Physics 231

Lecture 3: Op Amps I

Eric Landahl

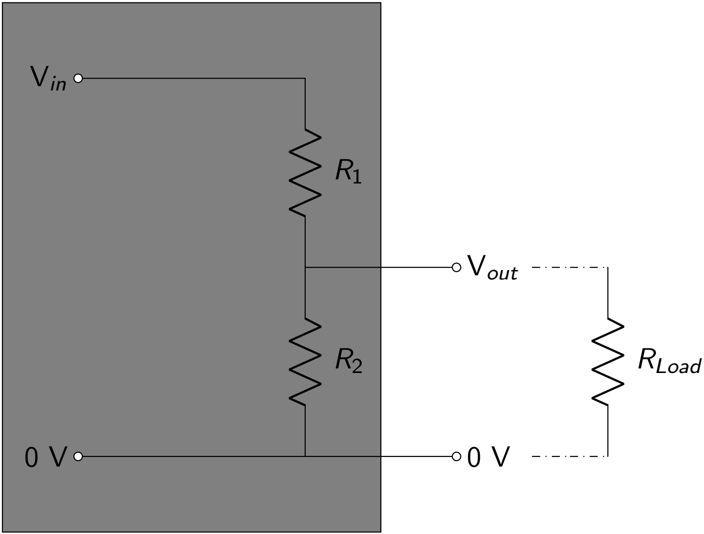
DePaul University Physics Department

April 28, 2025

Table of Contents

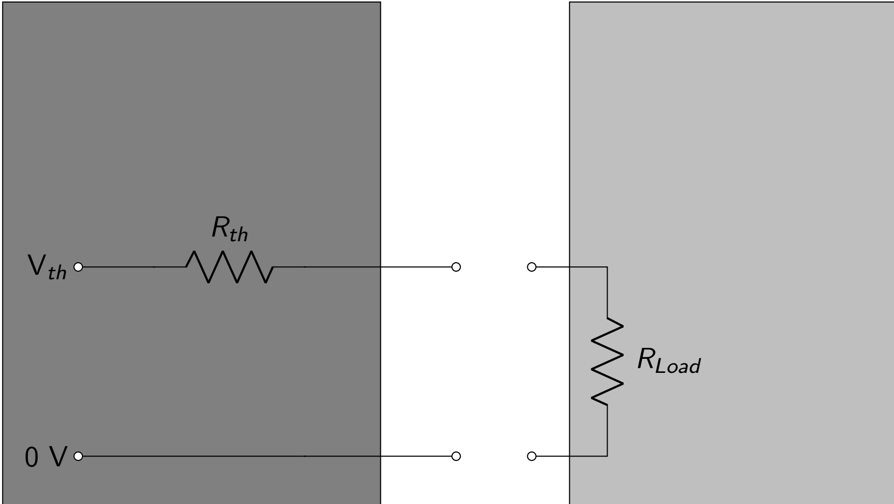
Thevenin Equivalent Circuits: Analysis

Replace the entire source with a "black box" with an equivalent voltage and an equivalent resistance in series.



Thevenin Equivalent Circuits: Analysis

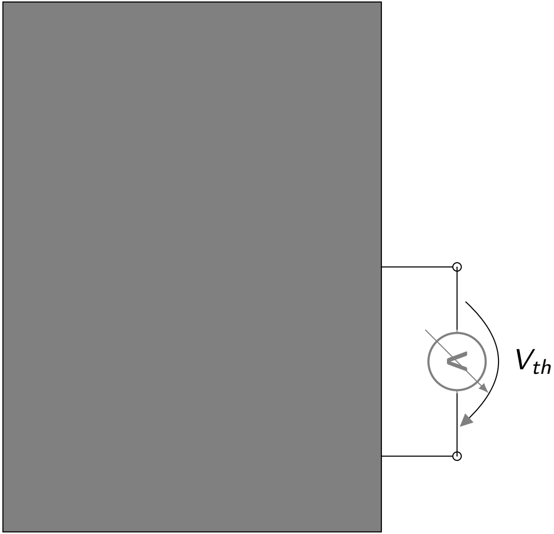
The "Thevenin Equivalent" Circuit is defined to be the one where the output voltage $V_{out} = \frac{V_{th}}{2}$ when connected to a load $R_{Load} = R_{th}$. *Every power supply has a* V_{th} *and* R_{th}.



