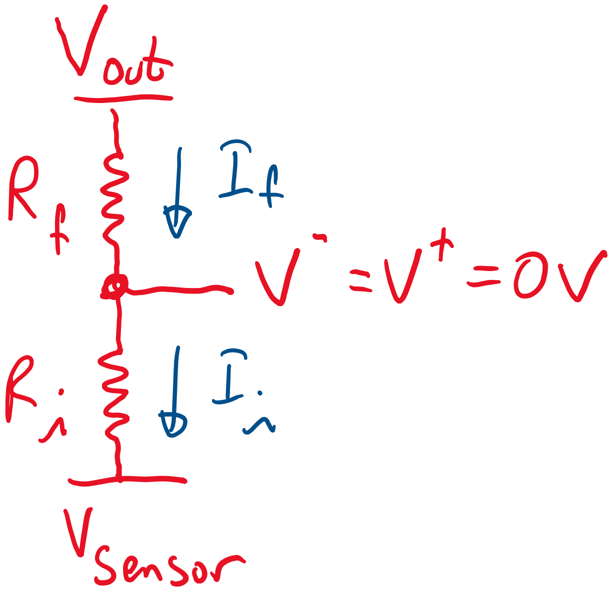




$$\frac{V_{out}}{R_f} = \frac{-V_{sensor}}{R_i} \Rightarrow V_{out} = -\frac{R_f}{R_i} V_{sensor}$$

The inverting op-amp circuit

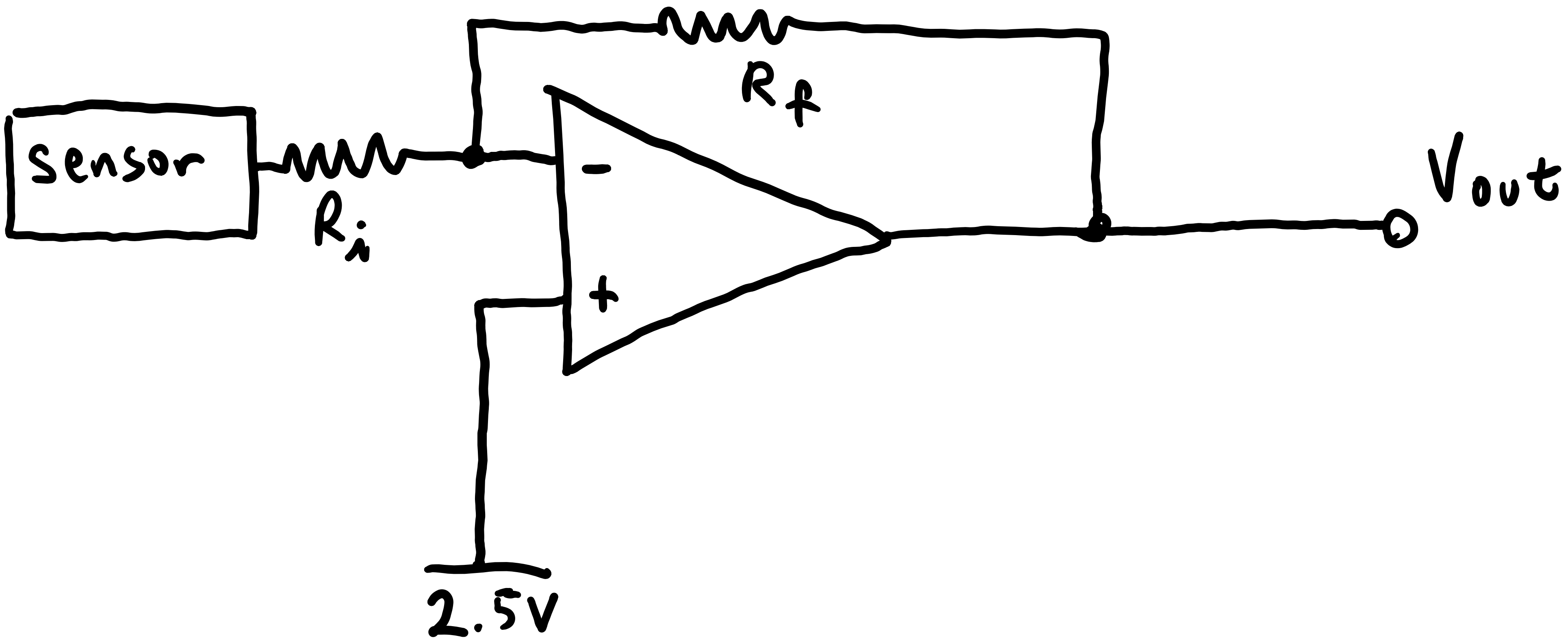




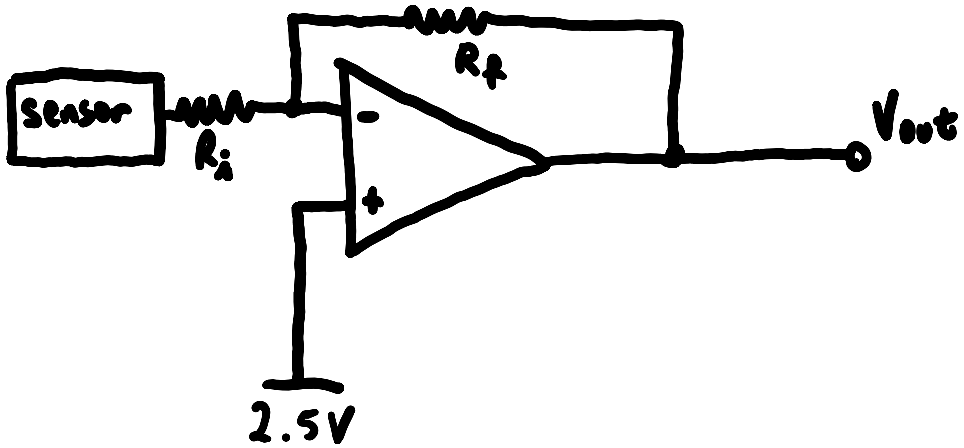
gain < 0!

