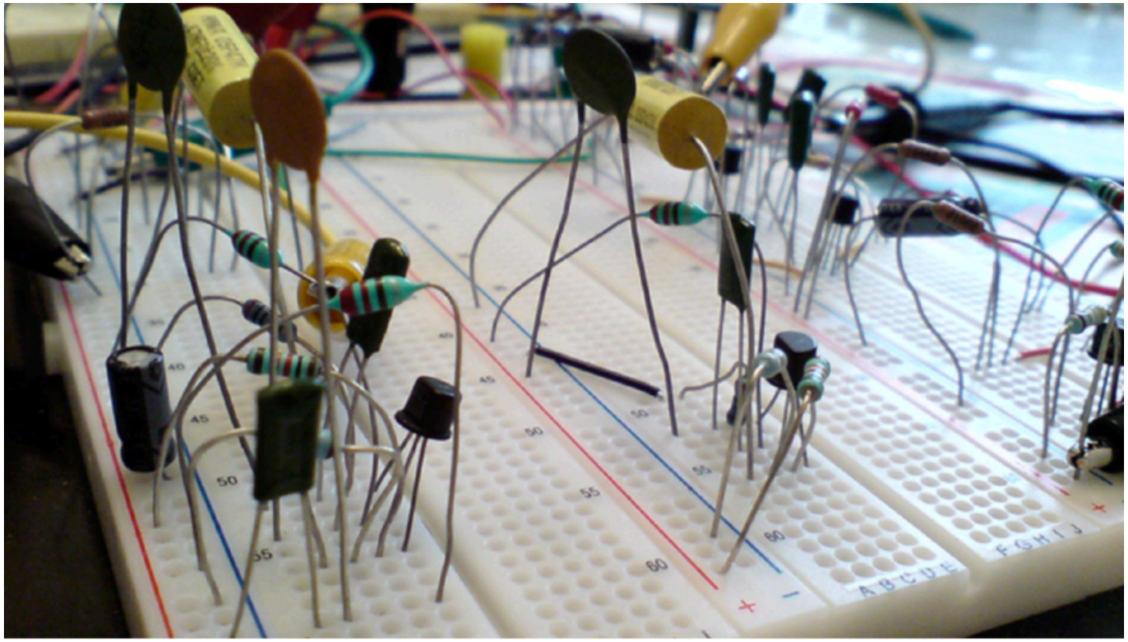
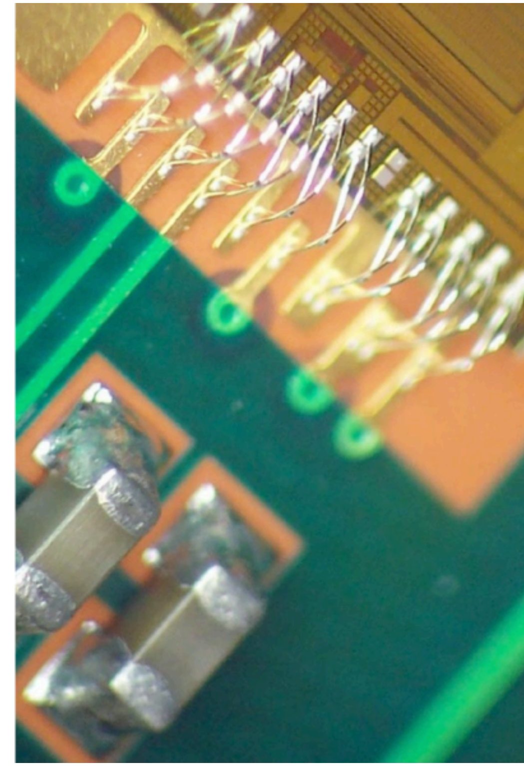
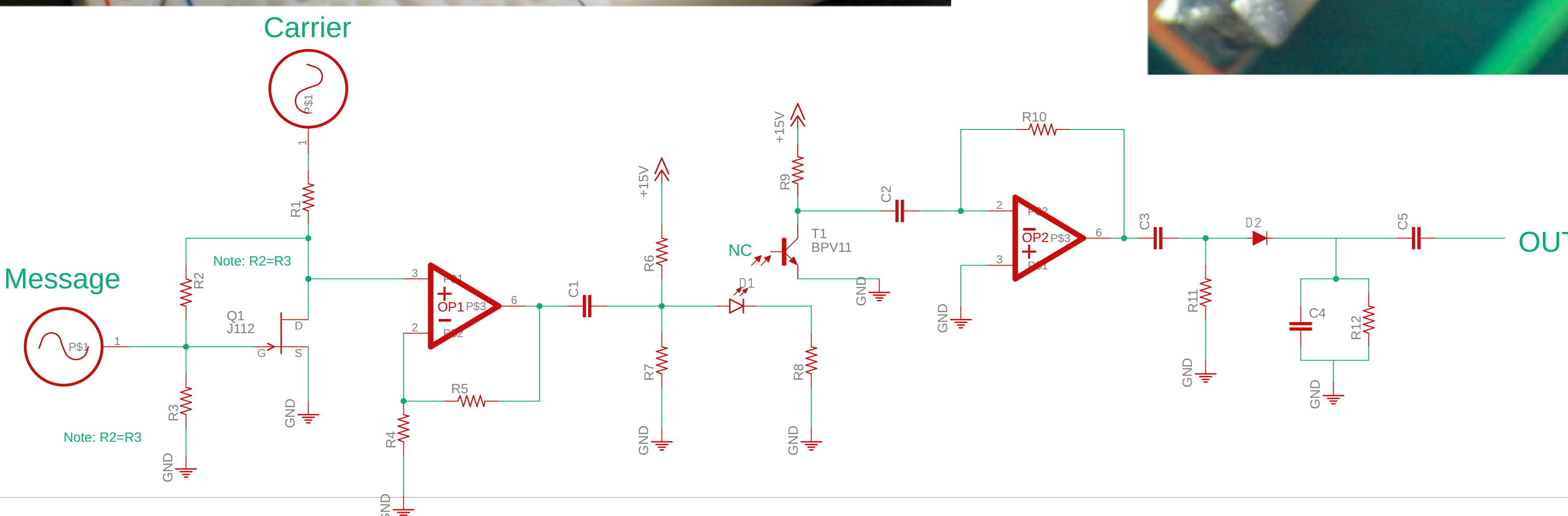
PHYS127AL Lecture 1

