PURDUE UNIVERSITY DEPARTMENT OF PHYSICS

Physics 53600

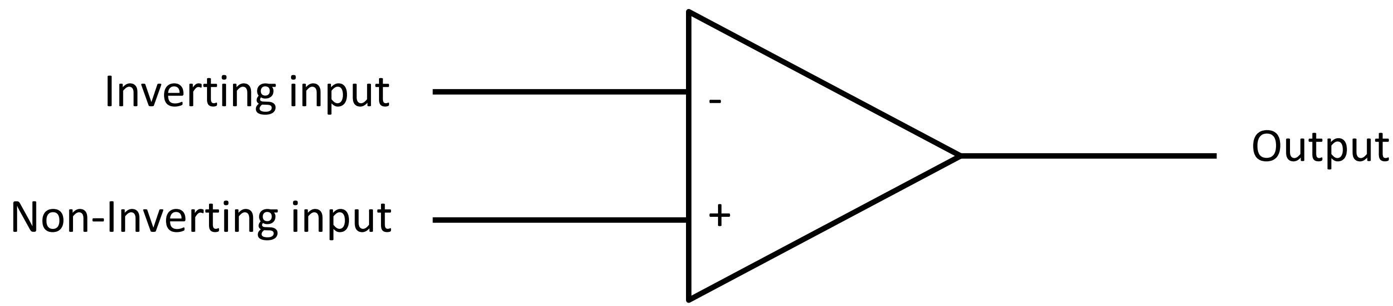
Electronics Techniques for Research

Now in PowerPoint!

Spring 2020 Semester

Prof. Matthew Jones

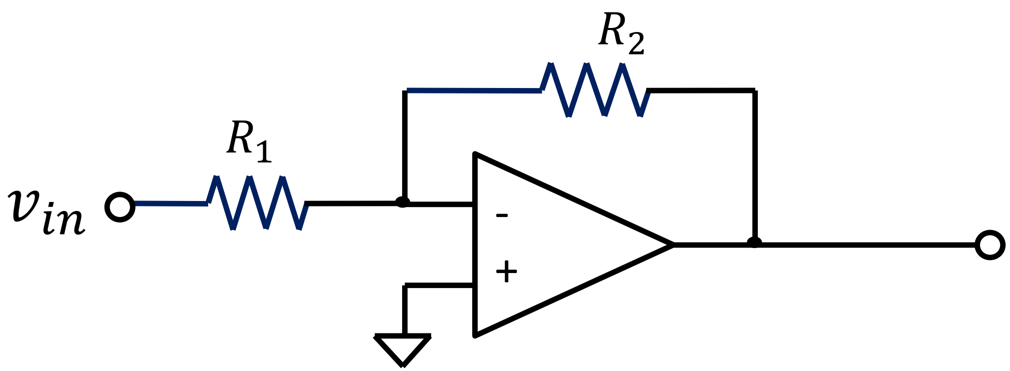
Operational Amplifiers



- Basic equation: $v_{out} = A_0(v_+ - v_-), A_0 \gg 1$
- Simplified design rules:
  1. Inputs draw negligible current
  2. Output produces whatever voltage will make $v_+ = v_-$
- Negative feedback:
  – Reduces intrinsic gain
  – Increases bandwidth

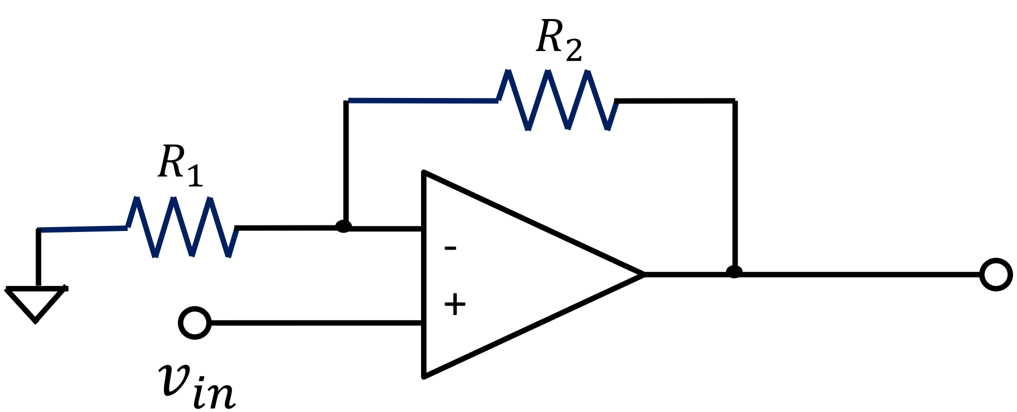
Operational Amplifiers

- Inverting amplifier:



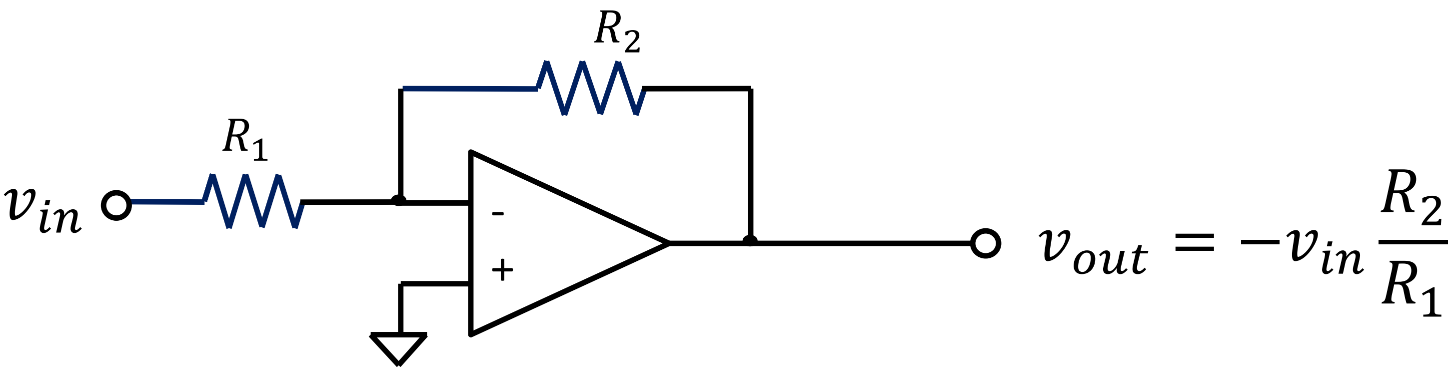
$$v_{out} = -v_{in}\frac{R_2}{R_1}$$

- Non-inverting amplifier:



$$v_{out} = v_{in}\left(1 + \frac{R_2}{R_1}\right)$$

Operational Amplifiers



- Input impedance:

$$v_{-} = 0 \text{ so } i_{R_1} = v_{in}/R_1$$

Input impedance is just R_1

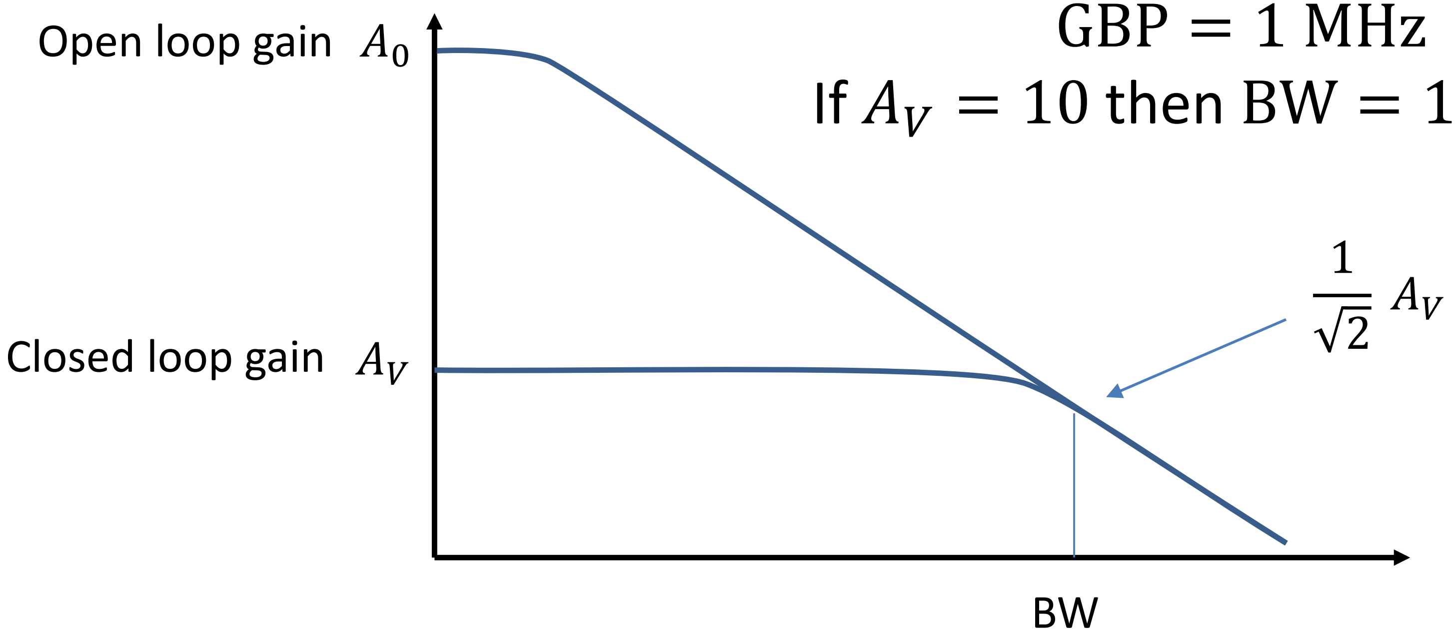
- Output impedance depends on the device in question. It also depends on the gain and the frequency.

Operational Amplifiers

- For low frequencies,

$$R_{out} \lesssim 100\ \Omega$$

- This is dynamically adjusted by the feedback loop
- Frequency response:

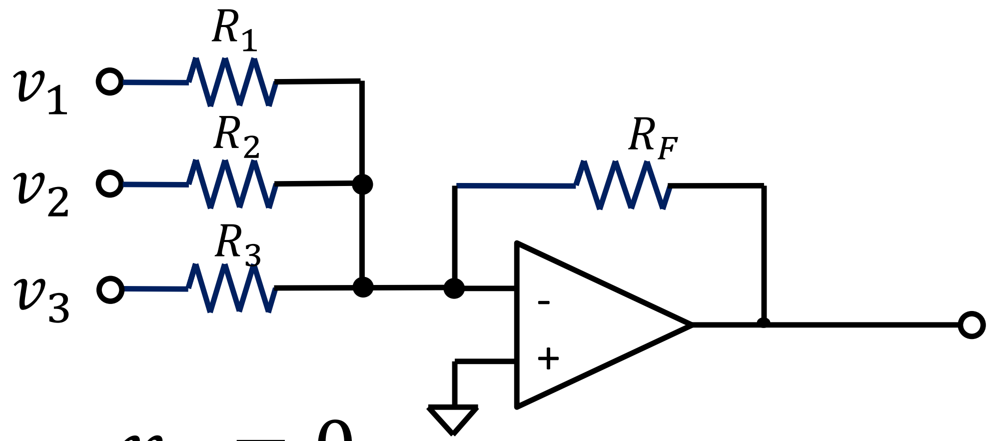


$$\mathrm{GBP} = 1\ \mathrm{MHz}$$

If $A_V = 10$ then $\mathrm{BW} = 100\ \mathrm{kHz}$

Operational Amplifiers

- Summing amplifier:



$$v_+ = 0$$
$$v_- = 0$$

- No current flows into the inverting input.

$$v_{out} = -(i_1 + i_2 + i_3)R_F$$
$$= -R_F\left(\frac{v_1}{R_1} + \frac{v_2}{R_2} + \frac{v_3}{R_3}\right)$$

