Electrical Engineering
Week 6

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EECE–2210
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Oct 2021

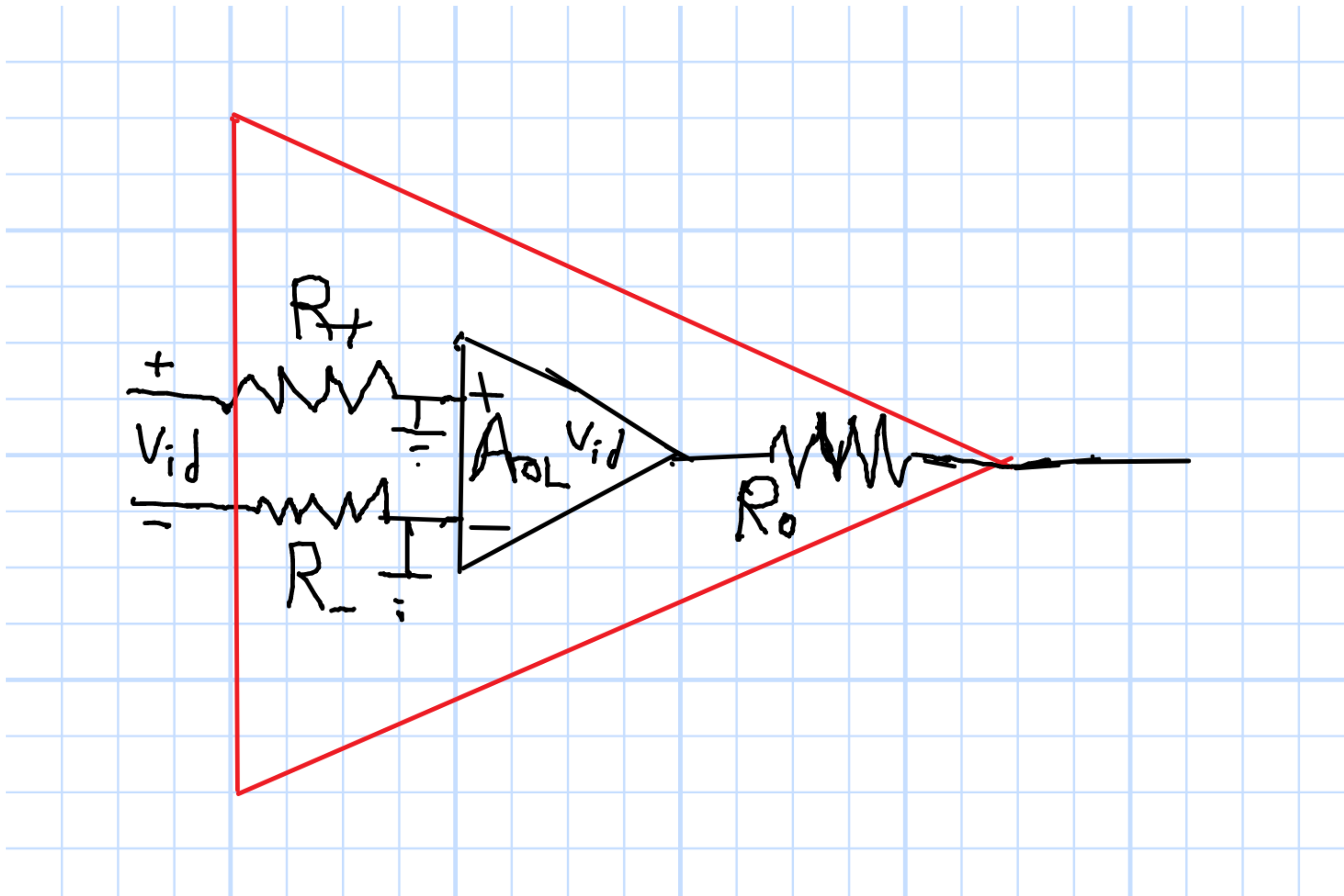
Week 6 Agenda: Operational Amplifiers

- Linear Effects
  - Input and Output Impedances
  - Finite Gain, A_{OL}
  - Gain–Bandwidth Product
- Nonlinear Effects
  - Voltage Limit
  - Current Limit
  - Slew Rate
- DC Imperfections
  - Bias and Offset Currents
  - Offset Voltage
- Differential Amplifiers

The Story so Far

- Assume Ideal Linear Operation
  - $v_{id} = 0$, $v_+ = v_-$ (Virtual short/virtual ground)
  - $i_+ = 0$ and $i_- = 0$
  - Calculate v_o to make this happen
  - Solve for any other variable
- Check Validity of Assumptions
  - v_o Is Between the Rails
  - Currents and Voltages Are “Large Enough”
  - More on that this Week