David Stuart, UC Santa Barbara







Introduction: Course goals

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Sensing is the basis of experiment, and analog electronics is about sensing and processing information. All modern experiments have a FET between the physics and the physicist.

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- Electronics is a good way to practice important physicist skills:
  - Debugging, which is just applying the scientific method in a controlled system.
  - Approximations
  - Effective theories
  - Intuition
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  - Pragmatism, ie learn or invent whatever is needed to get it done, where 'it' can be big, like detecting dark matter or alien life.

Introduction: Course administration

Syllabus

Textbook, ELog, Breadboard kits

Grades: 40% labs, 15% homework, 15% quizzes, 30% final exam

The labs are key. Attendance required; announcements at beginning.

Read the grading guidelines.

Ask the TAs and LAs questions if you get stuck.

They can help you learn to debug.

Introduction: Course administration

Office hours

A: Friday 3:00 - 4:00 in lab

B: Wednesday 3:00 - 4:00 in lab

C: Monday 2:30 - 3:00 in lab

Vote for:

A+B

A+C

B+C

Introduction: How to do well

Read the textbook before class and before lab.

Don't fall behind; topics build on each other. We have a lot to cover.

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This class is different from most physics classes.

Embrace the differences and appreciate the connections.

- Connections: approximations, effective theories, multiple solutions
- Differences: trade-offs so there is no single “right answer”, get comfortable treating things as a “black box”, forestry vs botany.

Fundamental observables in electronics

The fundamental observable is charge, electrons.

$q(t)$ and $dq(t)/dt$

and physically connected quantities, specifically the current and the voltage.

$I(t) = dq(t)/dt$ is the current of charges flowing *through* a point.

$$V(t) = \int_a^b \vec{E}(t) \cdot d\vec{x}$$ Is the voltage *between* points a and b.

But this E&M definition is too detailed for what we need.

A more useful definition is: voltage is the potential energy per unit charge.

$W_{ab} = q\,V_{ab}$ meaning the work done moving a charge from a to b,

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I through a point and V between points.

I through a component and V across a component.

Fundamental observables in electronics

Information is carried in the time dependence of current and voltage, I(t) and V(t).

Since it is the time variations in I and V that carry information, more than some offset value, the "small-signal variations" of current and voltage are given the lowercase symbols i and v. Think of these as

$$i = \delta I \quad \text{and} \quad v = \delta V$$

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$$i = \delta \mathrm{I} \qquad \text{and} \qquad v = \delta \mathrm{V}$$

A simple example of I(t) and V(t) carrying information is music through a speaker. V(t) carries the music information, and causes a corresponding I(t) to flow through a magnet pushing a diaphragm that produces sound as p(t). A microphone is the same thing in reverse.