Operational Amplifiers

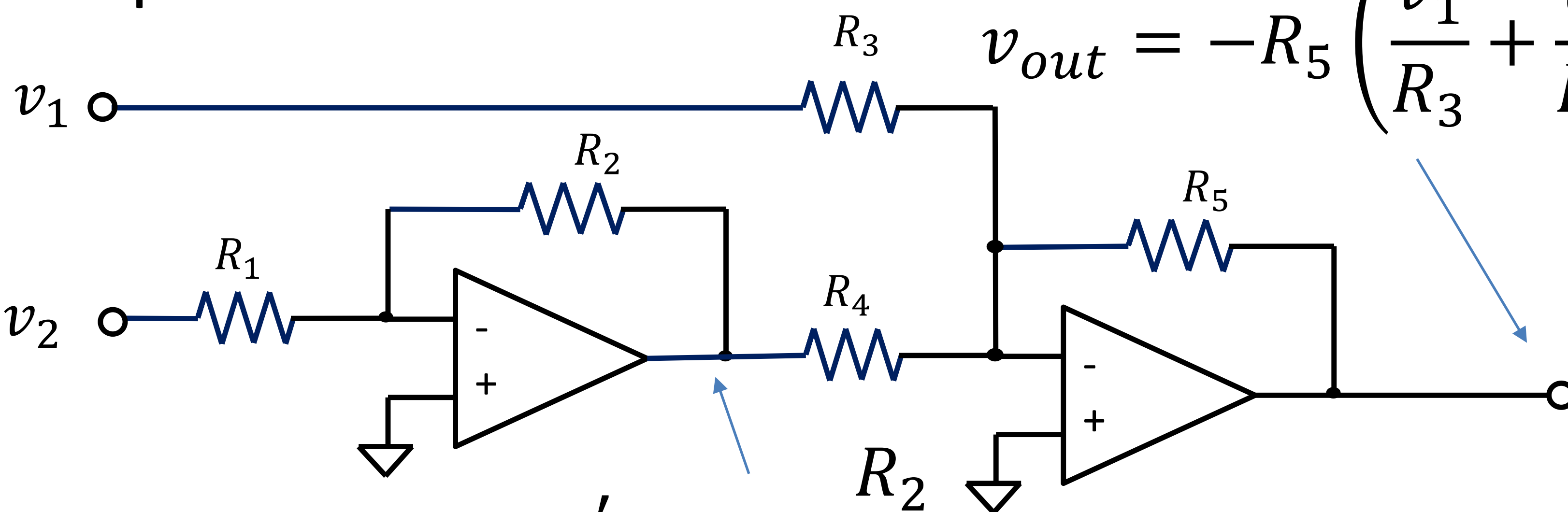
- If $R_1 = R_2 = R_3 \equiv R$ then

$$v_{out} = -\frac{R_F}{R}(v_1 + v_2 + v_3)$$

- If R_1, R_2, R_3 are large compared with the output impedance of any non-ideal voltage sources attached to v_1, v_2, v_3 then this will be a good approximation.

Subtracting Amplifier

- Connect an inverting amplifier to a summing amplifier:



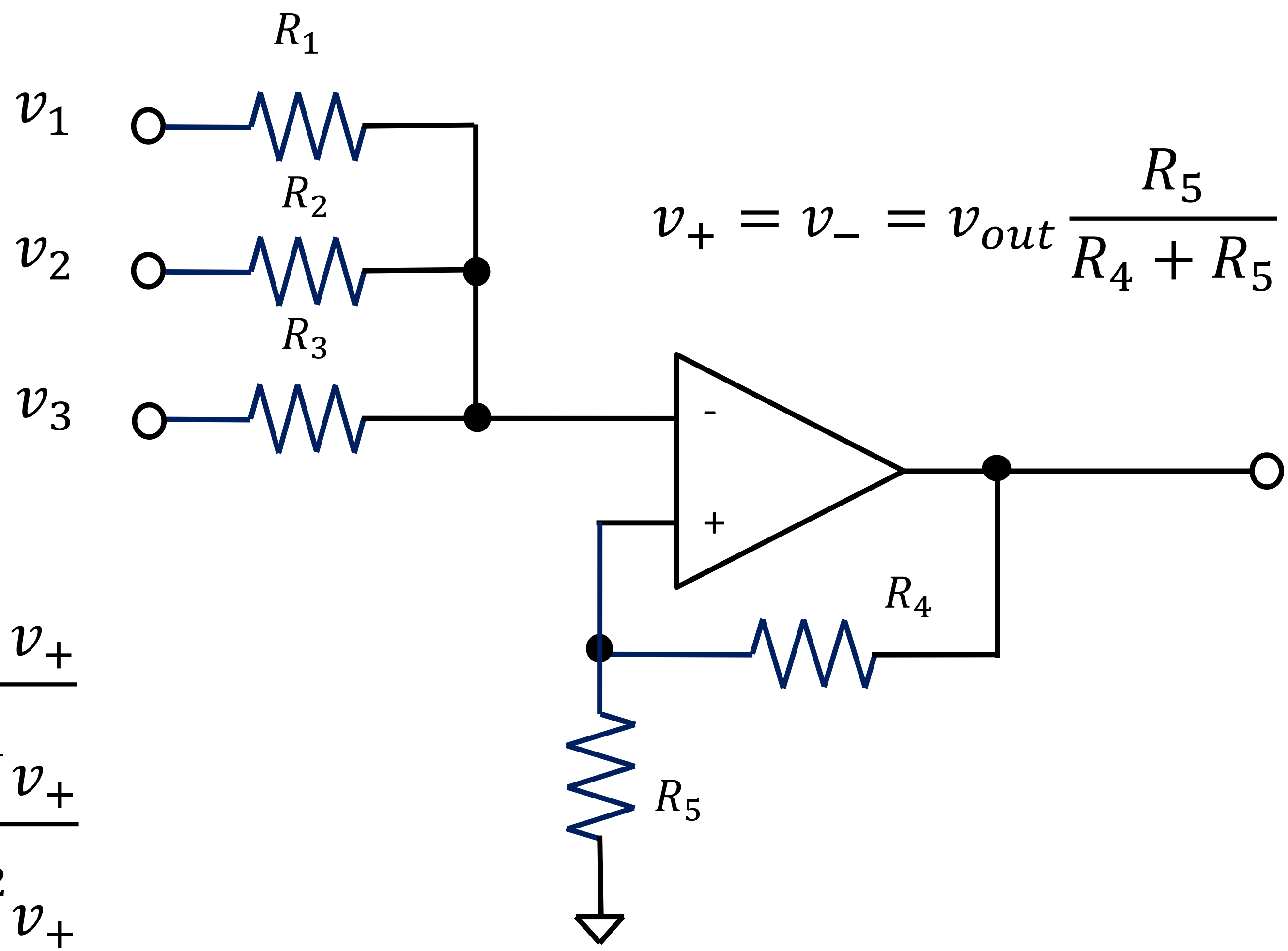
$$v_{out} = -R_5\left(\frac{v_1}{R_3} + \frac{v_2'}{R_4}\right)$$

$$v_2' = -v_2\frac{R_2}{R_1}$$

- If $R_1 = R_2$ and $R_3 = R_4$ then

$$v_{out} = -\frac{R_5}{R_3}(v_1 - v_2)$$

Non-inverting Summing Amplifier



$$v_+ = v_- = v_{out} \frac{R_5}{R_4 + R_5}$$

$$i_1 = \frac{v_1 - v_+}{R_1}$$

$$i_2 = \frac{v_2 - v_+}{R_2}$$

$$i_3 = \frac{v_3 - v_+}{R_3}$$

$$i_1 + i_2 + i_3 = 0$$

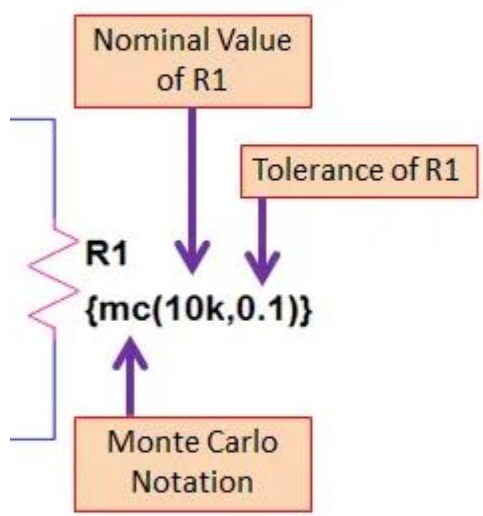
If $R_1 = R_2 = R_3$ and $R_4 = 2R_5$
then $v_{out} = v_1 + v_2 + v_3$