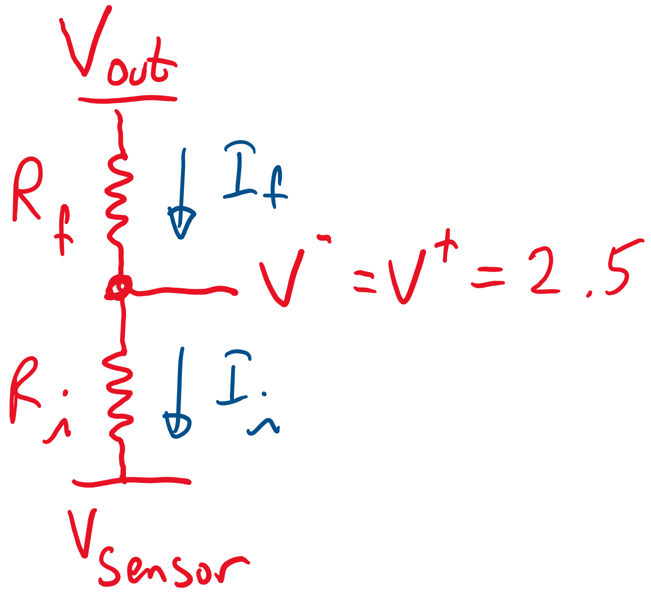
$$\frac{V_{out}}{R_f} = \frac{-V_{sensor}}{R_i} \Rightarrow V_{out} = -\frac{R_f}{R_i} V_{sensor}$$