Physical input ⇒ I(t) ⇒ V(t) ⇒ Processing ⇒ I(t) ⇒ Physical output

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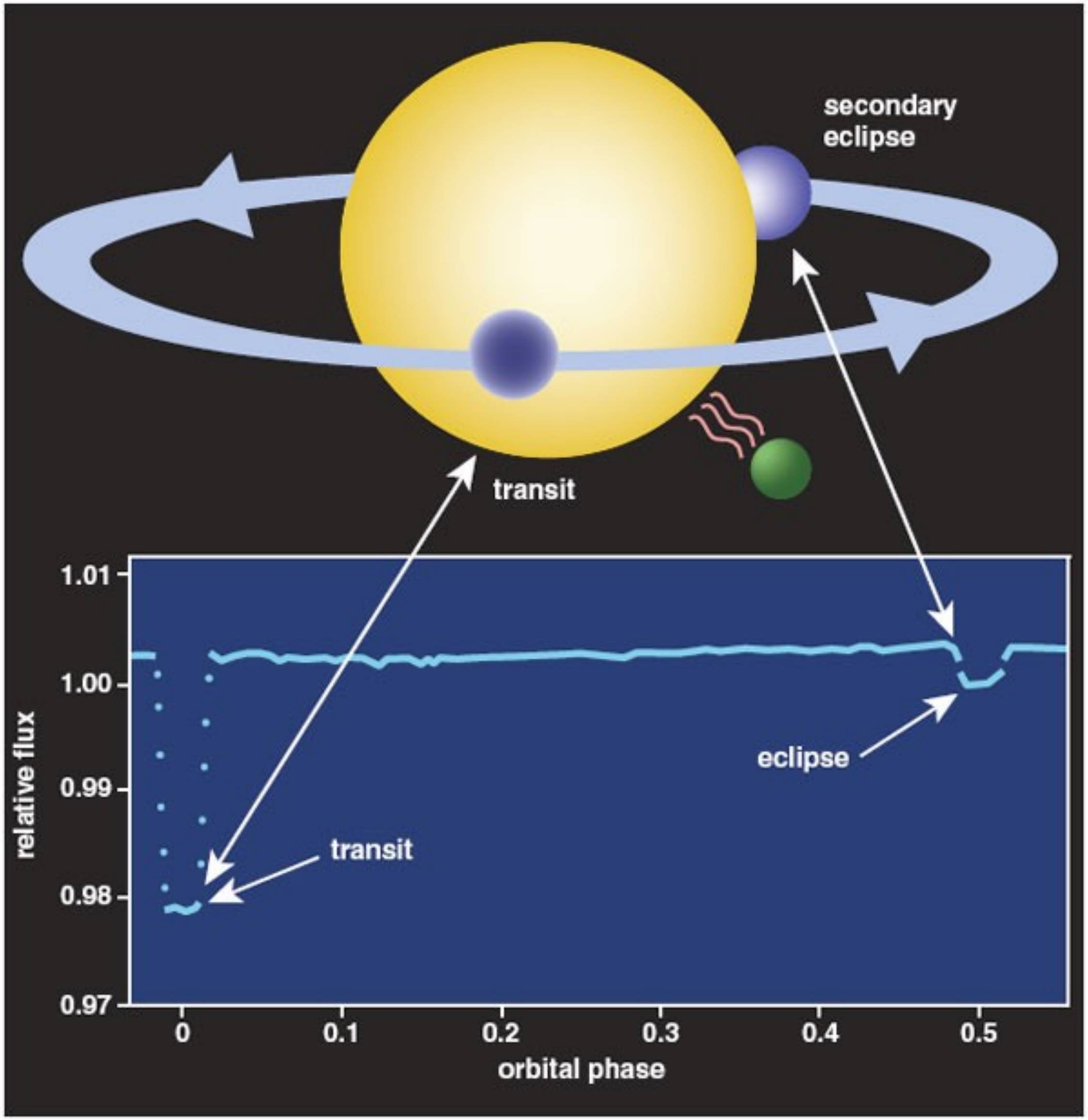
First detect an exoplanet through reduced observed flux during transits.

Measure $N_\gamma(t)$.