Sensitivity Analysis

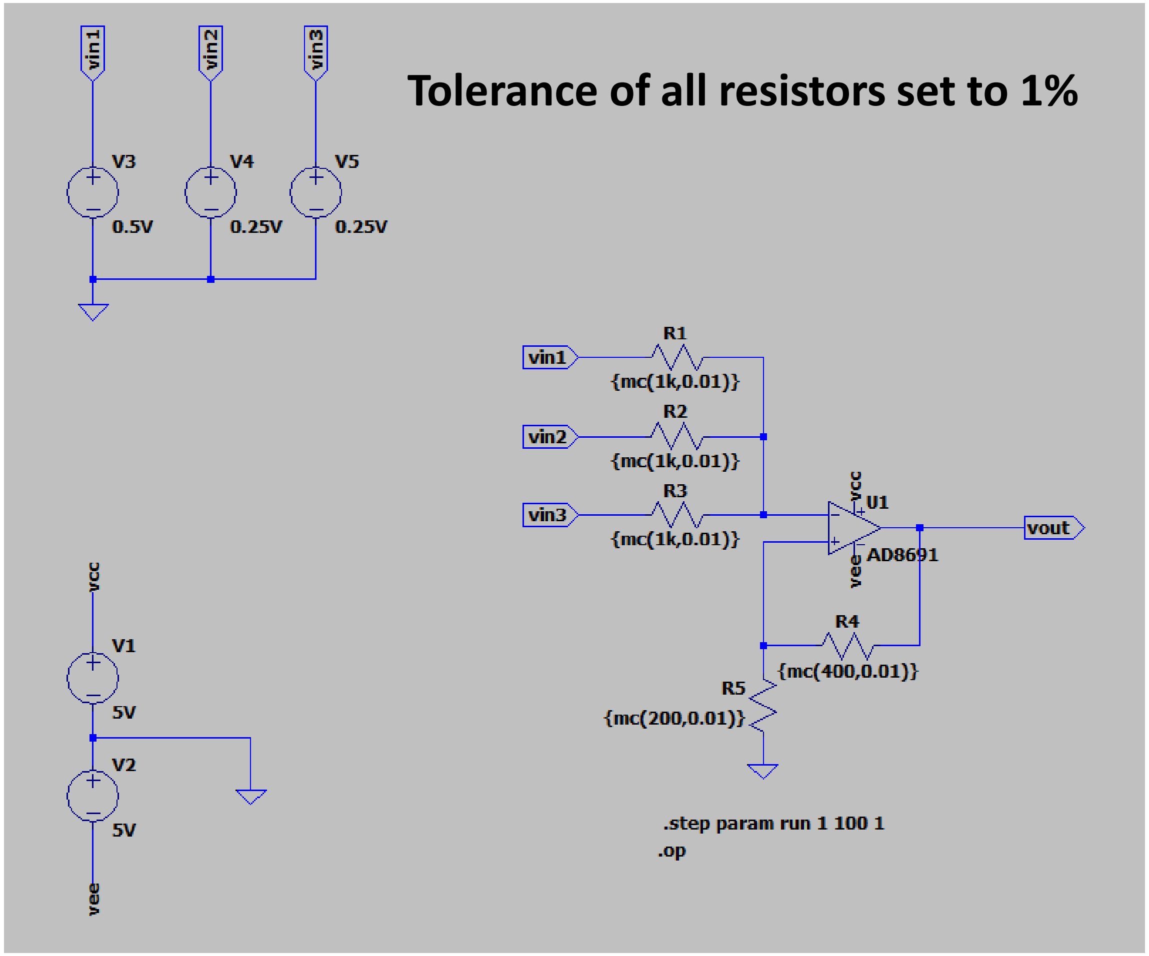
- Remember that resistors have finite tolerance
  (eg, 5%, 1%, 0.1%)
- How sensitive is the output to their values?
- Repeat the DC operating point analysis with randomly sampled resistor values
- In LTspice, one can specify the random tolerance of resistors using {mc(R,tolerance)}:
- Spice directive:

  .step param run 1 100 1

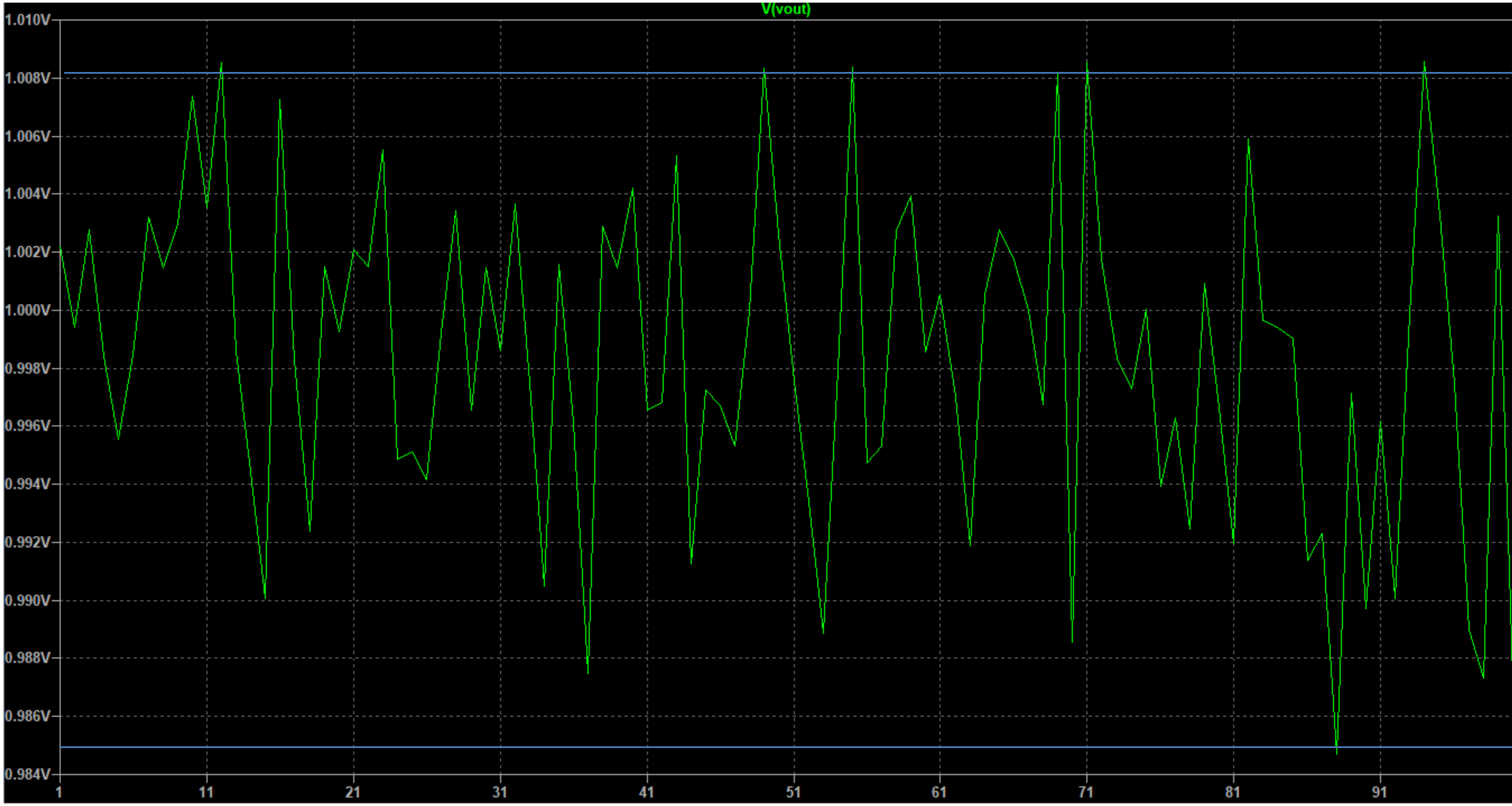
  (runs 100 iterations)



