One of the most important things in this course!

Consider some electronic device

\[
\text{Input Port} \quad \text{Output Port}
\]

Often

\[
\text{We'll put a signal in} \quad \text{(say a voltage)}
\]

What current will flow? Some.
Can model it with resistor

\[
R_{\text{in}} = \frac{V_{\text{in}}}{I_{\text{in}}}
\]

In fact current may depend non-linearly on voltage

\[
\frac{1}{R_{\text{in}}} = \frac{\partial I_{\text{in}}}{\partial V_{\text{in}}}
\]

Then we really want how much current changes when voltage changes (definition still works)
Our device puts out some voltage, but this voltage depends on how much current we draw! Depends on the "Load." Output Resistor.

\[ V_{out} = 5 \text{ V} \]

\[ R_L = 9.2 \Omega \]

\[ V_{out} = \frac{V_{in}}{R_L} = 4.47 \text{ V} \]

\[ V_{in} = \frac{V_{out}}{R_L} = 2.5 \text{ V} \]

Input voltage is result of voltage divider between Port 1 & Port 2.
Voltage Divider as Device

\[ V_{in} = \frac{R_1}{R_1 + R_2} \]

**Rout = ?**

\[ R_1 = R_2 = 10 \, k\Omega \]

\[ V_{in} = 5 \, V \]

\[ R_h = 0 \Omega \quad V_{out} = 2.5 \, V \]

\[ R_L = 100 \, k\Omega \quad V_{out} = \frac{100\Omega}{100\Omega + 10\Omega} \cdot 5 = \frac{300}{110} \cdot 5 = 24 \, V \]

\[ R_L = 10 \, k\Omega \quad V_{out} = \frac{5}{5+10} \cdot 5 = \frac{5}{3} = 1.7 \, V \]

\[ R_L = 1 \, k\Omega \quad V_{out} = \frac{1}{1+10} \cdot 5 = 0.45 \, V \]
Thevenin’s Theorem

For linear systems (or parts of systems that are linear),

Can be replaced by

How to find $V_{TH}$ and $R_{TH}$

1. $R_L = 0$ (open)
   
   $\Rightarrow V_{out} = V_{TH}$

2. $R_L = 0$
   
   $R_{TH} = \frac{V_{TH}}{I_{short}}$
Example

Replace left part with Thévenin Equivalent

1. \( R_L = \infty \) \( V = V_A = \frac{1.5k}{3.3k + 18k} \times 1.5V = \frac{1.5}{51} \times 1.5V = 0.53V \)

2. \( R_L = 0 \) \( I_{\text{tot}} = ? \)

\[
I_{\text{tot}} = I_{90} \\
I_{90} = 2I_{18k} = \frac{2}{3} \times I_{18k} \\
I_{18k} = \frac{1.5V}{3.3k + 18k/\pi} = \frac{1.5}{330 + 600} = 380\ mA
\]

\( I_{\text{short}} = 280\ mA \)

\( R_{\text{th}} = \frac{0.53V}{260\ mA} \approx 2.1\ k\Omega \)

Easier Step 2 (if you have circuit)

From Thévenin Method

\[ R_{\text{th}} = R_{10} + \frac{3.3k}{18k} \]
Norton's Theorem

Like Thévenin but for current supply
(for linear networks only)

To find:
1. Short: \( I_N = I_{\text{short}} \)
2. Open: \( R_N = \frac{V_{\text{open}}}{I_N} \)

Power & Impedance Matching

The power dissipated by a component is
\[ P = I \cdot V \]

\( \text{joules} = \frac{\text{coulombs}}{\text{sec}} \cdot \text{coulombs} = \frac{\text{coulombs}^2}{\text{sec}} = \text{watts} \)

For resistors where \( I \& V \) real (or impulse)
\[ V = IR \]
\[ P = IV = \frac{V^2}{R} = IR \]
How to get the most power out of a system?