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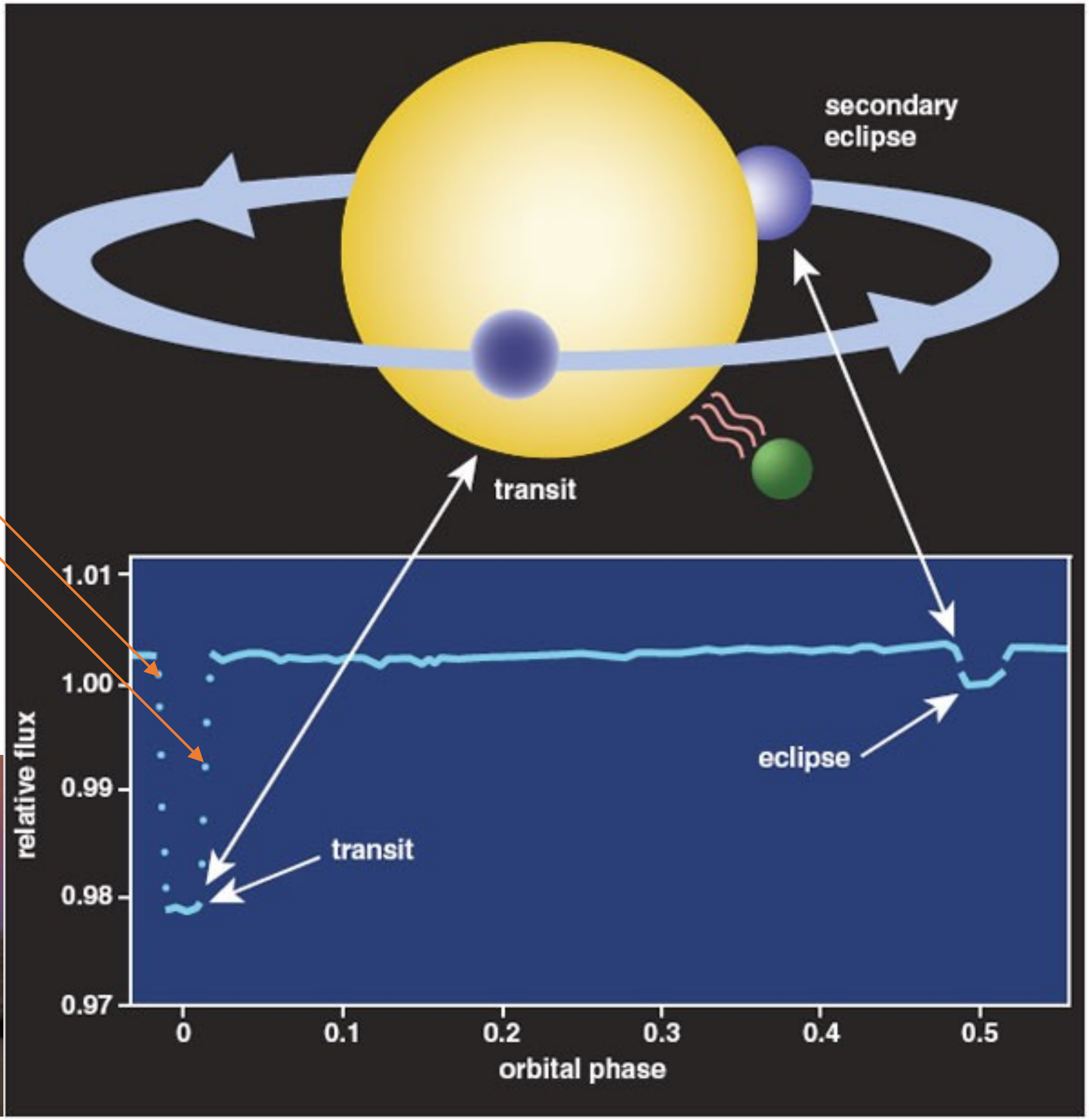
First detect an exoplanet through reduced observed flux during transits.

Measure $N_\gamma(t)$.

Then look at the alien sunsets and measure atmospheric composition with spectroscopy $N_\gamma(\lambda,t)$ to see if there are organic signatures.



An example of using electronics for a measurement

So measure $N_\gamma(t)$ at various positions along a grating's spectrum, $N_\gamma(t,\lambda)$.

For that we need a photon detector, aka photodetector.

PD converts $N_\gamma(t) \Rightarrow N_e(t) \Rightarrow I(t)$.

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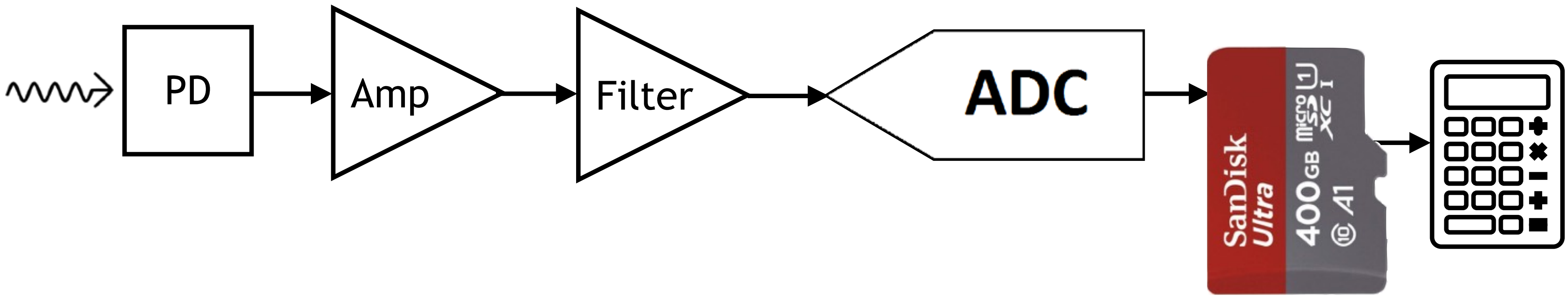
These are stages in a processing pipeline ⇒ stages in a circuit.

We can sketch those stages as shown below.