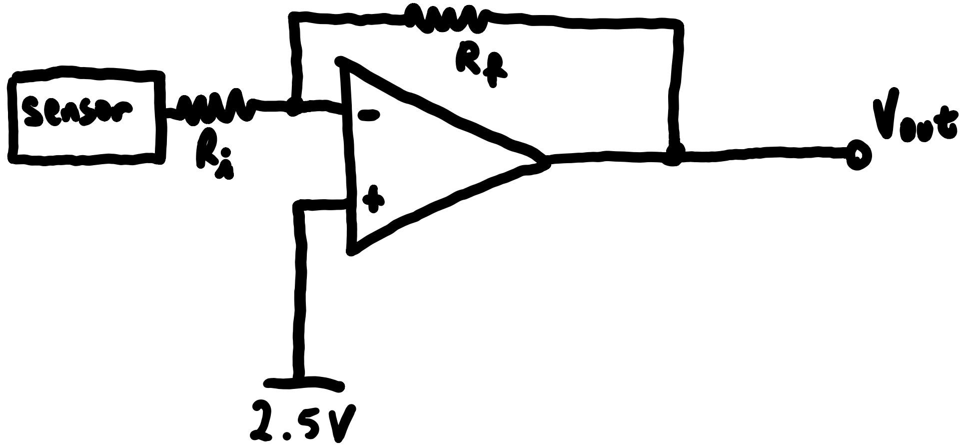
There's nothing magic about ground

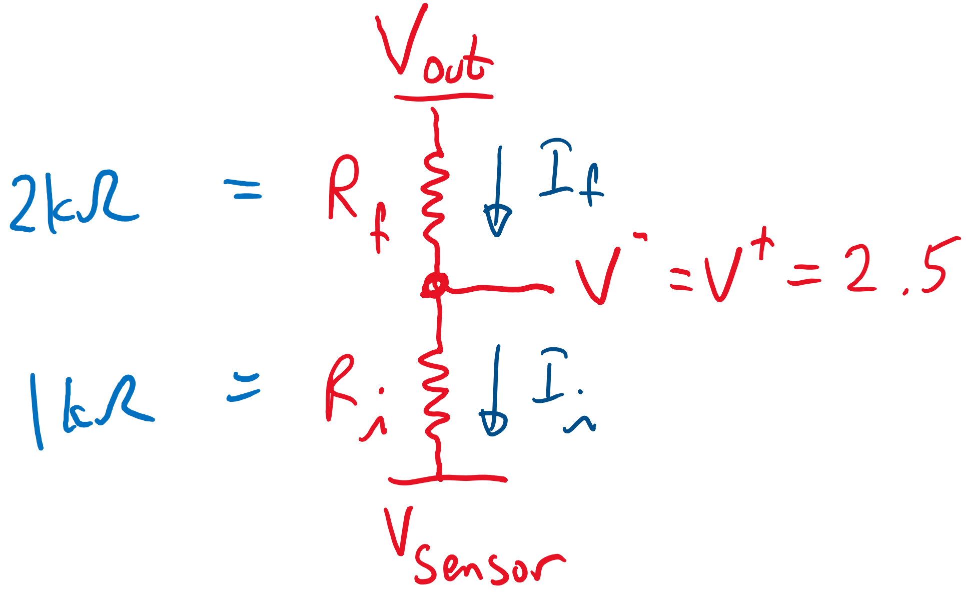


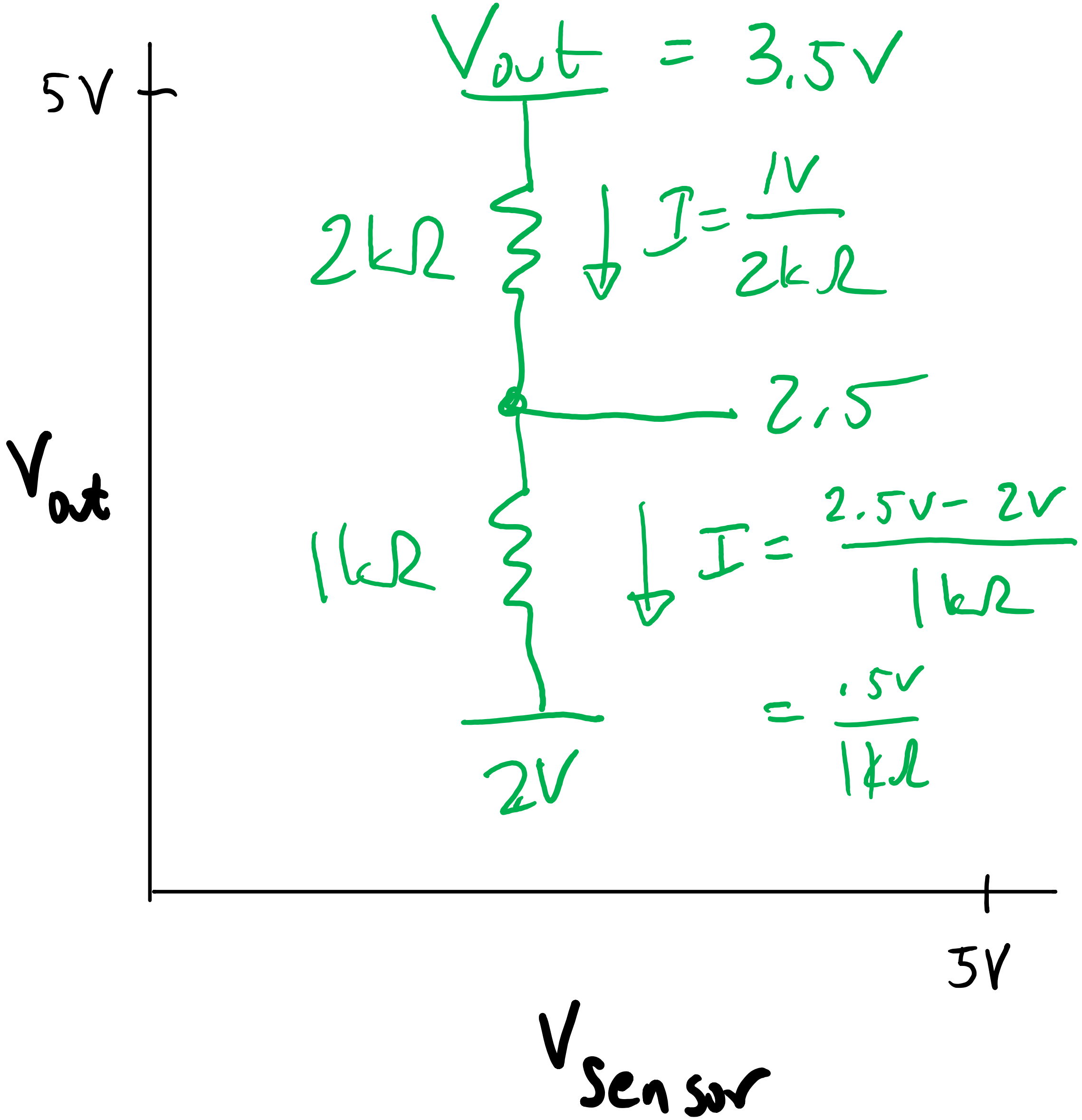
The inverting op-amp circuit

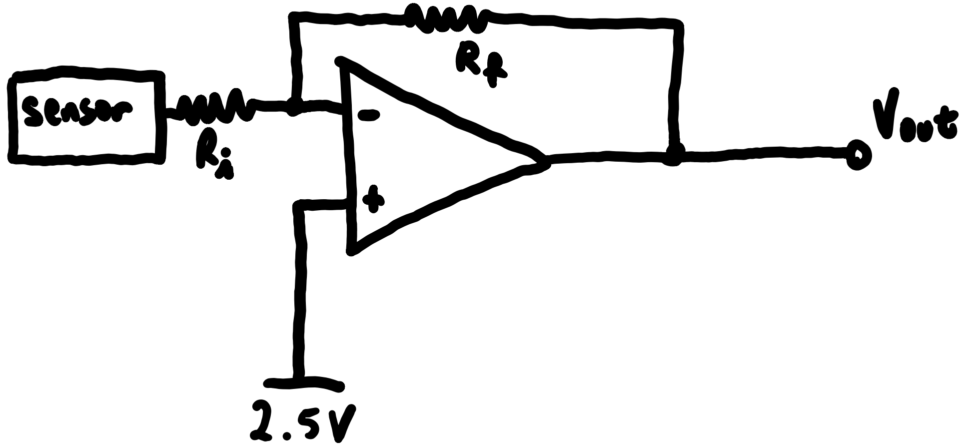