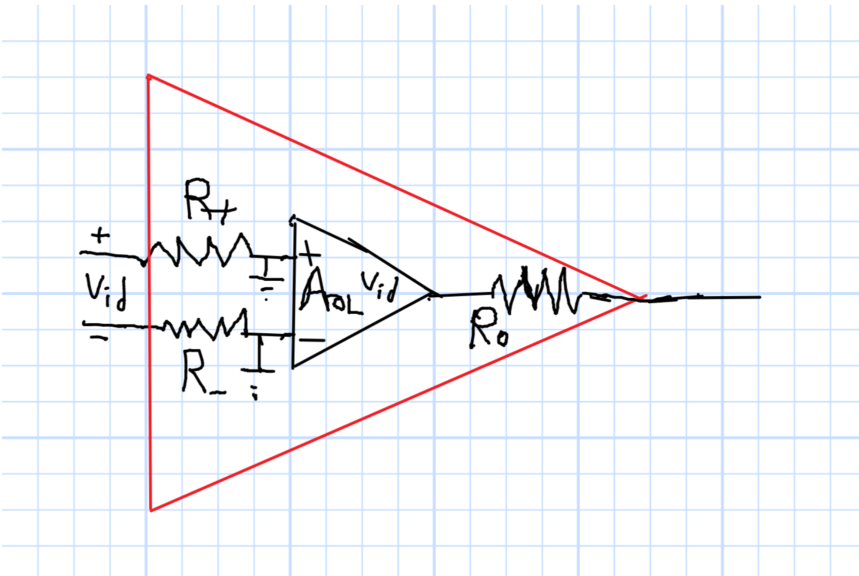
Op–Amp Impedances

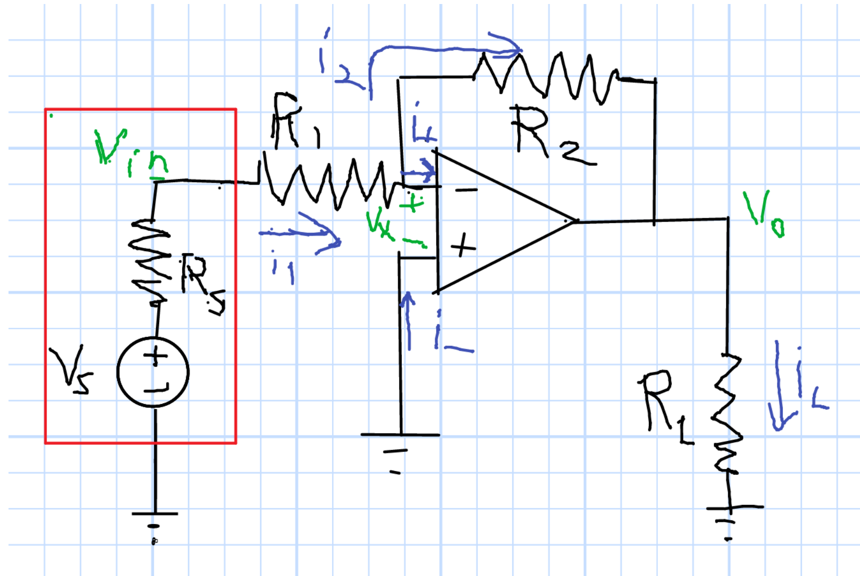


$R_+ \rightarrow \infty$ $R_- \rightarrow \infty$ $R_0 \approx 0$

Usually OK

Impedances in a Circuit





$R_+ \to \infty$

$R_- \to \infty$

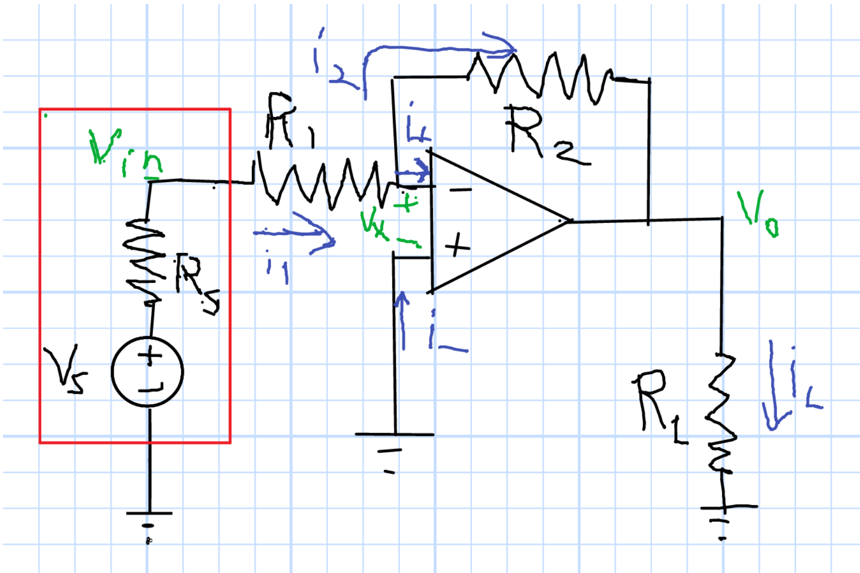
$R_0 \approx 0$

$i_1 \approx i_2$

$$A = -\frac{R_2}{R_1}$$

v_o independent of R_L

Finite Gain Effects (1)



$$v_o = A_{OL}\left(v_+ - v_-\right)$$

$$v_+ = 0$$

$$v_- = -\frac{v_o}{A_{OL}}$$

Virtual Ground Fails.

$$v_- = v_{in} + (v_o - v_{in})\frac{R_1}{R_1 + R_2}$$

$$-\frac{v_o}{A_{OL}} = v_{in} + (v_o - v_{in})\frac{R_1}{R_1 + R_2}$$

$$-\frac{v_o}{A_{OL}} - v_o\frac{R_1}{R_1 + R_2} = v_{in}\frac{R_2}{R_1 + R_2}$$

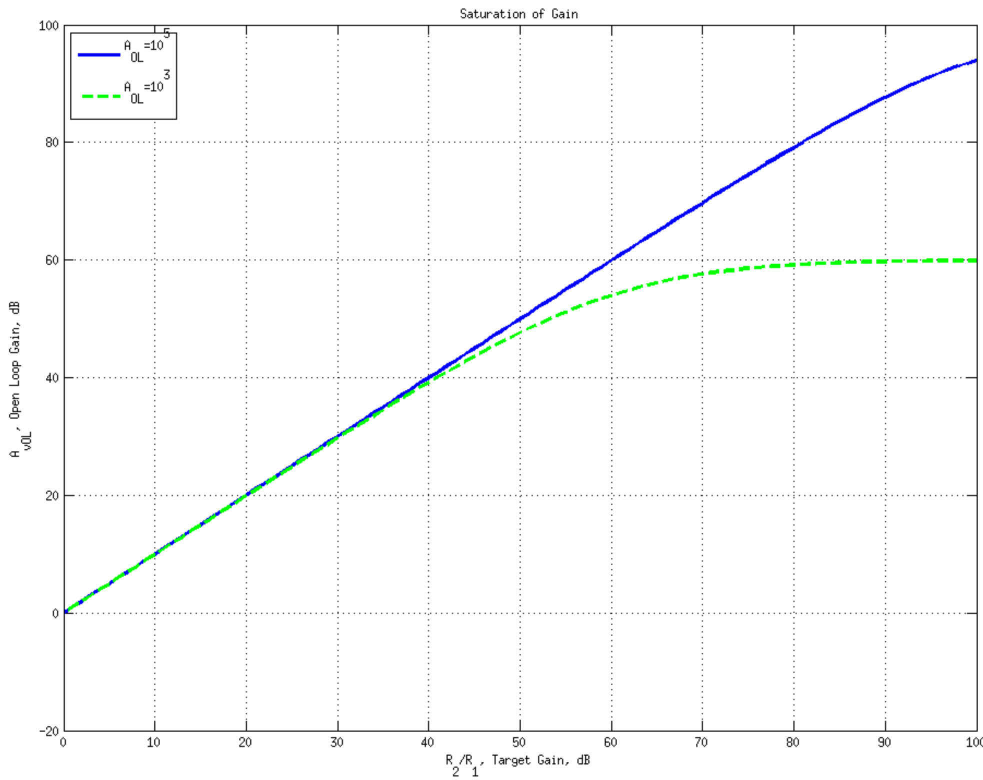
multiply by $A_{OL}(R_1 + R_2)$

$$-v_o(R_1 + R_2 + A_{OL}R_1) = v_{in}R_2A_{OL}$$

$$\frac{v_o}{v_{in}} = -\frac{R_2A_{OL}}{R_1 + R_2 + A_{OL}R_1}$$

$$\frac{v_o}{v_{in}} = -\frac{R_2}{R_1}\frac{A_{OL}}{\frac{R_2}{R_1} + A_{OL} + 1}$$