Thevenin Equivalent Circuits: Analysis

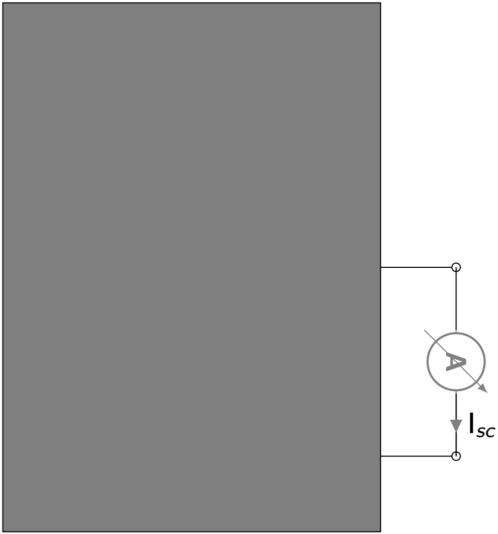
Step 1: Determine the voltage across the outputs without the load attached (as an open circuit). This open circuit voltage is V_{th}.

Remember, the voltmeter draws no current.



Thevenin Equivalent Circuits: Analysis

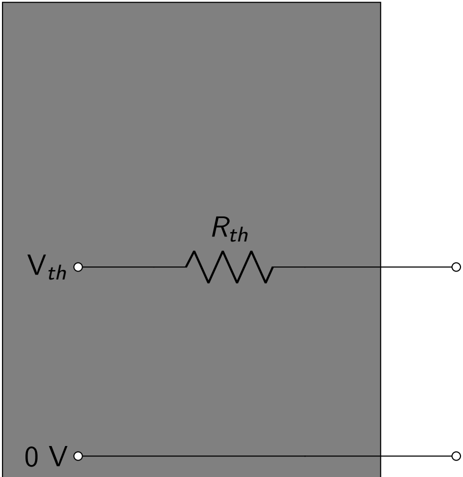
Step 2: Determine the current through the outputs when they are shorted. This short circuit current is I_{sc}. *Remember, the ammeter has zero resistance and is a short.*



Thevenin Equivalent Circuits: Analysis

Step 3. Calculate the equivalent (or source, or Thevenin) resistance by dividing the open-circuit voltage by the short-circuit current.

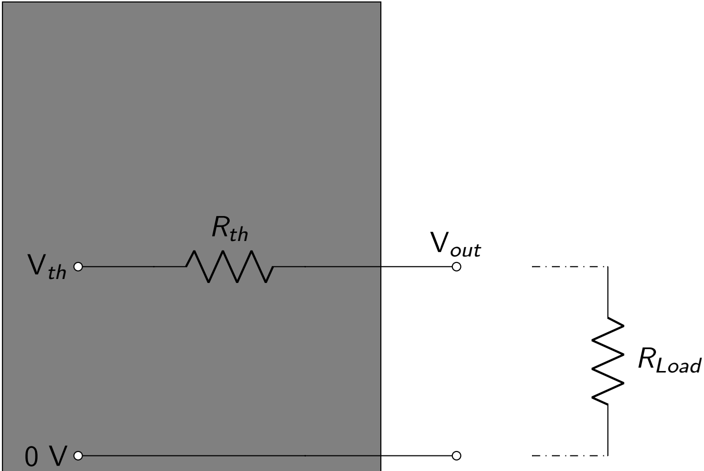
$$R_{th} = \frac{V_{th}}{I_{sc}} \tag{1}$$



Thevenin Equivalent Circuits: Analysis

Step 4. The output voltage V_{out} can now be determined for any load resistance R_{Load} by using the voltage divider equation.

$$V_{out} = \left(\frac{R_{Load}}{R_{Load} + R_{th}} \right) V_{th} \tag{2}$$



Thevenin Equivalent Circuits: Analysis

Special cases of load resistance:

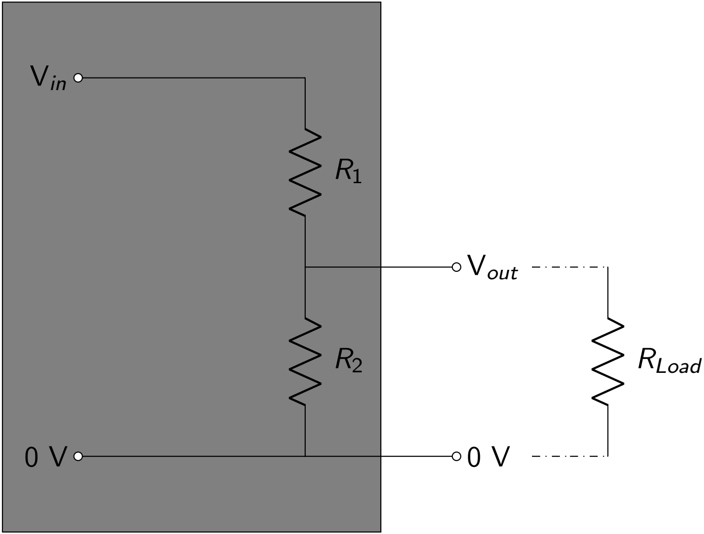
$$V_{out} = \left(\frac{R_{Load}}{R_{Load} + R_{th}} \right) V_{th} \tag{3}$$