What $R_L$ makes $P$ greatest?

\[ P = IV \left( \frac{V_{th}}{R_{th} + R_L} \right) \left( \frac{R_L}{R_{th} + R_L} \right) \]

\[ = \frac{R_L V_{th}^2}{(R_{th} + R_L)^2} \]

\[ \text{Maximize } \frac{dP}{dR_L} = 0 \]

\[ \frac{dP}{dR_L} = \frac{V_{th}^2}{(R_{th} + R_L)^2} \cdot 2 - 2 \frac{R_L V_{th}^2}{(R_{th} + R_L)^3} = 0 \]

\[ 1 - \frac{2R_L}{(R_{th} + R_L)^2} = 0 \]

\[ 2R_L = R_{th} + R_L \]

\[ R_L = R_{th} \]

Maximum power when load matches output resistance (impedance)
Recall that the voltage divider is a lever of a given type.

Basic Tool in Mechanics

Basic Tool in Electronics

What about other types of lever?

Motion opposite than push (and maybe bigger)

Motion bigger than push

Need to add energy
(active components, not passive only)

Still will have voltage divider!
Dependent Sources

General Dep. Source

Usually controlled by current or voltage somewhere in circuit

VCVS
VCCS
CCVS
CCCS

Note that power for source doesn't come from control!
(Active element)

Can use this to create an operational amplifier (OpAmp)

Symbol
+ input is "Non-inverting input"
- input is "Inverting input"

Actually two more inputs: power

The "ground" is actually \( \frac{V_{cc} + (-V_{cc})}{2} \)

Can't produce higher voltage than supplied
Real Op Amps
\[ a = 10^5 \]
\[ R_m = 1-10 \, \text{M\Omega} \]
\[ R_o < 1 \, \Omega \]

Ideal Op Amps
\[ a = \infty \rightarrow ? \]
\[ R_m = \infty \rightarrow \text{No current} \]
\[ R_o = 0 \rightarrow \text{Load has no effect on voltage} \]

Infinite gain?
Only meaningful with negative feedback (or if you want output at the rails)

Feedback (Negative)
Take some of output, connect to
Inverting (negative) input

Simpler case - all of output into - input

\[ V_o \rightarrow + \]
\[ V_{out} \rightarrow - \]
**1st Principle (Open Loop Negative Feedback)**

\[ V_f = V_i \quad (\text{or else } V_o = \pm V_c) \]

![Diagram](image)

- **Voltage Follower**
  - \( V_{out} = V_{in} \)

**What good is this?**

The power for \( V_{out} \) comes from somewhere other than \( V_{in} \!\).

Another way of saying this:

*We've changed the output resistance!*

Say we need to run a device at 2.5 V **but** have 5 V supply and two 10 kΩ resistors.

\[ \begin{align*}
2.5 \text{V} & \quad \text{Easy to get 2.5 V with Volt. divider} \\
\frac{2.5 \text{V}}{10 \text{kΩ}} & \quad \text{but } R_{out} = 5 \text{kΩ}
\end{align*} \]
Attach device

\[ V = \frac{100/10k \cdot 5V}{10k/10k + 10k} = 0.5V \]

It doesn't work!

Insert voltage follower

\[ V_A = \frac{10k/100}{10k/100 + 10k} \cdot 5V = \frac{10k}{10k + 10k} \cdot 5V = \frac{1}{2} \cdot 5V = 2.5V \]

\[ V_B = \frac{100}{100 + 0} \cdot 2.5V = 2.5V \]

It works!
Finally to the levers:

![Inverting Amplifier Diagram]

1st Principle: \( V_c = V_a = 0 \)

\[ V_a \text{ is a "virtual" ground!} \]

\[ i = \frac{V_in - V_a}{R_1} = \frac{V_in}{R_1} \]

2nd Principle: no current into \( V_a \)

All of \( i \) goes into \( R_2 \) branch.

\[ V_a = V_a - V_{out} = i R_2 \]

\[ V_{out} = i R_2 \]

\[ V_{out} = -\frac{V_in}{R_1} R_2 \]

\[ V_{out} = -\frac{R_2}{R_1} V_{in} \]

The virtual ground is the fulcrum in our lever. 
\( R_1 \) & \( R_2 \), still voltage divider, but fixed in.