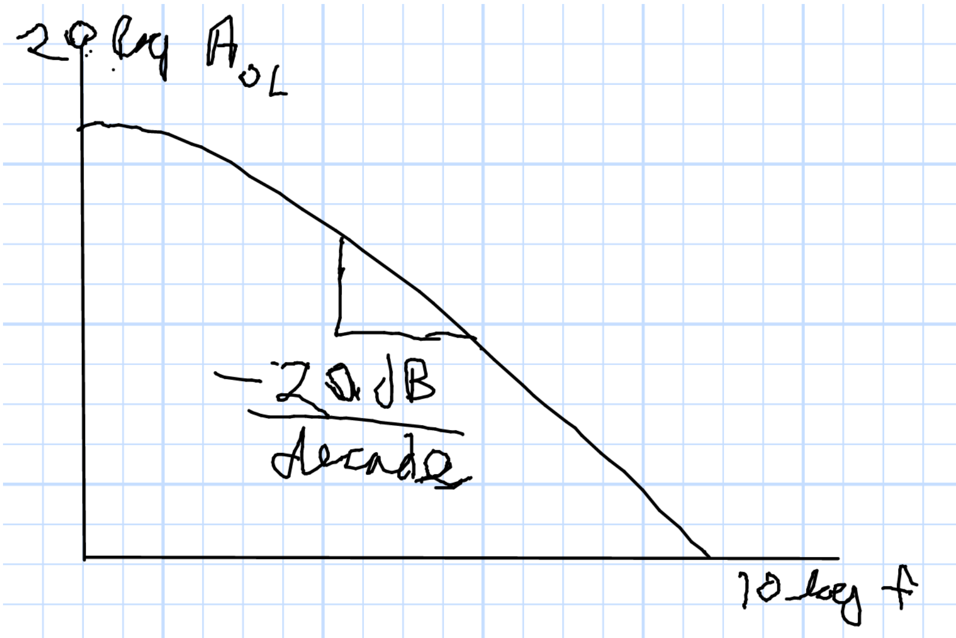
Finite Gain Effects (2)



$$\frac{v_o}{v_{in}} = -\frac{R_2}{R_1}\,\frac{A_{OL}}{\frac{R_2}{R_1} + A_{OL} + 1}$$

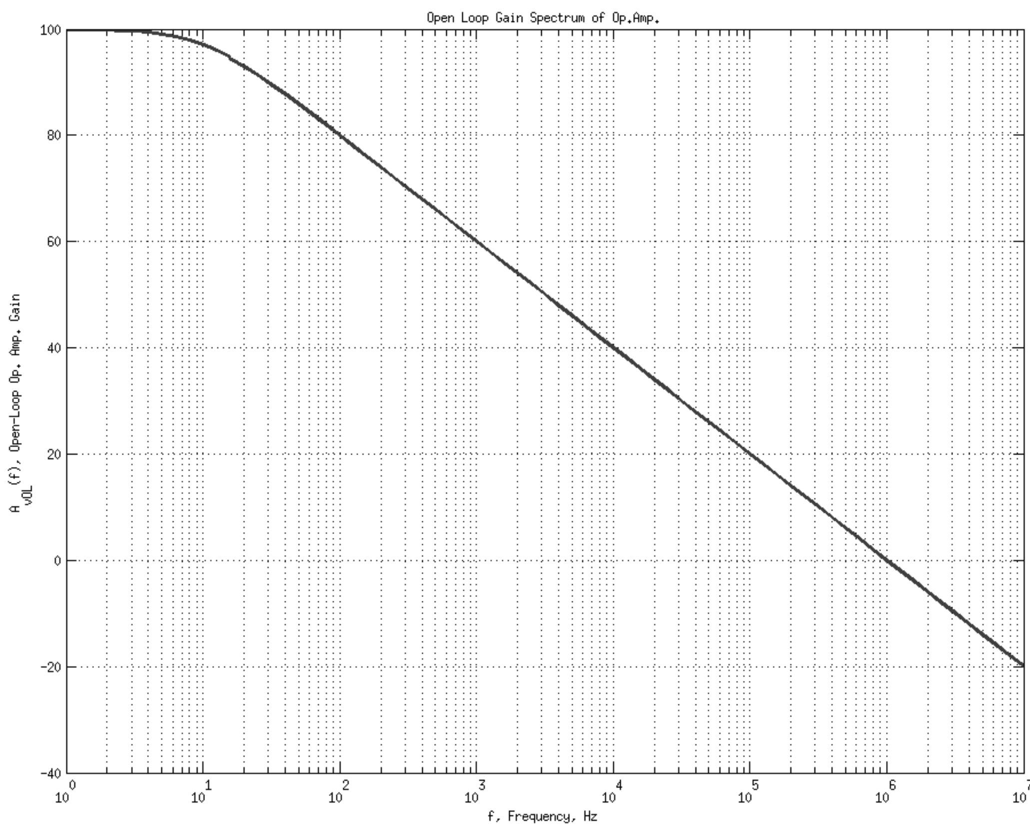
A_{OL} is unpredictable; Don't trust it. Keep $R_2/R_1 \ll A_{OL}$

Op–Amp Gain Spectrum



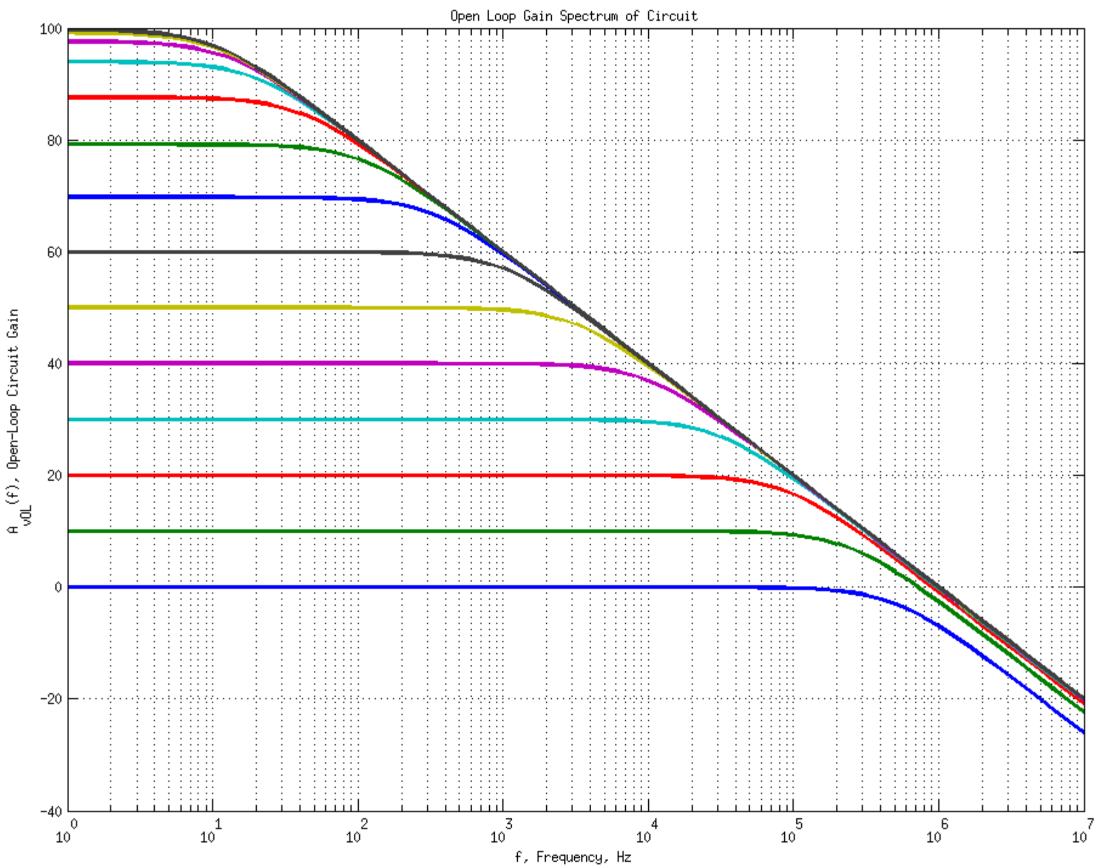
- A_{OL} Varies with Frequency
- $A_{OL}(0)$ is Maximum
- f_{oOL} is Cutoff Frequency
- $A_{OL}(f_{oOL}) = \frac{A_{OL}(0)}{\sqrt{2}}$
- Why Square Root of 2?