1. If $R_{Load} = \infty$ (no load), the circuit is open and $V_{out} = V_{th}$
2. If $R_{Load} = 0$, the circuit is shorted and $V_{out} = 0$
3. If $R_{Load} = R_{th}$ then $V_{out} = \frac{V_{th}}{2}$
4. If $R_{Load} \gg R_{th}$ then $V_{out} = V_{th}$, or a "good load"
5. If $R_{Load} \approx R_{th}$ then $V_{out} < V_{th}$, or a "poor load"

Always check your answer by Property 3:
Loading with the source resistance halves the output voltage.

Thevenin Equivalent Circuits: The Voltage Divider Source

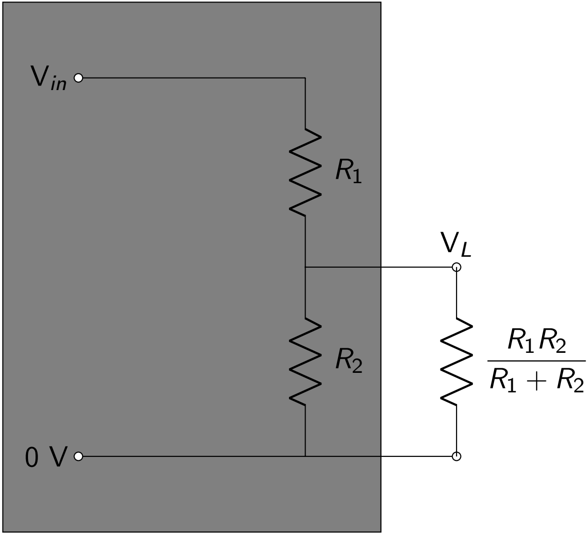
$$\frac{1}{R_{th}} = \frac{1}{R_1} + \frac{1}{R_2} \qquad or \qquad R_{th} = \frac{R_1 R_2}{R_1 + R_2} \tag{4}$$



Thevenin Equivalent Circuits: The Voltage Divider Source

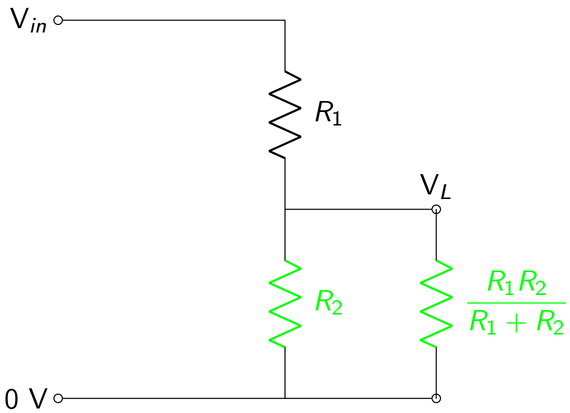
Check by first inserting the calculated R_{Load}

Then V_{out} drops to the “Loaded” value V_L:



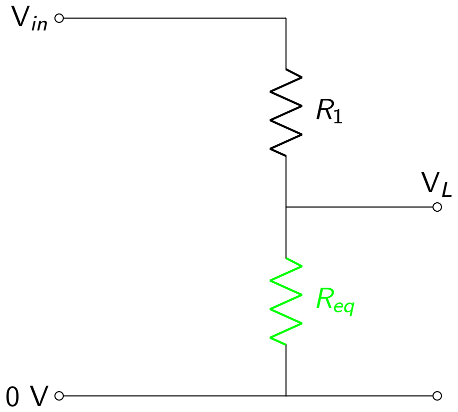
Thevenin Equivalent Circuits: The Voltage Divider Source