Sensitivity Analysis



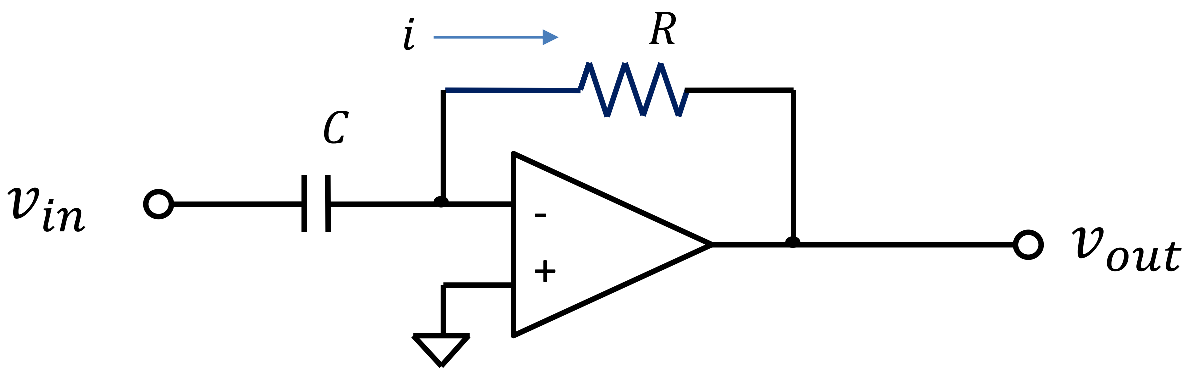
Sensitivity Analysis



Worst case scenarios: $0.985\ V < v_{out} < 1.008\ V$ (2.3% variation)

More Op-Amp Circuits

- Differentiator:



$$v_+ = 0$$
$$v_- = 0$$

- But $v_{out} = -iR$ where i is the current that flows through the capacitor.

Differentiator

$$v_{in} = -\frac{1}{C}\left(Q_0 + \int_0^t i(t)dt\right) = 0$$

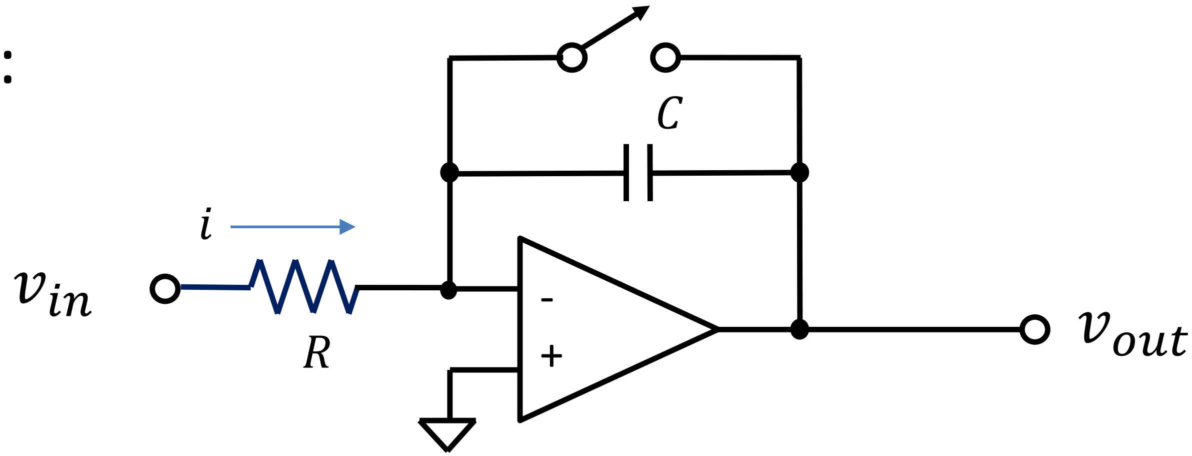
$$v_{in} = -\frac{1}{C}\left(Q_0 - \frac{1}{R}\int_0^t v_{out}(t)dt\right) = 0$$

$$\frac{dv_{in}}{dt} + \frac{1}{RC}v_{out}(t) = 0$$

$$v_{out}(t) = -RC\frac{dv_{in}}{dt}$$

More Op-Amp Circuits

- Integrator:



- Open switch at $t = 0$ so that $Q_0 = 0$

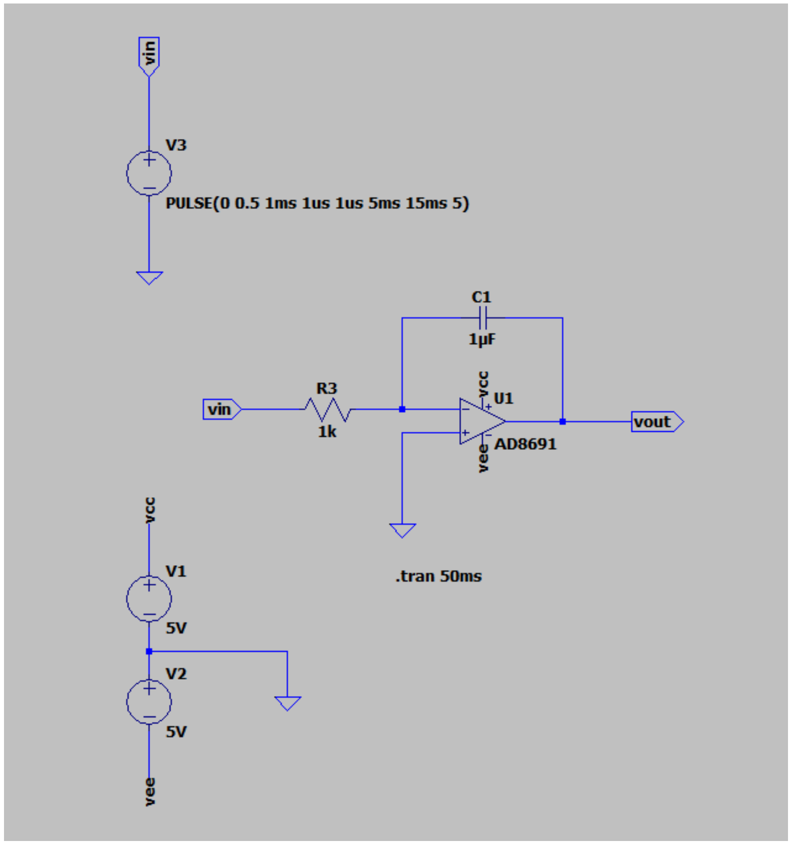
$$v_+ = v_- = 0$$

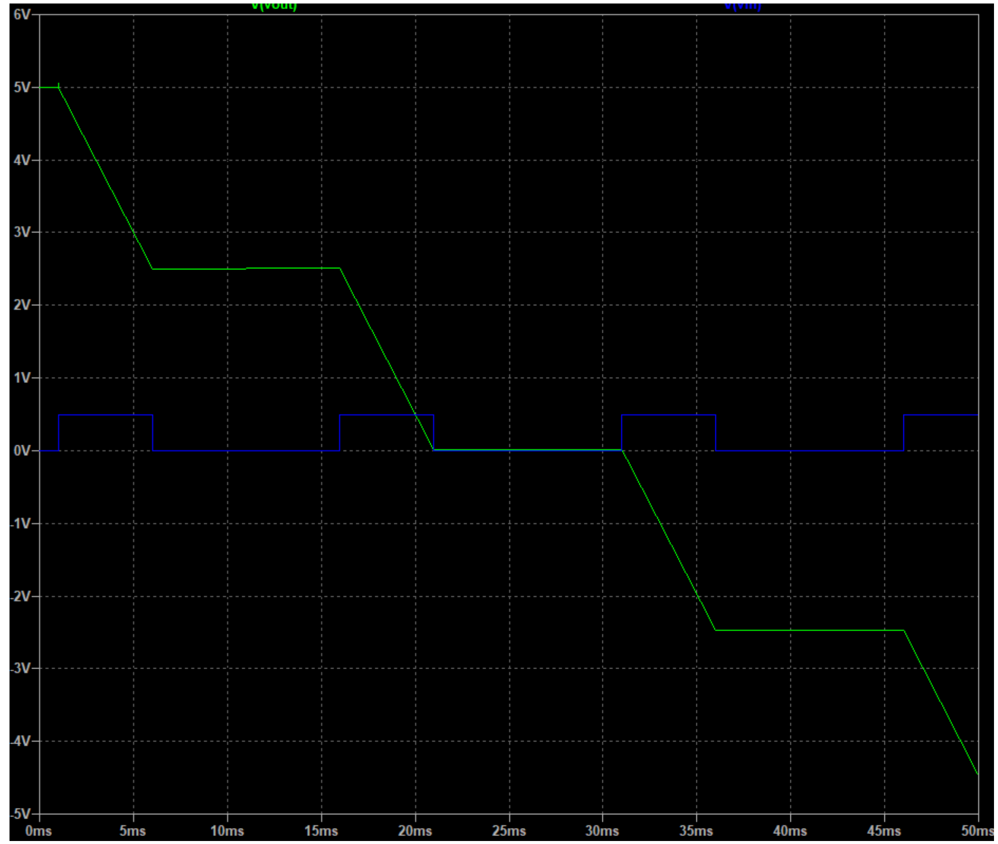
$$i(t) = \frac{v_{in}(t)}{R}$$

$$-\frac{1}{C}\int_0^t i(t)dt = v_{out}$$

$$v_{out}(t) = -\frac{1}{RC}\int_0^t v_{in}(t)dt$$

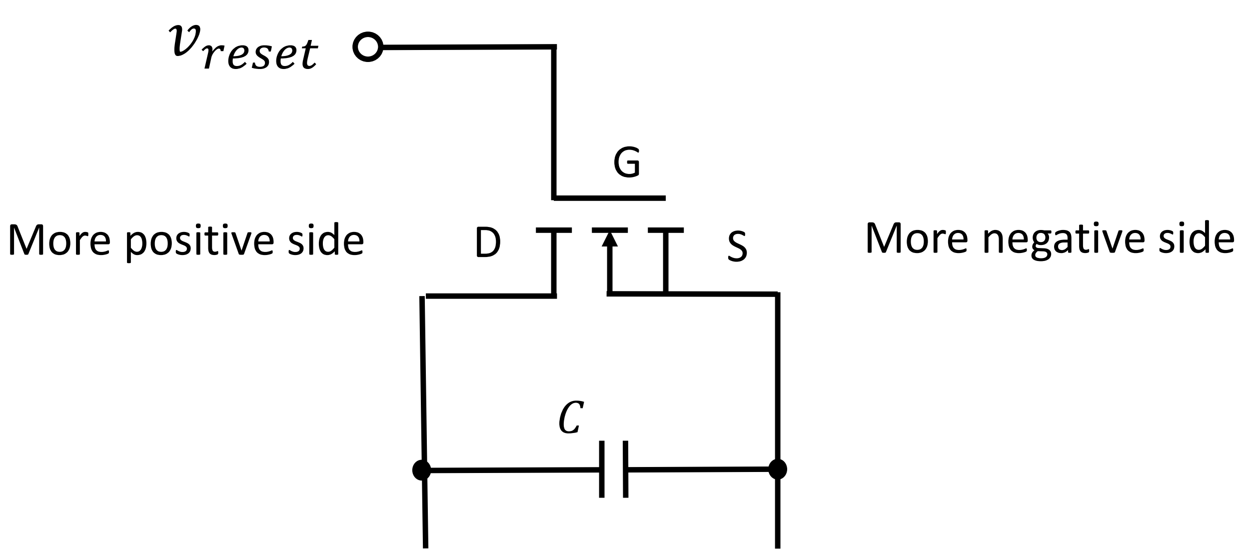
Example


vin
V3
PULSE(0 0.5 1ms 1us 1us 5ms 15ms 5)
C1
1µF
vin
R3
1k
vcc
U1
AD8691
vee
vout
.tran 50ms
vcc
V1
5V
V2
5V
vee