Open–Loop Gain Spectrum



$$A_{OL}^2(f) = \frac{A_{OL}^2(0)}{1 + \left(\frac{f}{f_{0OL}}\right)^2} \qquad A_{OL}(f_{0OL}) = \frac{A_{OL}(0)}{\sqrt{2}}$$

Closed–Loop Gain Spectrum



$A_{CL} f_{0CL} = A_{OL} f_{0OL}$ Gain–Bandwidth Product

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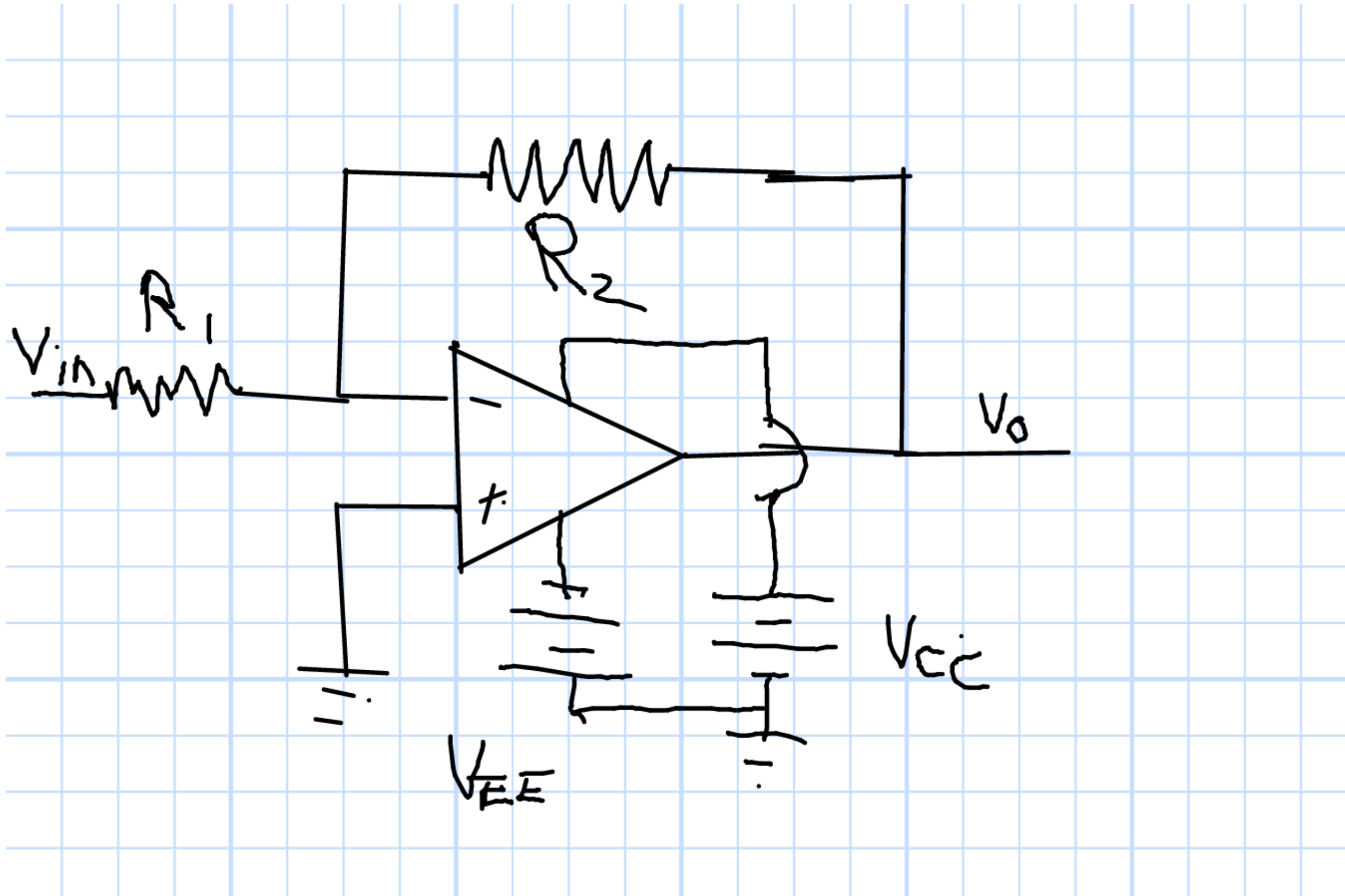
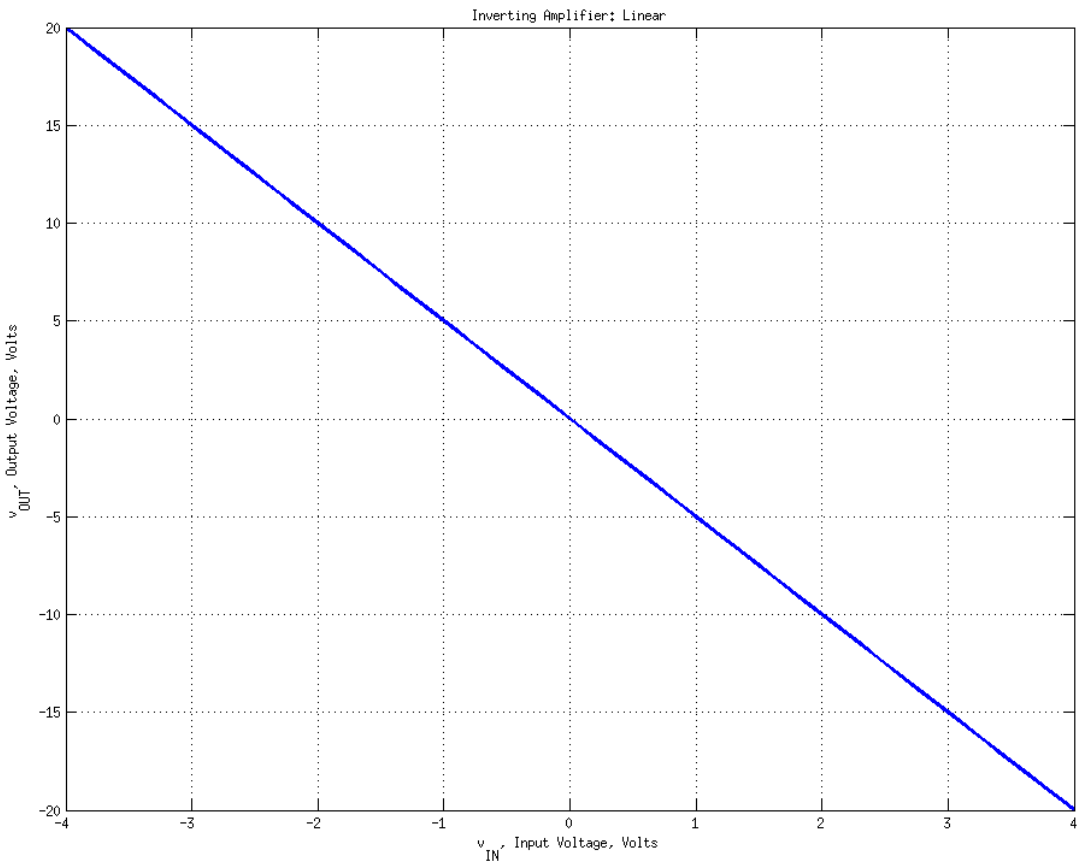
Voltage Limits