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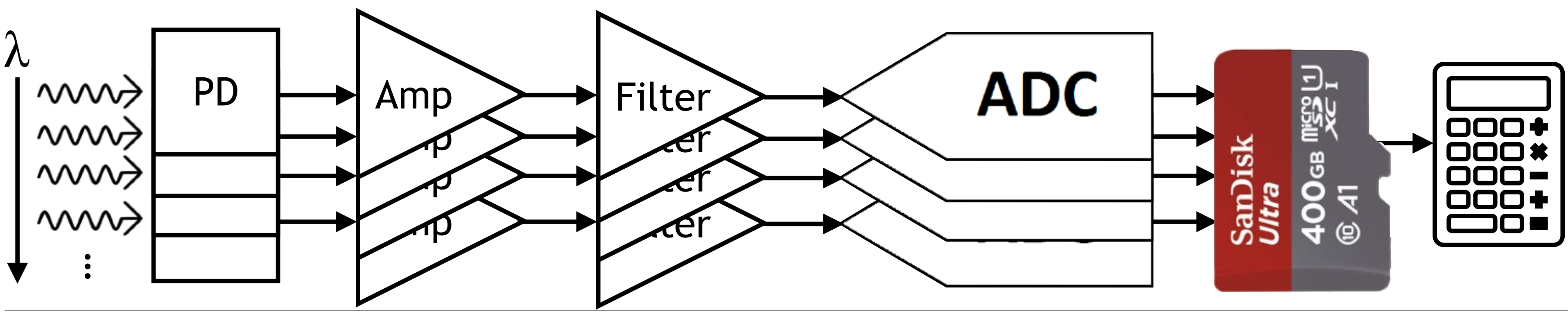

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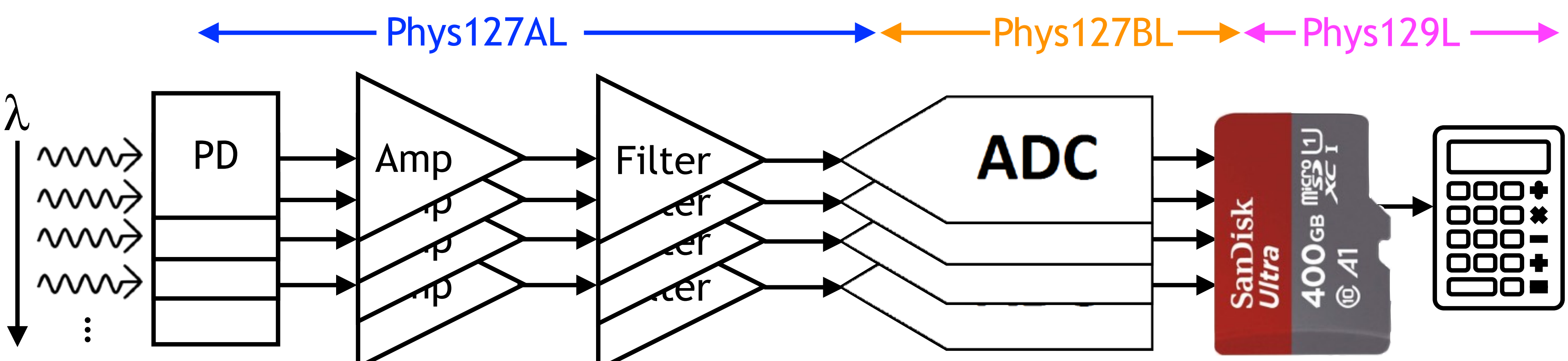
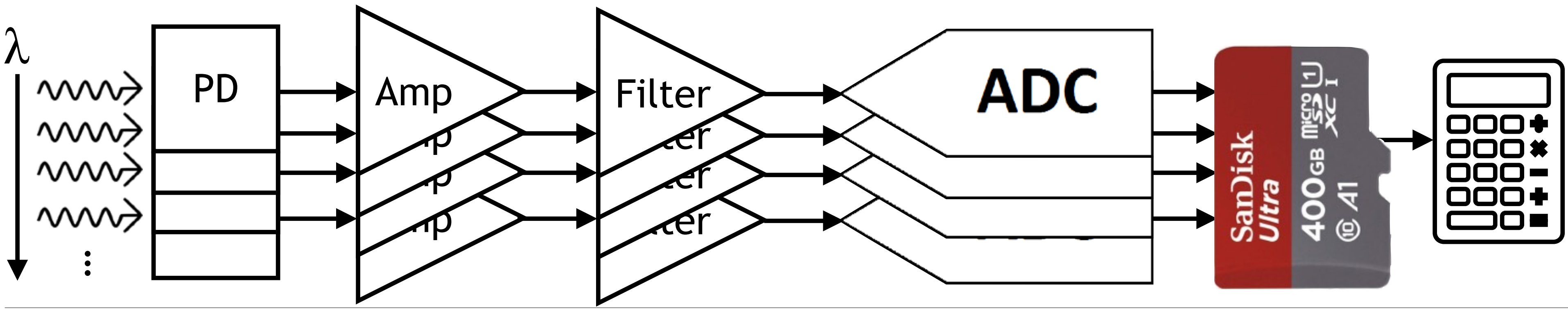


Independent circuit stages

Building a circuit out of *independent stages* is a great simplification.

We can treat the photodetector as a black box as long as we know its IO.

Same with the amplifier, etc.