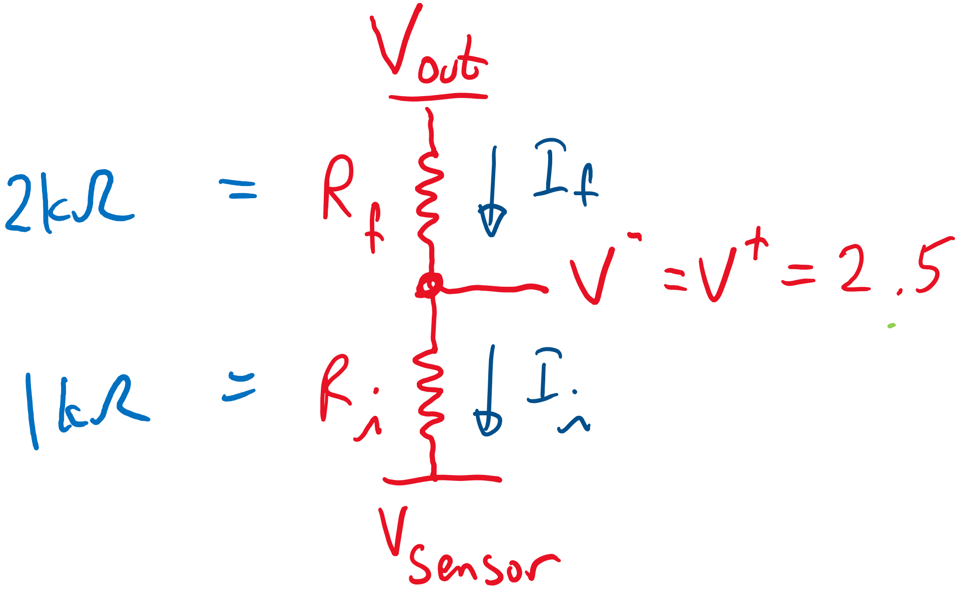


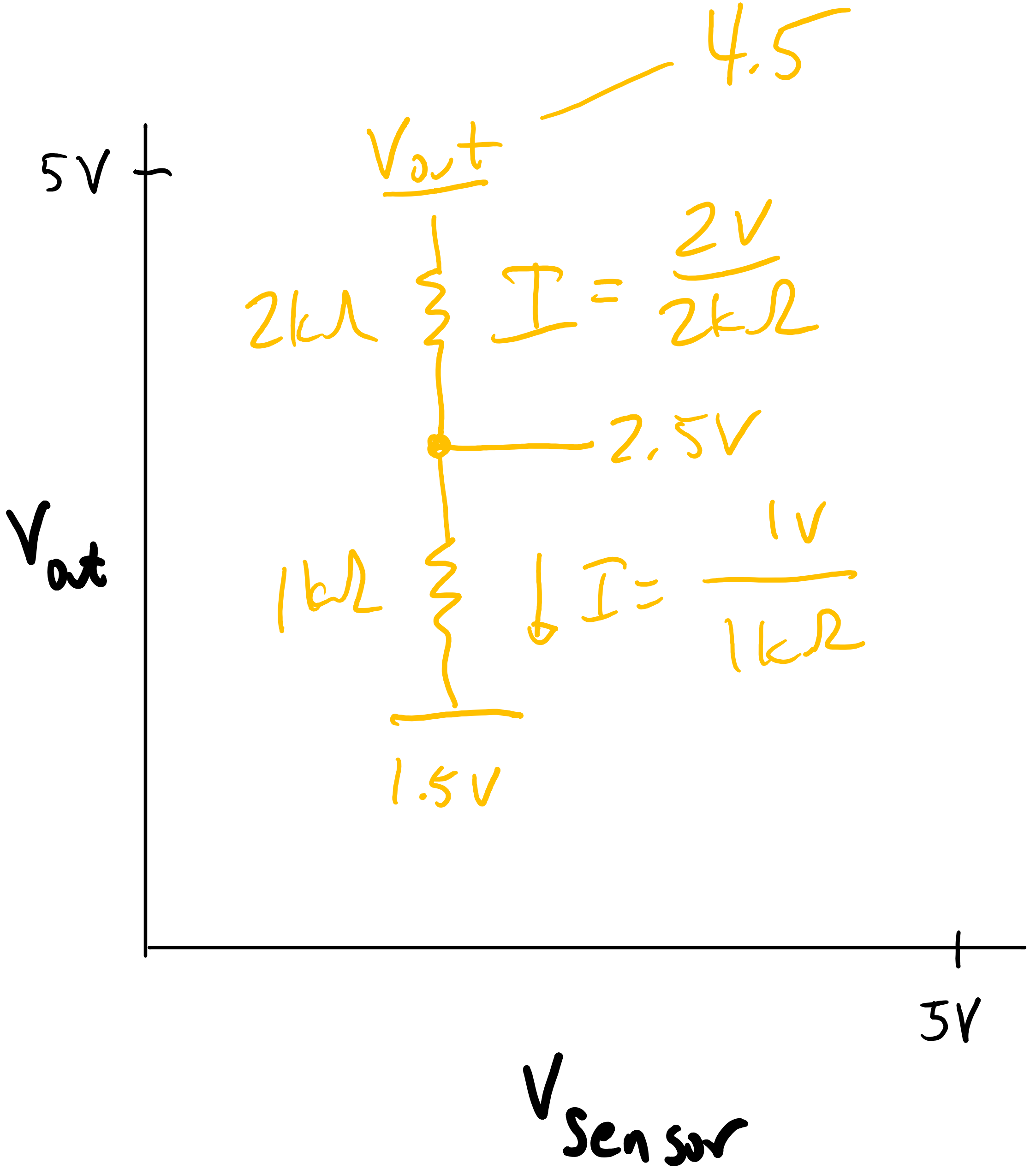

Sensor
R_f
R_i
-
+
V_{out}
2.5V

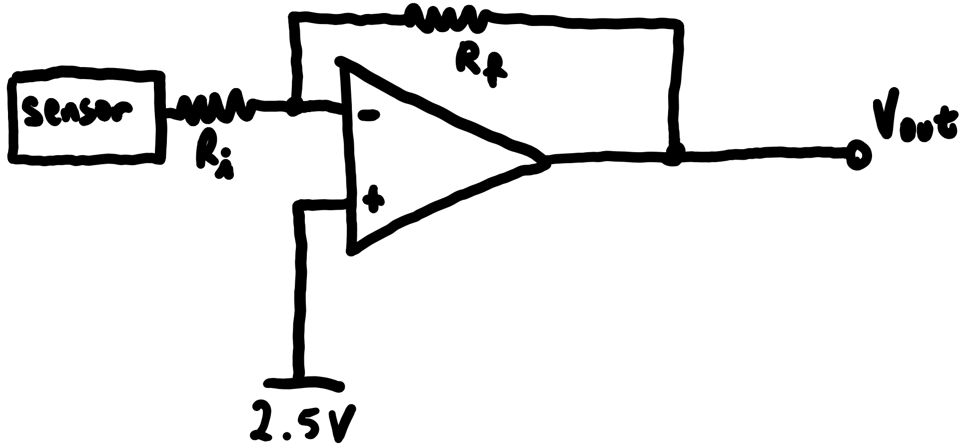

V_{out}
$2k\Omega = R_f$
I_f
$V^- = V^+ = 2.5$