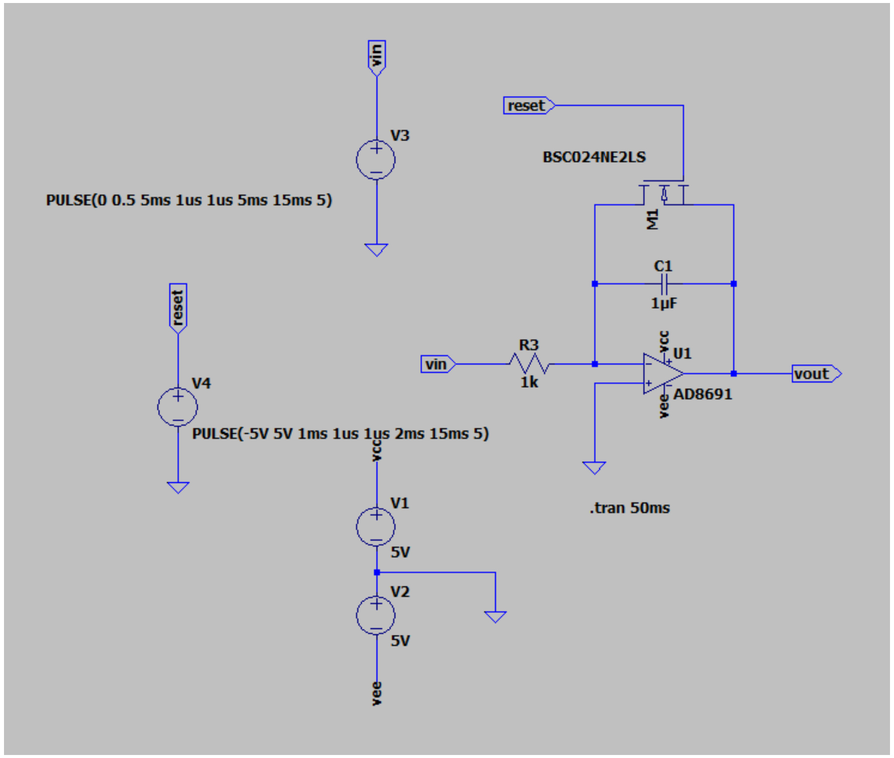

6V
5V
4V
3V
2V
1V
0V
-1V
-2V
-3V
-4V
-5V
0ms
5ms
10ms
15ms
20ms
25ms
30ms
35ms
40ms
45ms
50ms

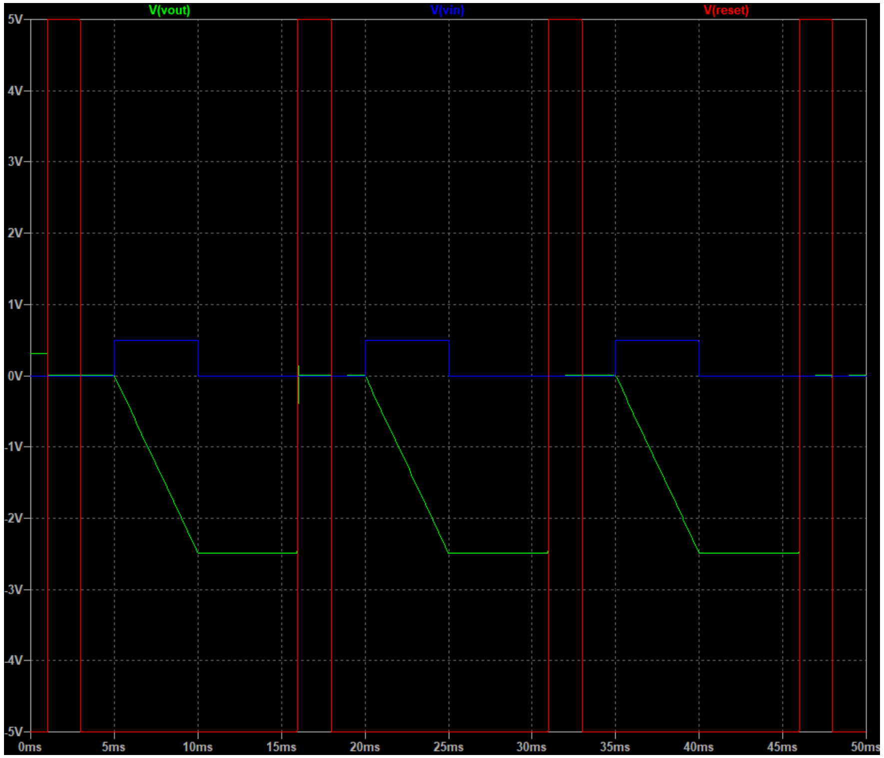
Integrator

- A problem with an integrator is that a mechanical switch can be impractical
- Instead, one can use an n-channel MOSFET



Integrator

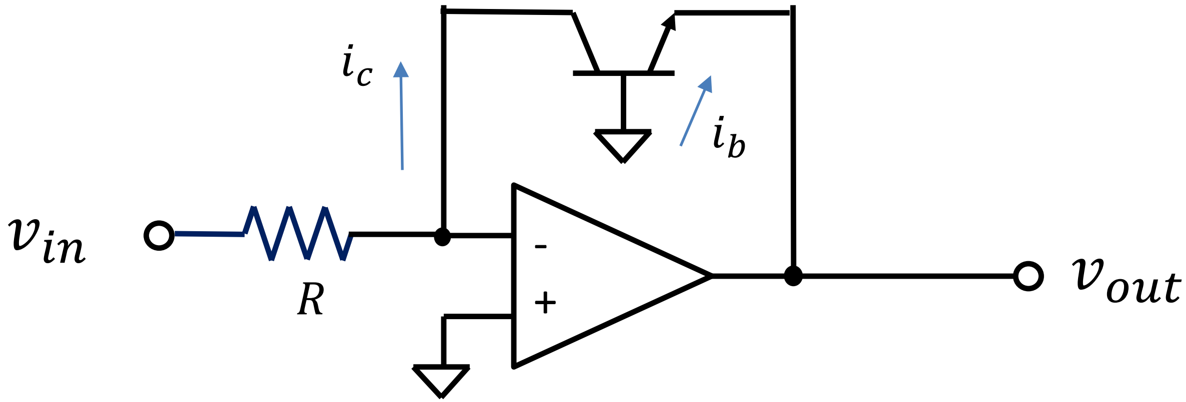




One annoying feature about MOSFET's is that the gate voltage is not compatible with most digital interfaces which range from 0 to 2.5, 3.3V or 5V.