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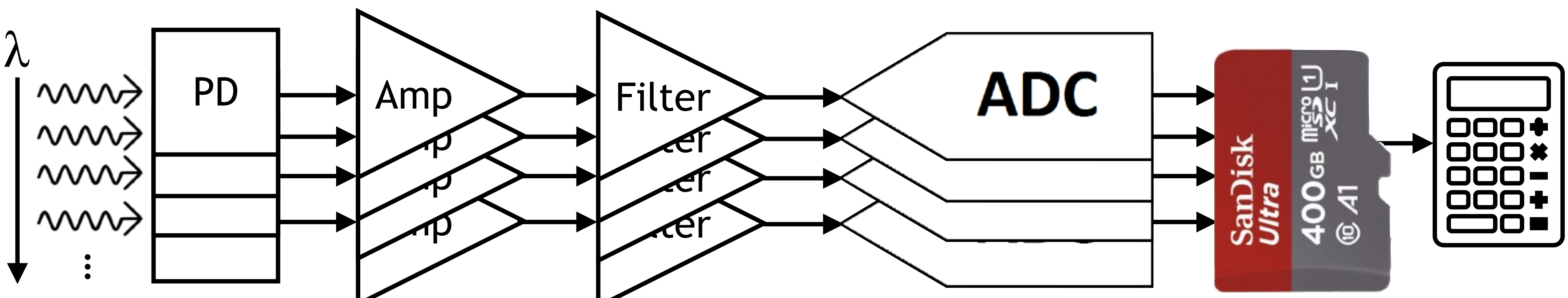
We'll learn about each of these in the course, but you don't have to deal with all the details of each stage to build a usefully complex circuit.

Each stage simply needs to have a well defined input and output, then you can put them together like LEGO blocks.

But that requires *well-defined input* and *output*, and *independence*.

That independence is a key idea that will run through the course.

I'll illustrate it with a simple example in a bit.



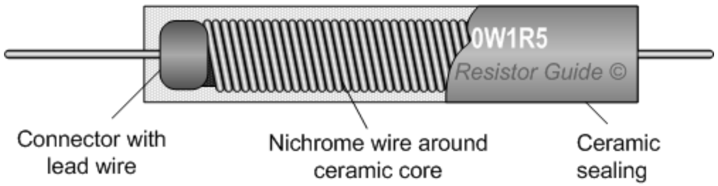
Resistors

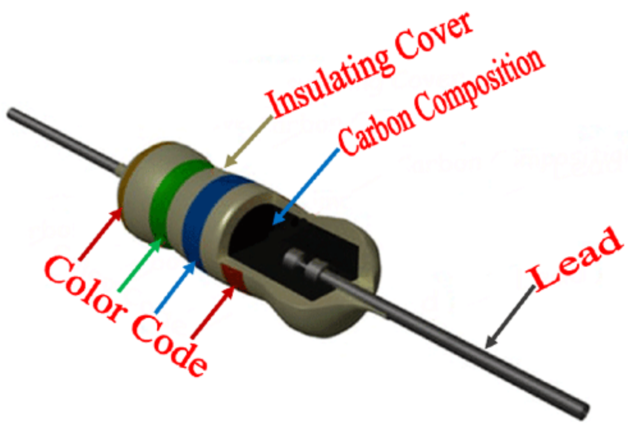
But first we need some simple components with which to build circuits.

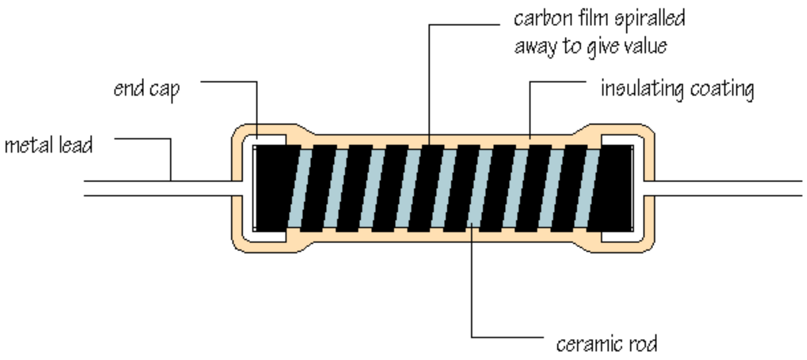
The simplest is a resistor.

Can be made in several ways.

Typical precision is 10%, 1%, or 0.1%.