Next, turning R_{Load} and R_2 into an equivalent resistor



Thevenin Equivalent Circuits: The Voltage Divider Source

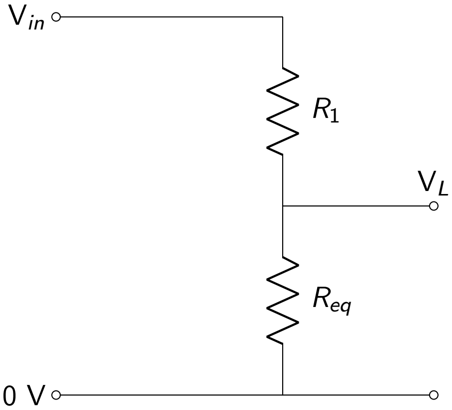
$$\frac{1}{R_{eq}} = \frac{1}{R_2} + \frac{1}{R_{th}} = \frac{1}{R_2} + \left(\frac{1}{R_1} + \frac{1}{R_2}\right) = \frac{2}{R_2} + \frac{1}{R_1} \qquad (5)$$



Thevenin Equivalent Circuits: The Voltage Divider Source

Then applying the voltage divider equation

$$V_L = \left(\frac{R_{eq}}{R_{eq} + R_1} \right) V_{in} \tag{6}$$



Thevenin Equivalent Circuits: The Voltage Divider Source

Simplifying using algebra:

$$V_L = \left(\frac{R_{eq}}{R_{eq} + R_1}\right) V_{in} \tag{7}$$

$$= \left(\frac{R_{eq} R_1}{R_{eq} + R_1}\right) \frac{V_{in}}{R_1} \tag{8}$$

$$= \left(\frac{1}{R_1} + \frac{1}{R_{eq}}\right)^{-1} \frac{V_{in}}{R_1} \tag{9}$$

$$= \left(\frac{1}{R_1} + \frac{2}{R_2} + \frac{1}{R_1}\right)^{-1} \frac{V_{in}}{R_1} \tag{10}$$

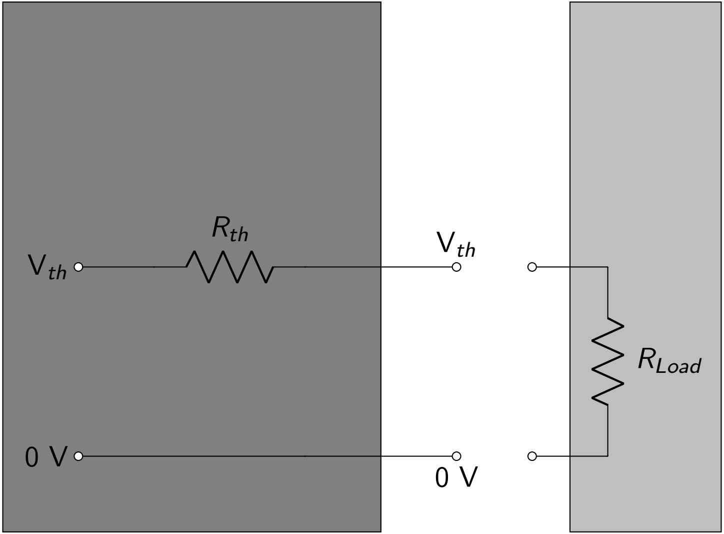
$$= \left(\frac{2}{R_1} + \frac{2}{R_2}\right)^{-1} \frac{V_{in}}{R_1} \tag{11}$$

$$= \left(\frac{R_1 R_2}{R_1 + R_2}\right) \frac{V_{in}}{2R_1} \tag{12}$$

$$V_L = \left(\frac{R_2}{R_1 + R_2}\right) \frac{V_{in}}{2} = \frac{V_{out}}{2} \tag{13}$$

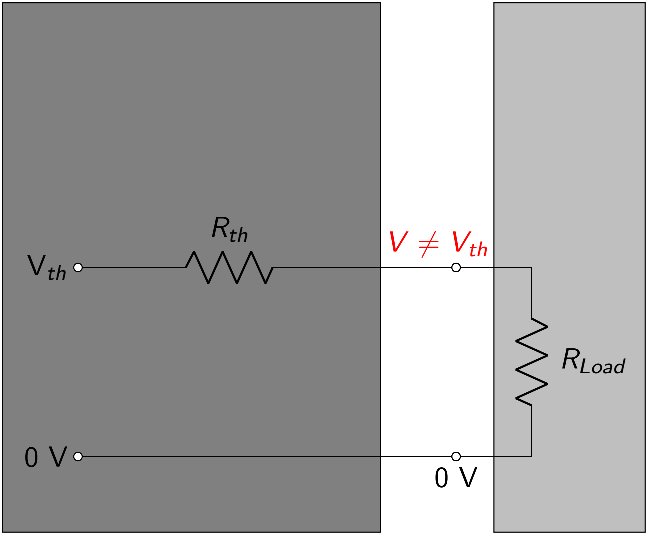
Thevenin Equivalent Circuits: The Loading Problem

Any circuit can be split into a Source and a Load.