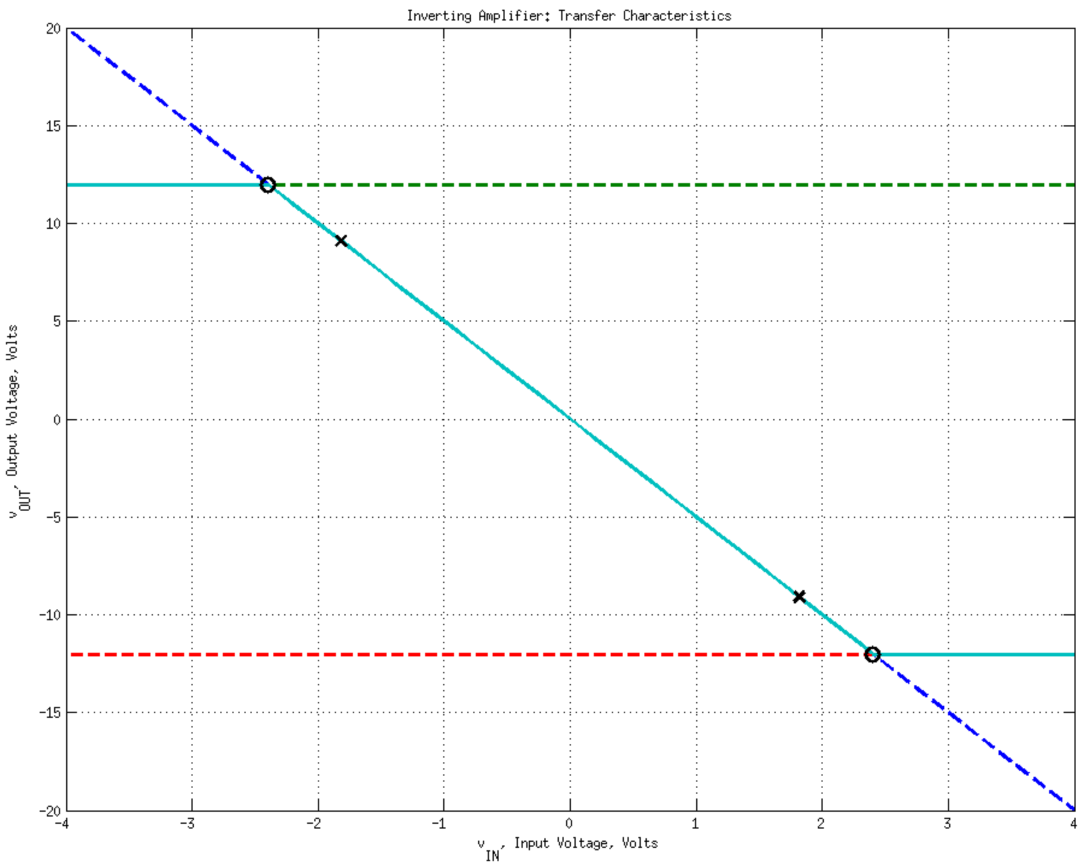


Ideal Gain: $-R_2/R_1 = -5$

New Concept: Transfer Function (Plot of output vs. input)