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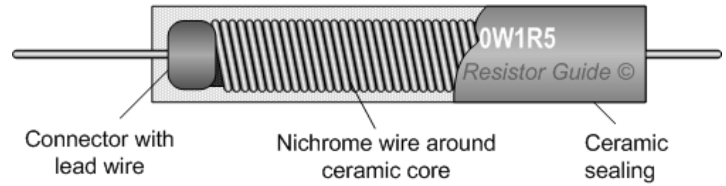
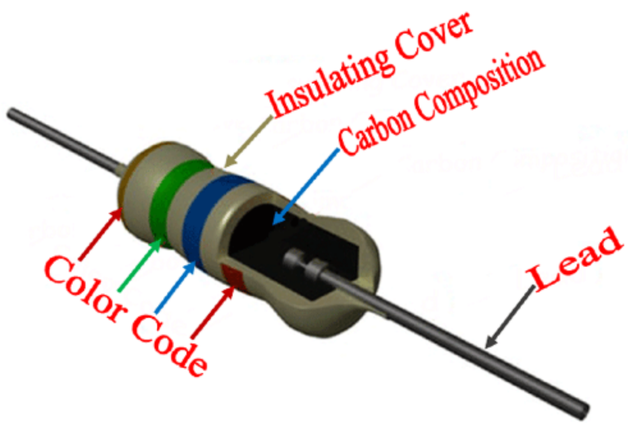
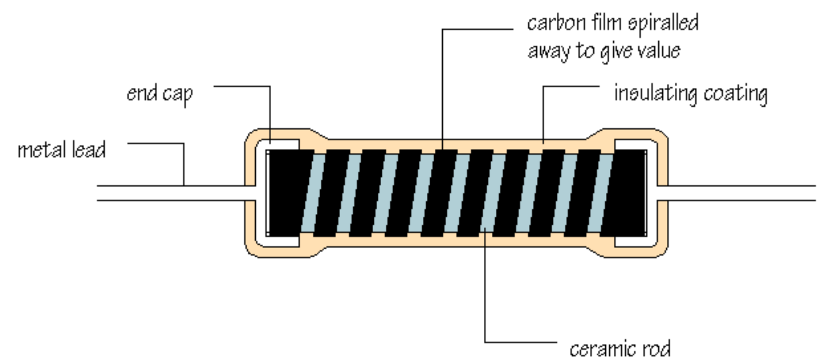
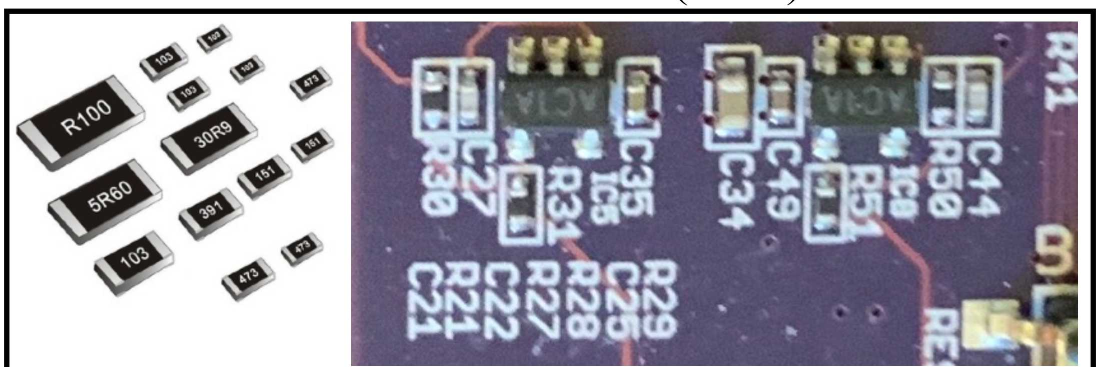






Surface Mount (SMT)



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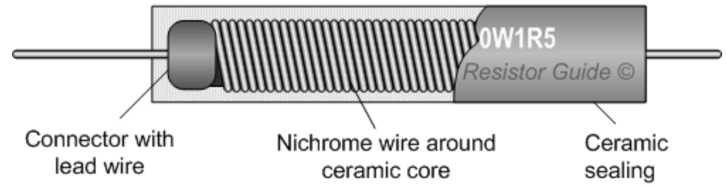
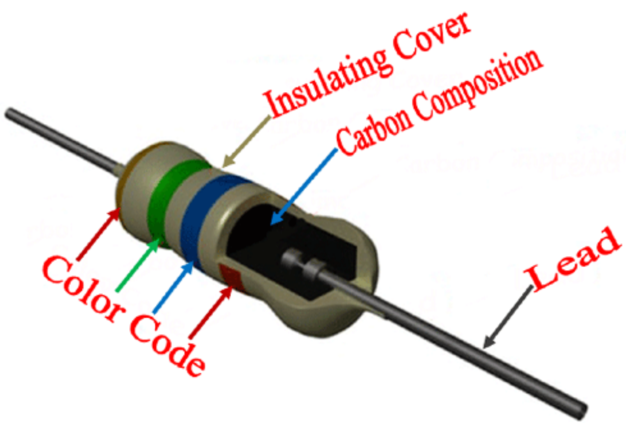
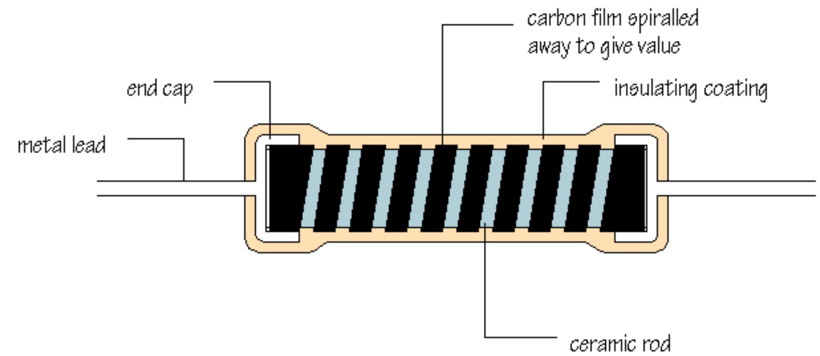
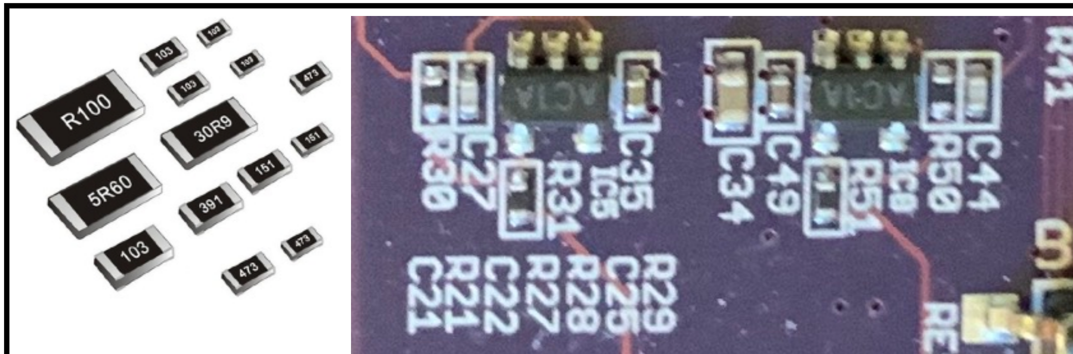