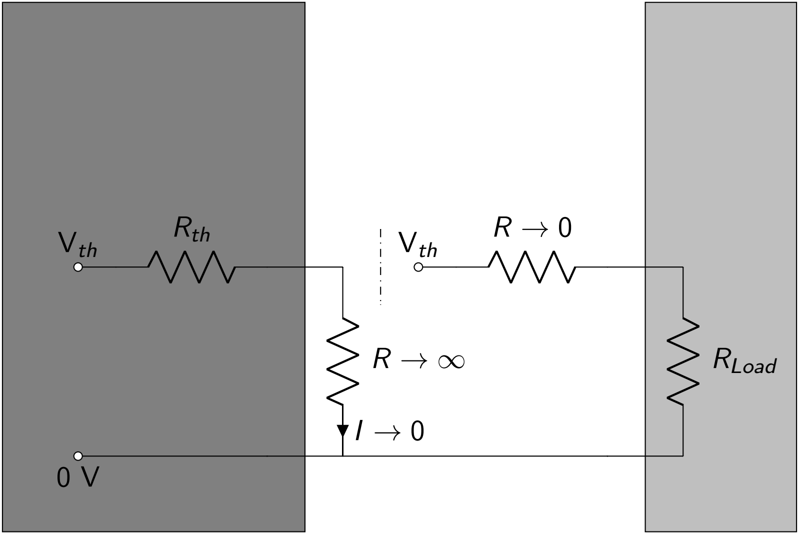
Thevenin Equivalent Circuits: The Loading Problem

But connecting them changes the voltage.



Thevenin Equivalent Circuits: The Loading Problem

We need a "matchmaker": a component that
looks like a high resistance when viewed from the Source, but
looks like a low resistance when viewed from the Load.

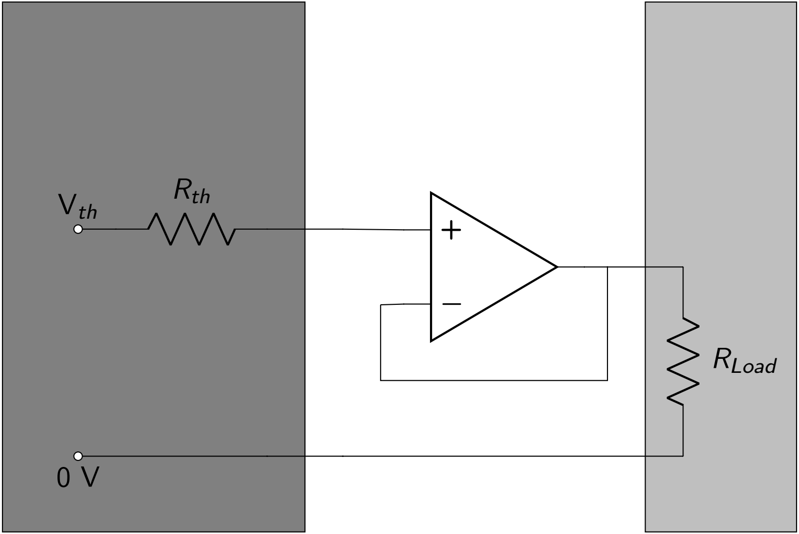


The Op Amp: Basic Properties

The input leads draw no current

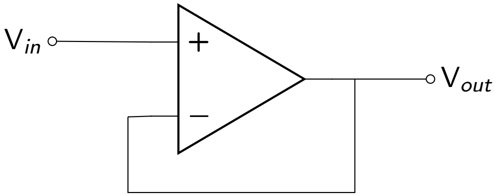
The output has zero source resistance

The output output attempts to make the input voltages the same



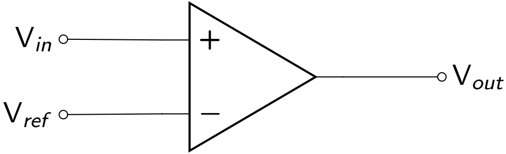
The Op Amp: Follower/Buffer

$$V_{out} = V_{in}$$



The Op Amp: Comparator

$$V_{out} \rightarrow \begin{cases} HIGH, & \text{if } V_{in} > V_{ref}. \\ LOW, & \text{if } V_{in} < V_{ref}. \end{cases}$$



The Op Amp: Amplifier (non-inverting)

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