Other Clever Circuits

- Logarithmic amplifier:



- Shockley equation:

$$i_b = I_0\left(e^{eV_{be}/kT} - 1\right)$$

$$i_c = \frac{\beta}{\beta + 1} i_b = \alpha i_b$$

Logarithmic Amplifier

$$i_b = I_0\left(e^{eV_{be}/kT} - 1\right) \approx I_0 e^{eV_{be}/kT}$$

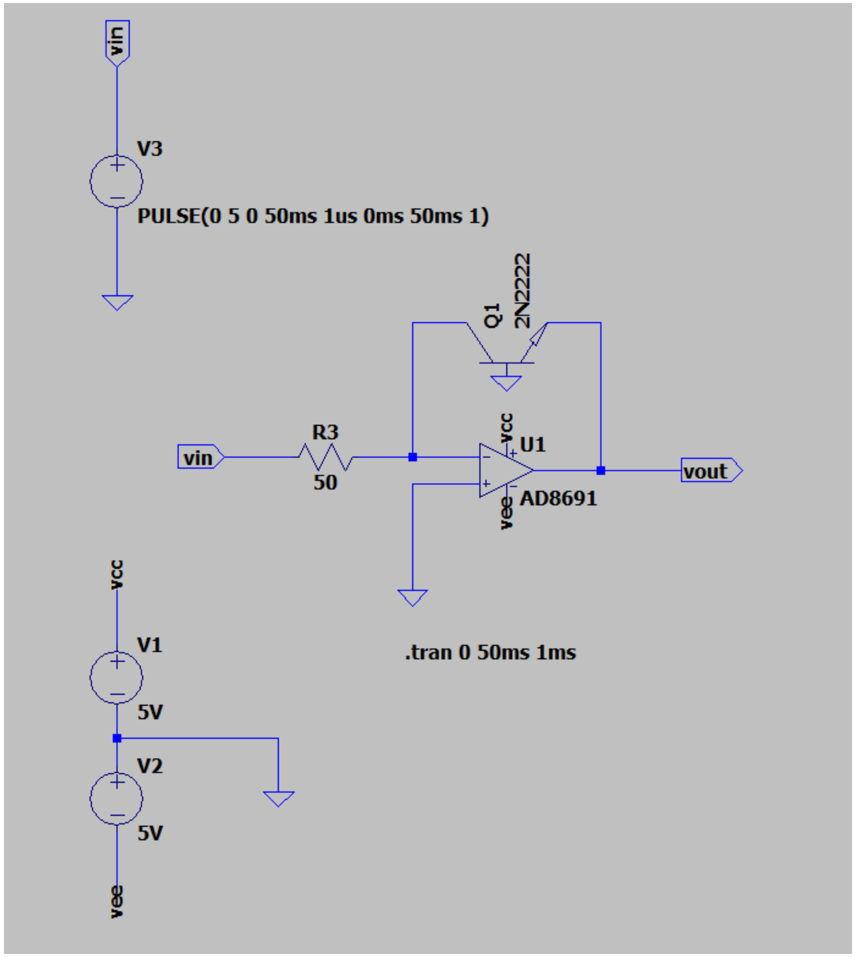
$$i_c = \frac{\beta}{\beta + 1} i_b = \alpha i_b$$

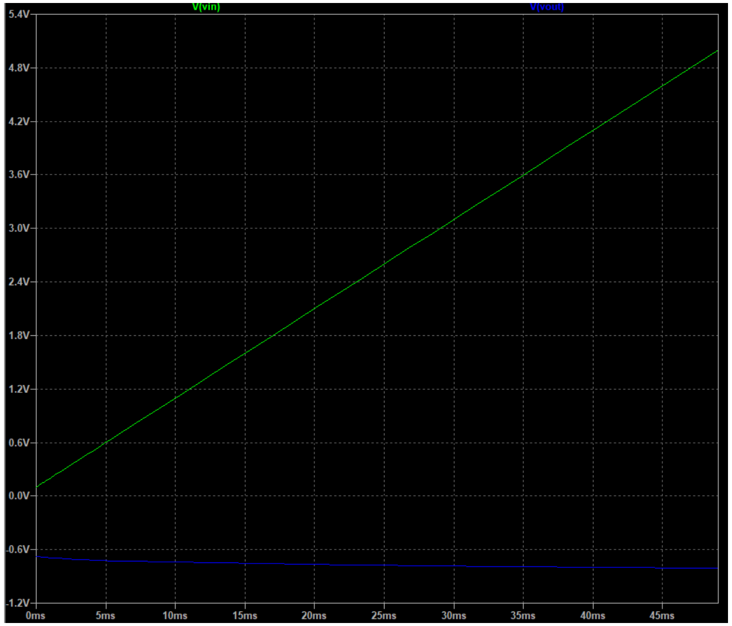
- But $V_{be} = v_{out}$
- All the collector current must flow through the resistor

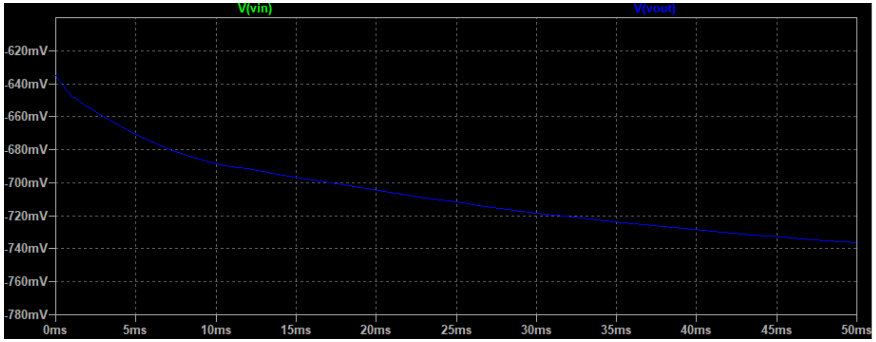
$$\frac{v_{in}}{R} = \alpha I_0 e^{ev_{out}/kT}$$

$$v_{out} = -\frac{kT}{e}\log\left(\frac{v_{in}}{\alpha I_0 R}\right)$$

Logarithmic Amplifier







The dynamic range is somewhat limited and there is a significant voltage offset. These can be addressed by adding a summing amplifier as a second stage.