$1k\Omega = R_i$
I_i
V_{sensor}

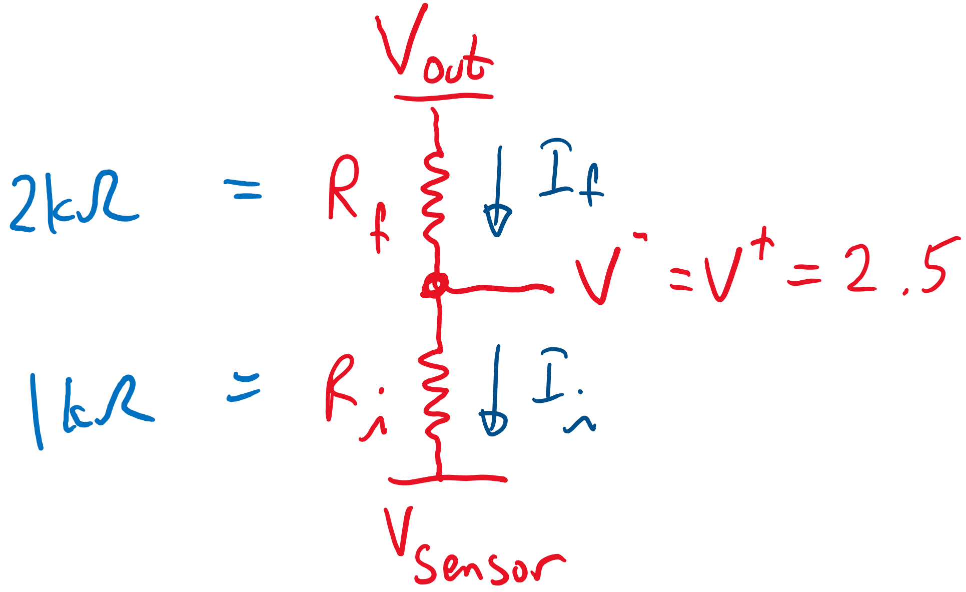

5V
V_{out}
5V
V_{sensor}
$V_{out} = 3.5V$
$2k\Omega$
$I = \frac{1V}{2k\Omega}$
2.5
$1k\Omega$
$I = \frac{2.5V - 2V}{1k\Omega}$
$= \frac{.5V}{1k\Omega}$
2V