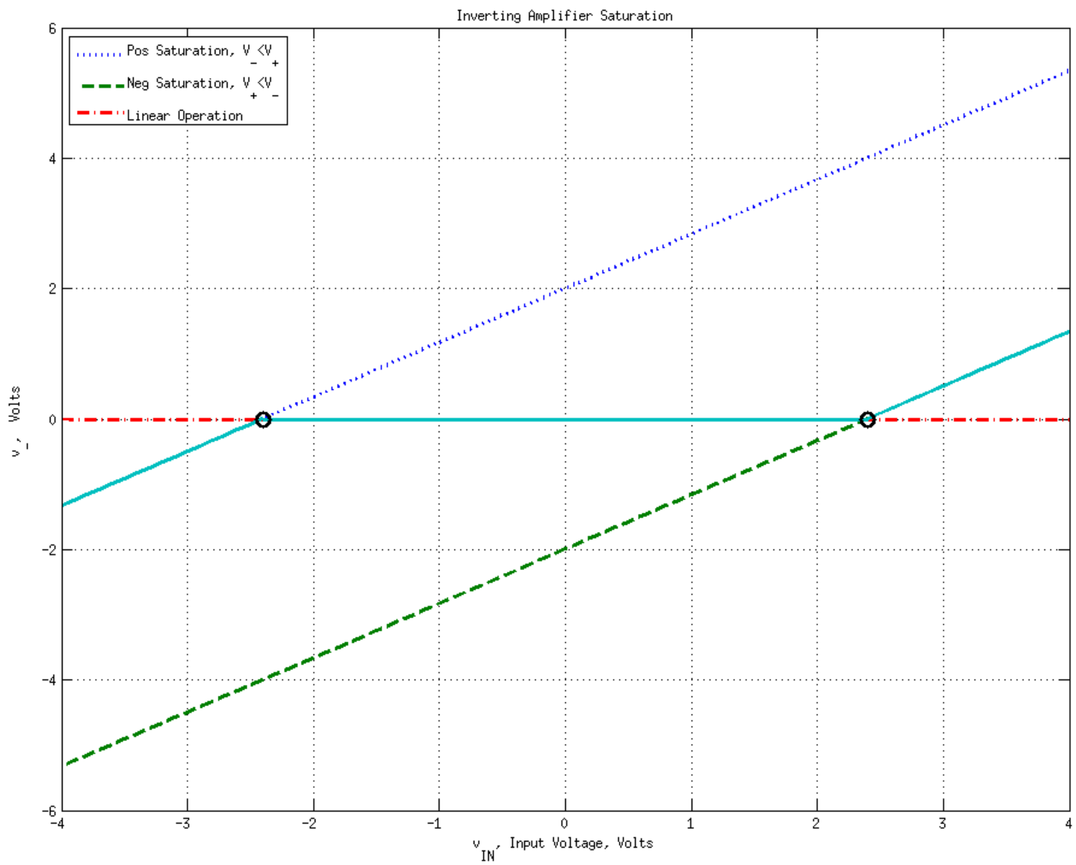


Voltage Limits Example



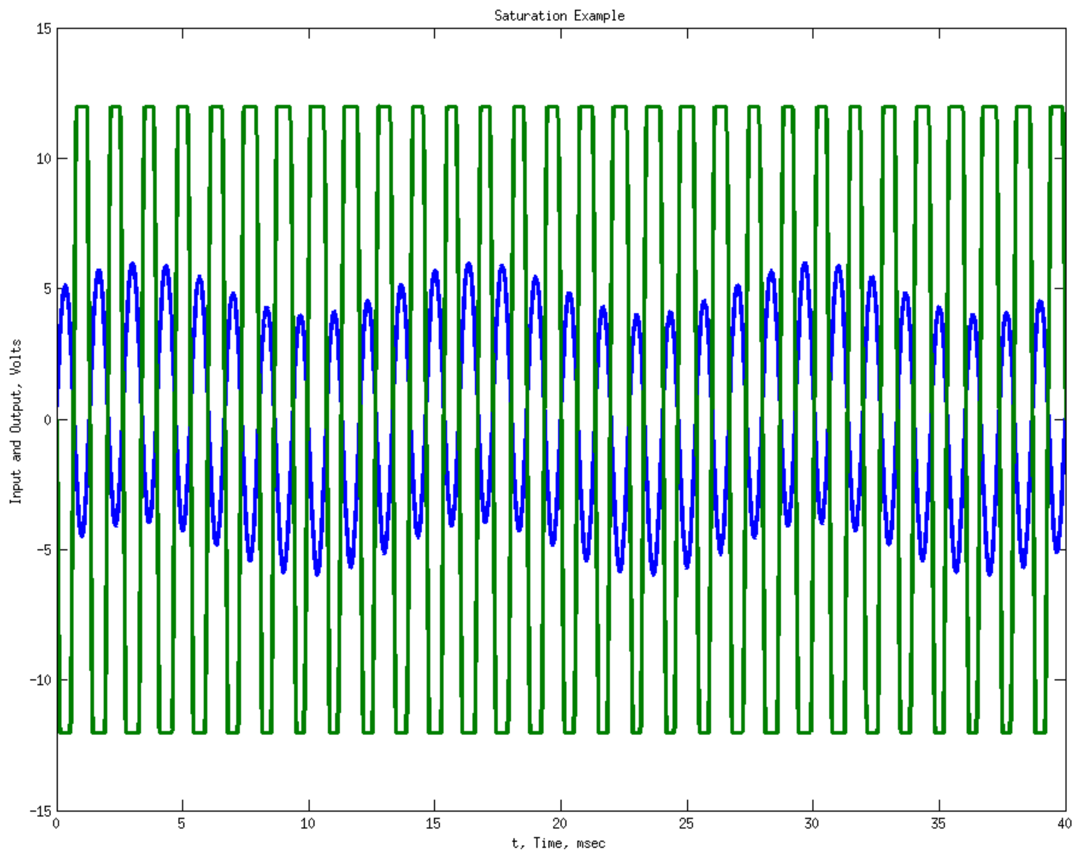
±12–Volt Power Rails. Blue dash is ideal. Cyan solid is actual.

Voltage on −Input



Virtual Ground Fails.