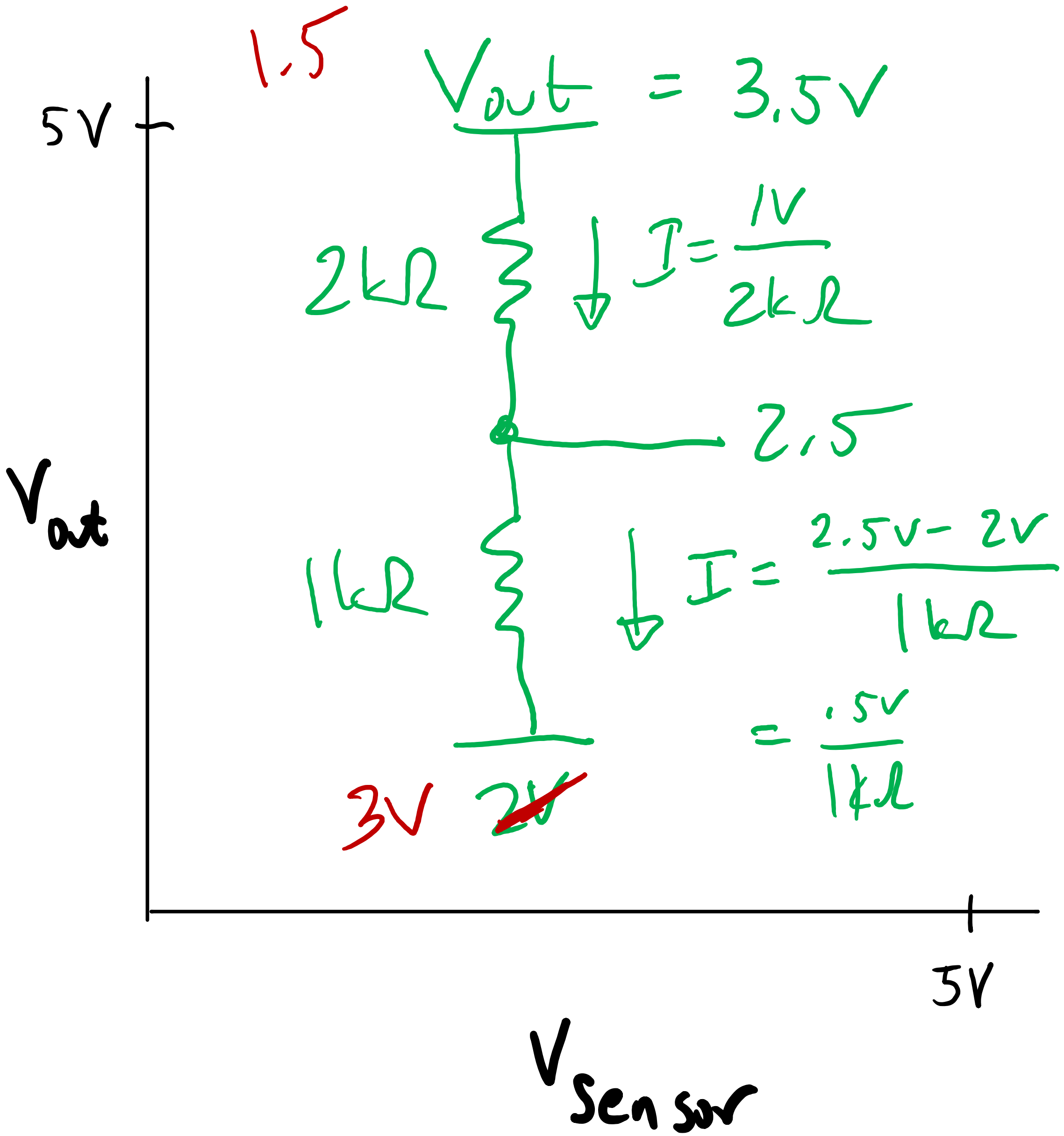

Sensor
R_i
R_f
-
+
V_{out}
2.5V

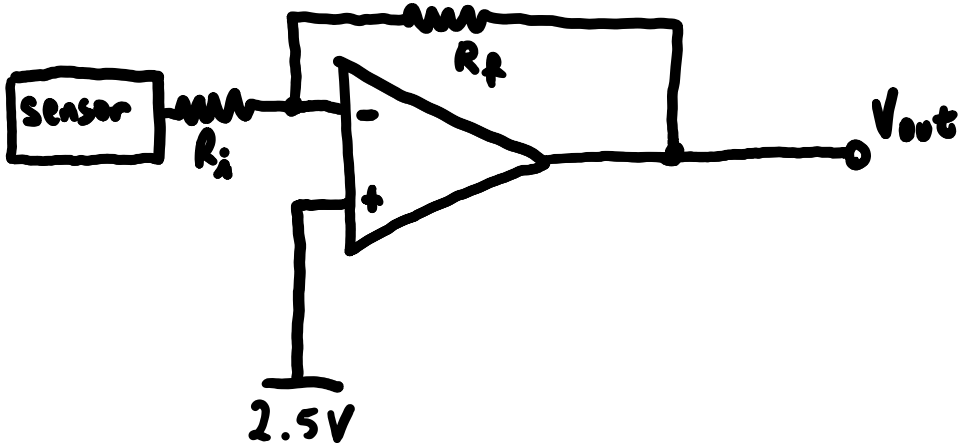

V_{out}
$2k\Omega = R_f$
I_f
$V^- = V^+ = 2.5$
$1k\Omega = R_i$
I_i
V_{sensor}

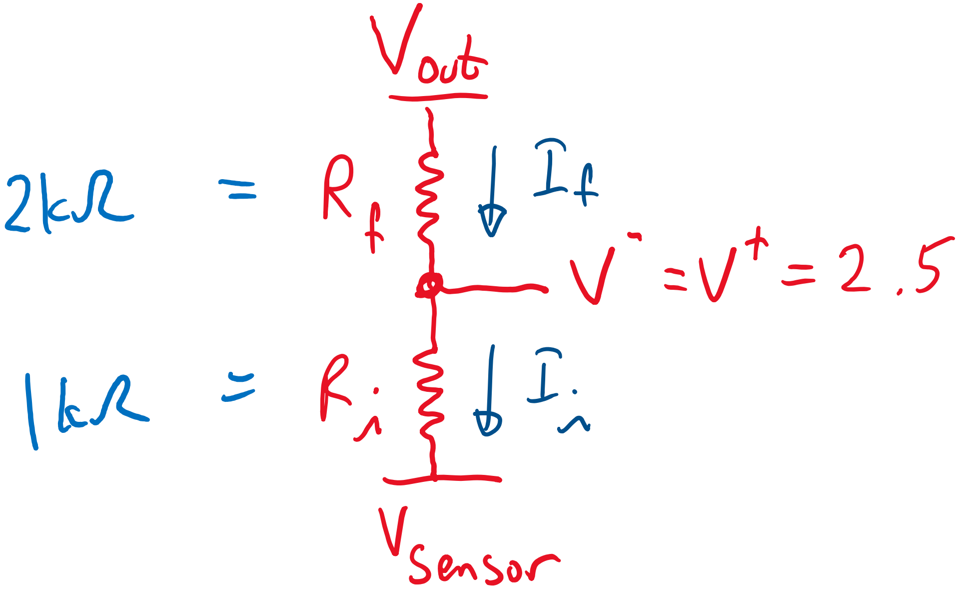

5V
V_{out}
4.5
V_{out}
$2k\Omega$
$I = \frac{2V}{2k\Omega}$
2.5V
$1k\Omega$
$I = \frac{1V}{1k\Omega}$
1.5V
5V
V_{sensor}