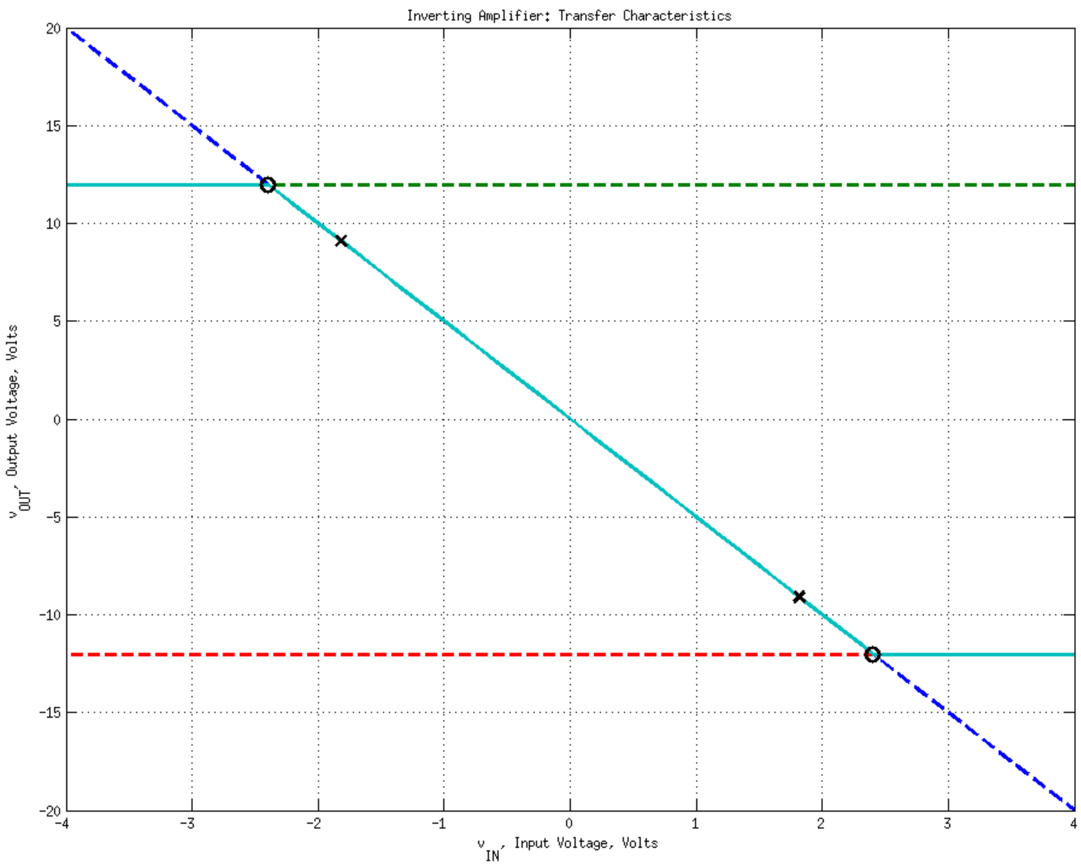
Gain Saturation Example



Blue in, green out. 1V at 75Hz 5V at 750Hz

$R_2/R_1 = 5000/1000$, $\pm$ 12 V rails

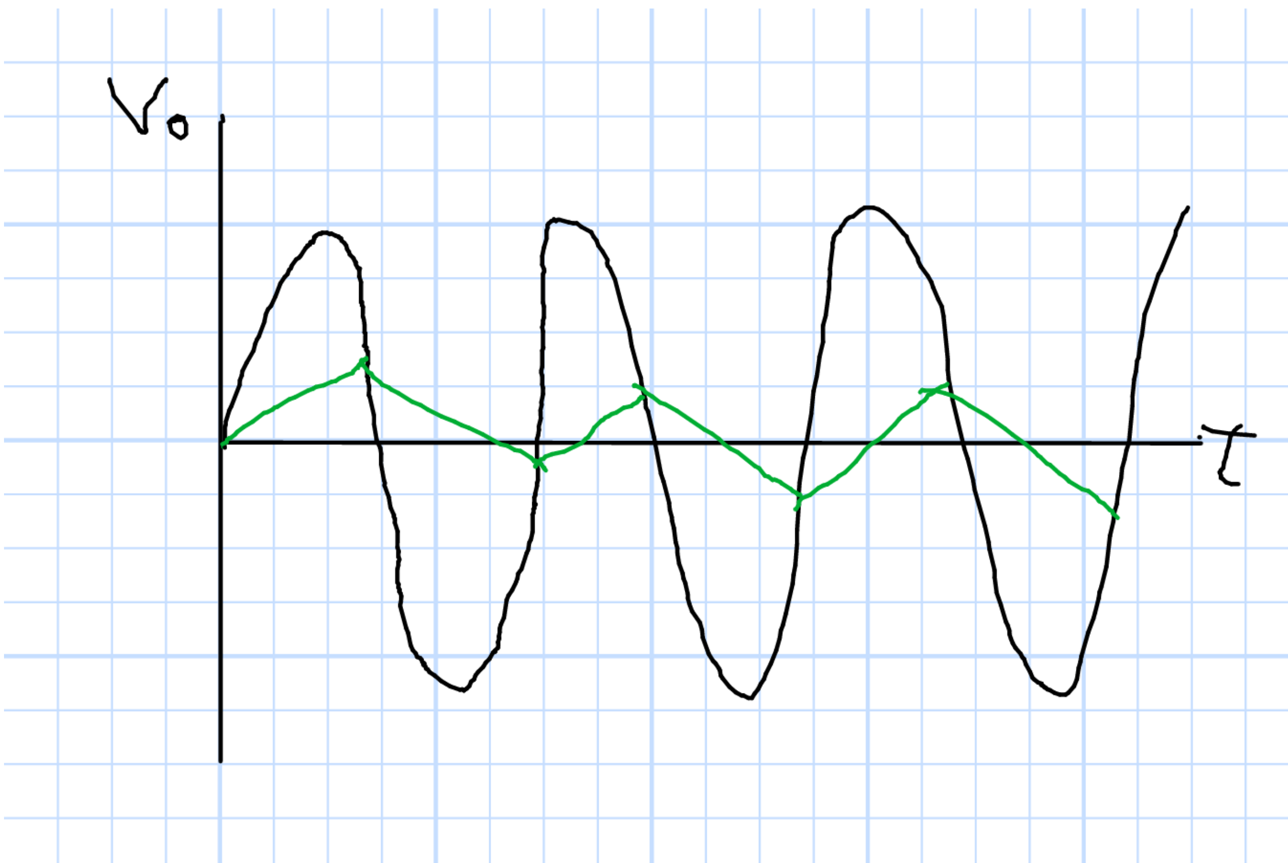
Current Limits



x shows current limit, $I_{max} = 20$mA at $v = i_{max} R_L \parallel R_2$.
$R_L = 500\Omega$, $R_2 = 5$kΩ

Slew Rate Limit

Desired voltage, $A_V v_{in}$ in Black varies too fast.
Result is Green.



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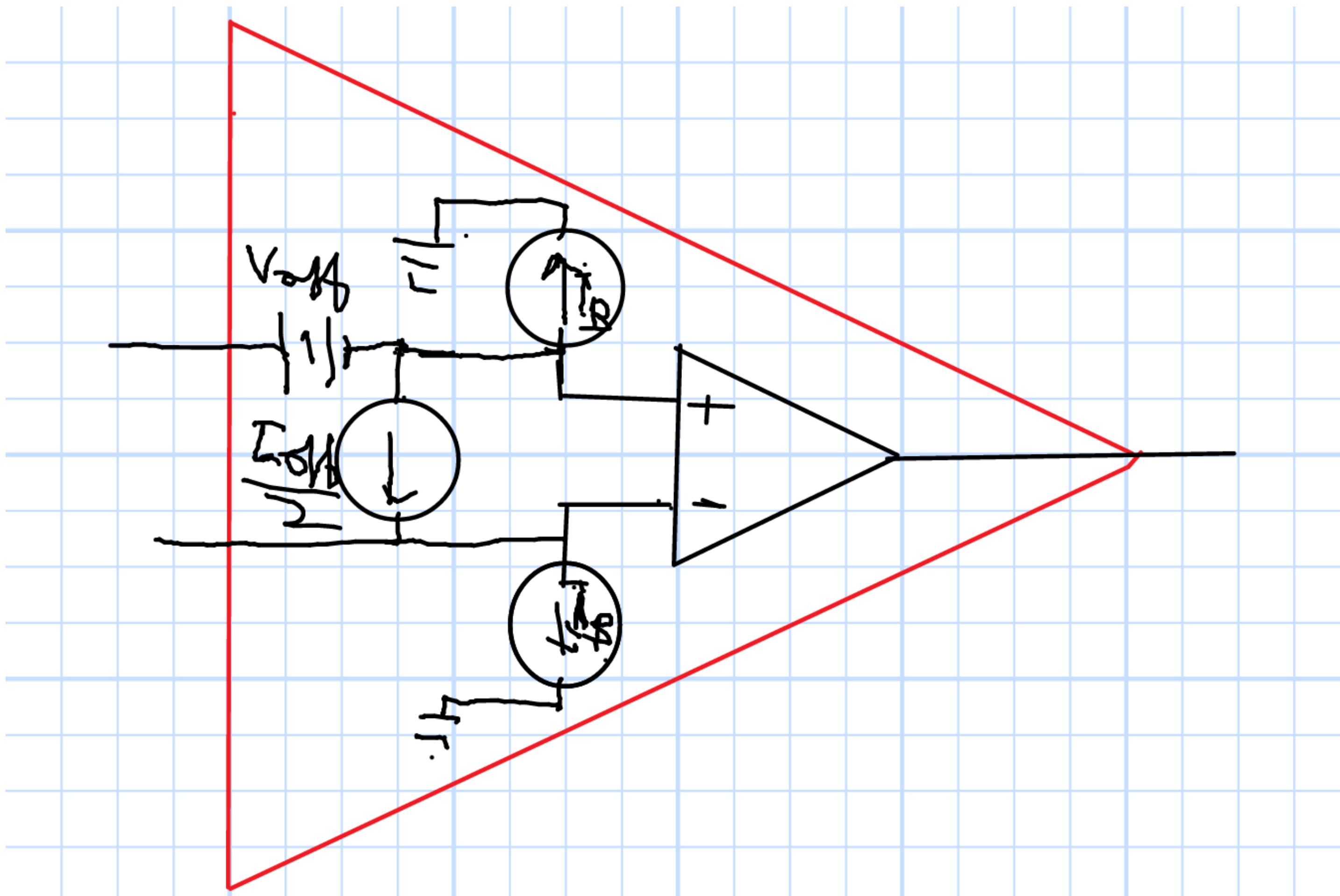
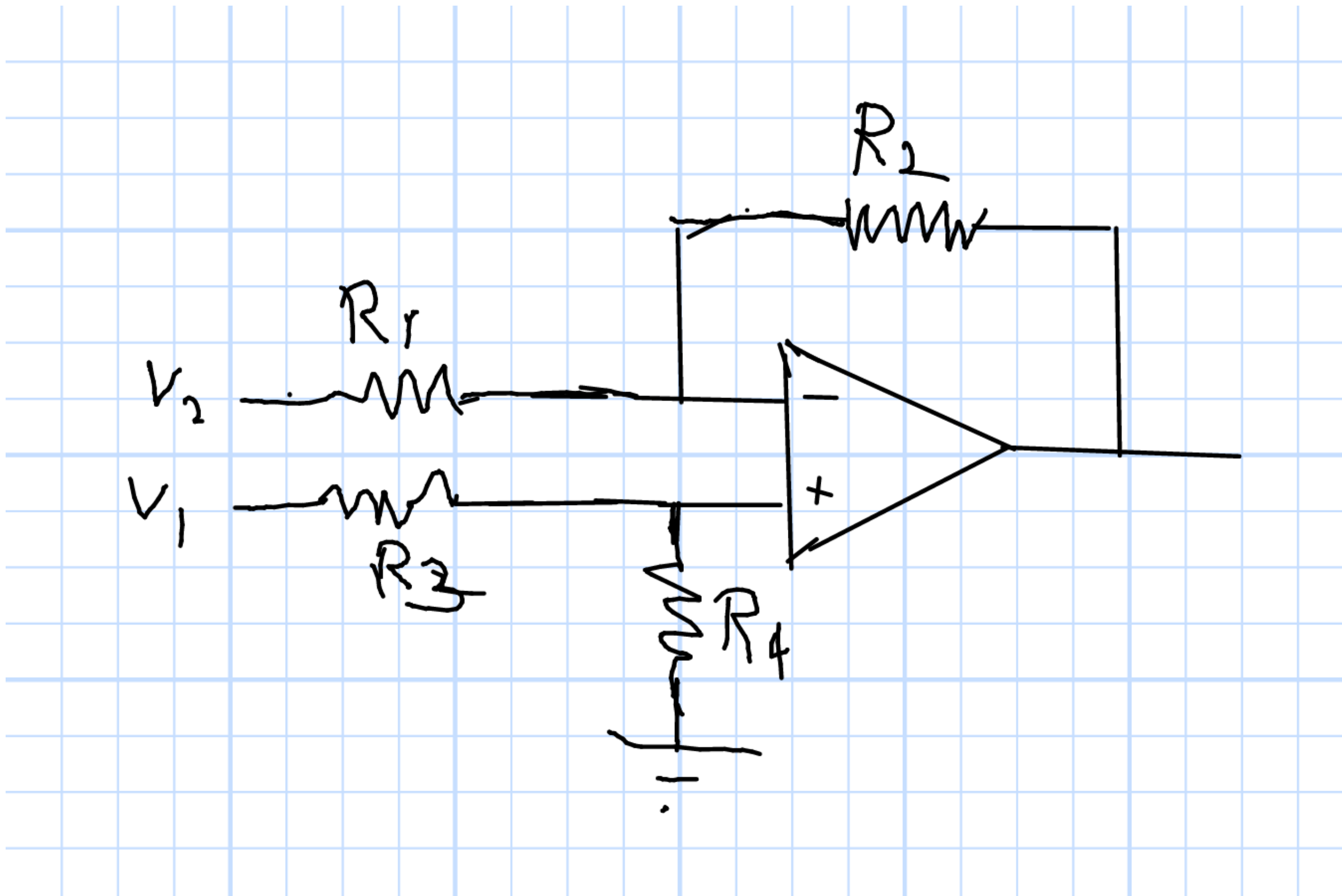
DC Imperfections