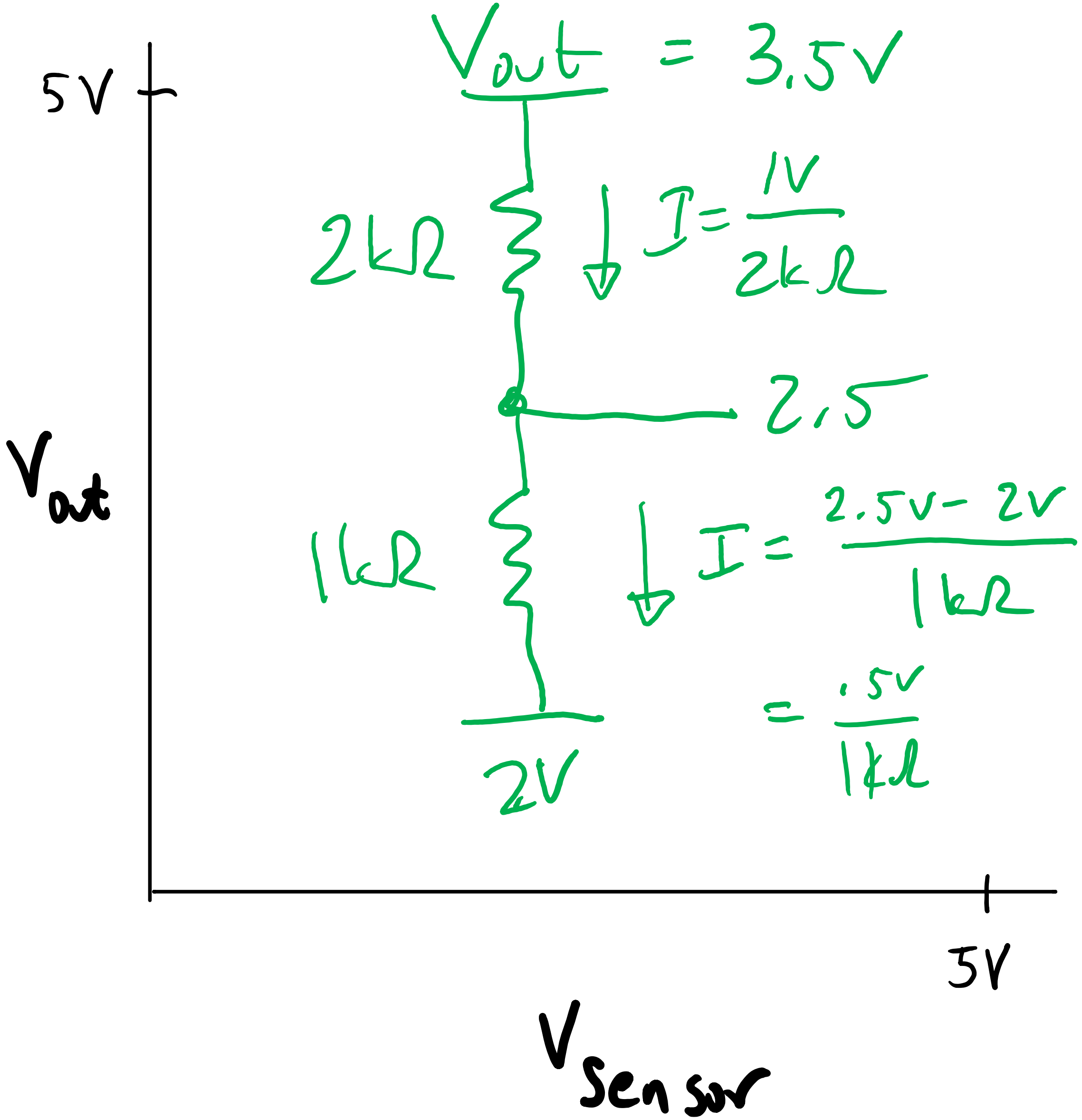

Sensor
R_i
R_f
V_{out}
2.5V

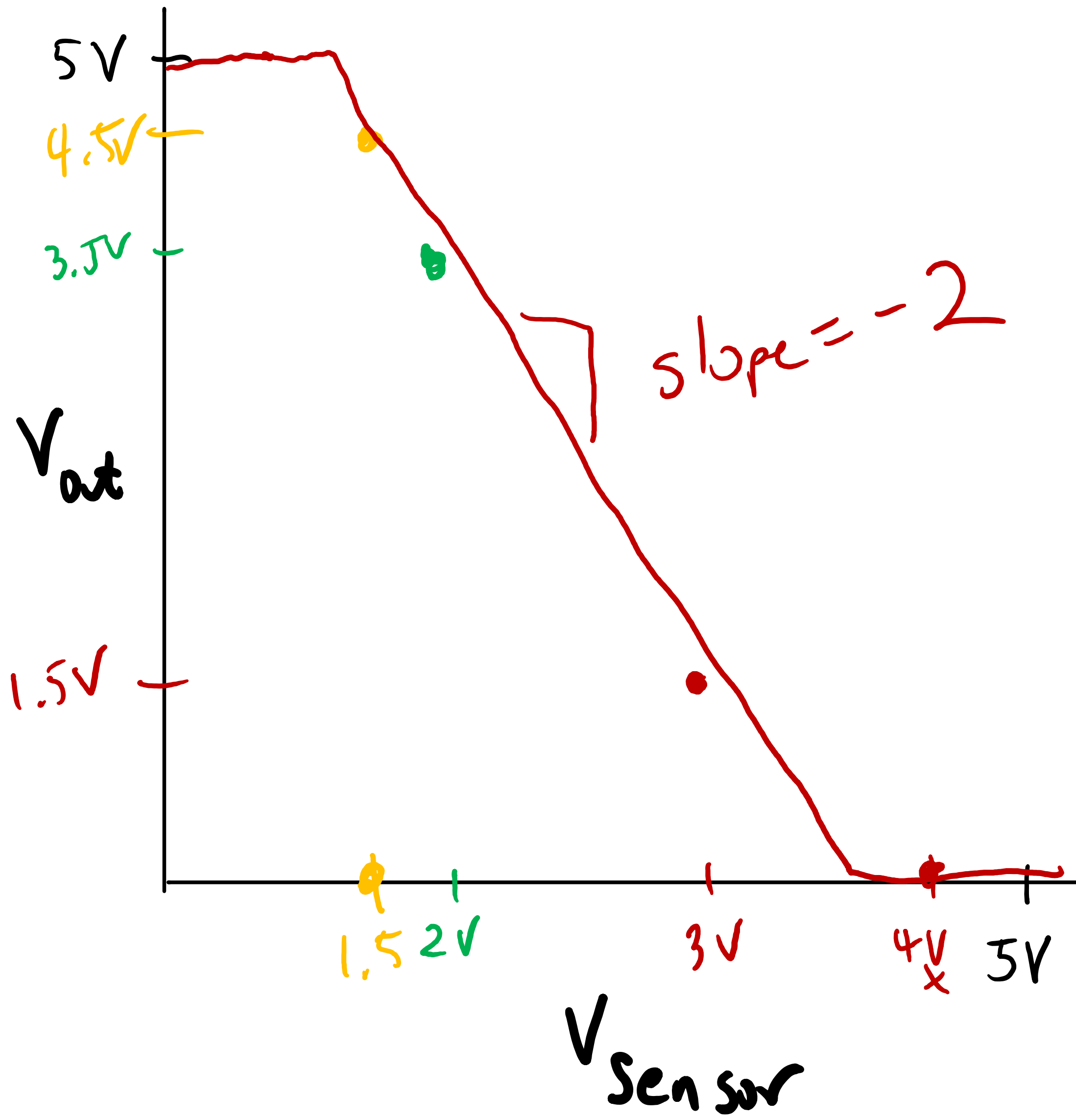

V_{out}
$2k\Omega = R_f$
I_f
$V^- = V^+ = 2.5$
$1k\Omega = R_i$
I_i
V_{sensor}


1.5
$V_{out} = 3.5V$
5V
$2k\Omega$
$I = \frac{1V}{2k\Omega}$
2.5
V_{out}
$1k\Omega$
$I = \frac{2.5V - 2V}{1k\Omega}$
$= \frac{.5V}{1k\Omega}$
3V $\cancel{2V}$
5V
V_{sensor}


Sensor
R_f
R_i
-
+
V_{out}
2.5V


V_{out}
$2k\Omega = R_f$
I_f
$V^- = V^+ = 2.5$
$1k\Omega = R_i$
I_i
V_{sensor}


$V_{out} = 3.5V$
5V
$2k\Omega$
$I = \frac{1V}{2k\Omega}$
2.5
V_{out}
$1k\Omega$
$I = \frac{2.5V - 2V}{1k\Omega}$
$= \frac{.5V}{1k\Omega}$
2V
5V
V_{sensor}



5V
4.5V
3.5V
1.5V
V_{out}
slope = -2
1.5
2V
3V
4V
5V
V_{sensor}