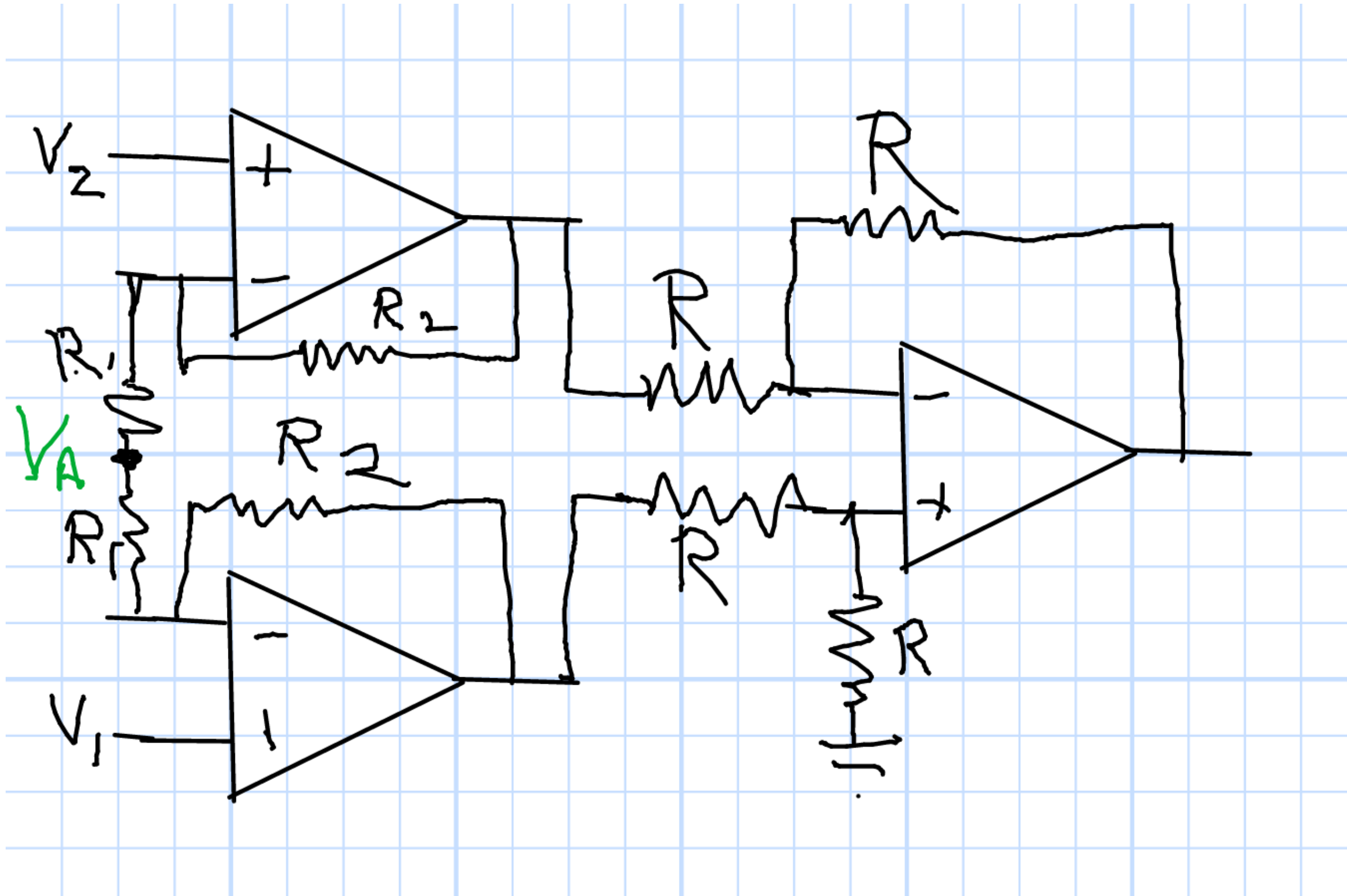
Adjustment for v_{off}, Circuit design for currents.
Not needed for typical applications.

Differential Amplifier



v_2 affects current in v_1 source (try superposition)

Good Differential Amplifier



Infinite input impedance. Low common–mode gain.

A Little Review

- Circuit Concepts
- KCL, KVL
- Ohm's Law, Resistivity, Resistance and Geometry
- Series and Parallel Combinations
- Node and Mesh Analysis
- Superposition
- Wheatstone Bridge Circuit
- Op–Amps; Inverting, Non–inverting, Impedances, Limits