Intuitive circuit symbol

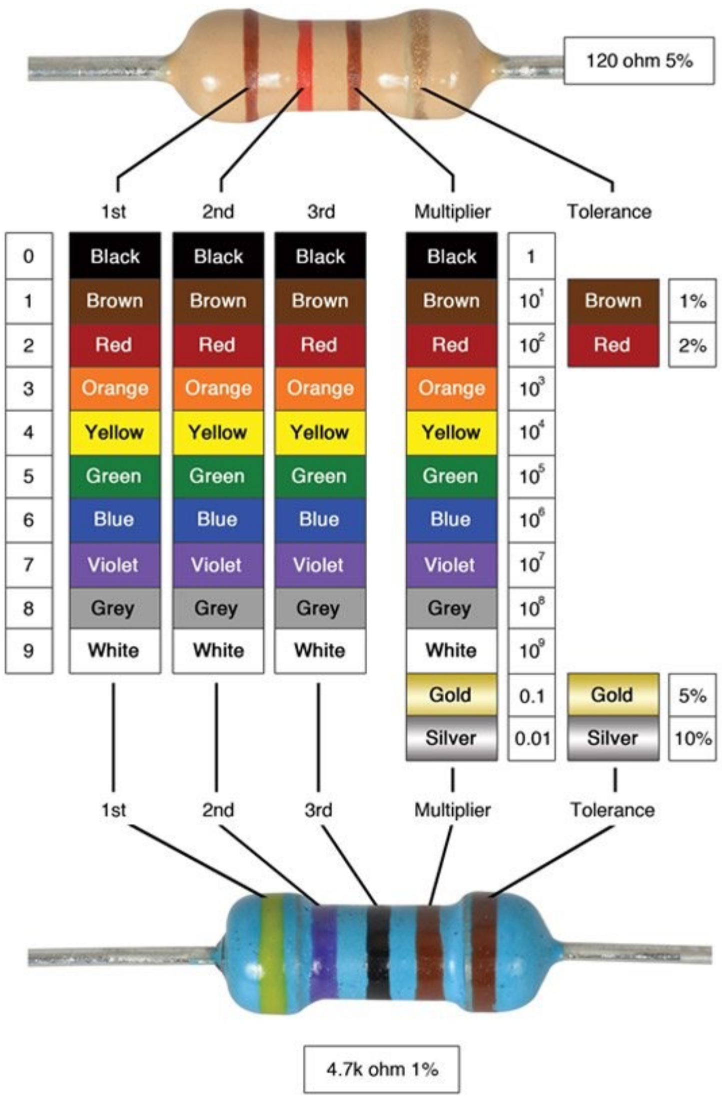
Surface Mount (SMT)



Resistor values

The leaded resistors you will use are marked with a color code.

Learn it to save yourself time.



Resistors come in standard values:

Ecobion Labs - Common E6 and E24 (bold) Resistor Values

1	**10**	**100**	**1K**	**10K**	**100K**	**1M**	**10M**
1.2	1.2	1.2	1.2	1.2	1.2	1.2	
1.5	**15**	**150**	**1.5K**	**15K**	**150K**	**1.5M**	
1.8	18	180	1.8K	18K	180K	1.8M	
2.2	**22**	**220**	**2.2K**	**22K**	**220K**	**2.2M**	
2.7	27	270	2.7K	27K	270K	2.7M	
3.3	**33**	**330**	**3.3K**	**33K**	**330K**	**3.3M**	
3.9	39	390	3.9K	39K	390K	3.9M	
4.7	**47**	**470**	**4.7K**	**47K**	**470K**	**4.7M**	
5.6	56	560	5.6K	56K	560K	5.6M	
6.8	**68**	**680**	**6.8K**	**68K**	**680K**	**6.8M**	
8.2	82	820	8.2K	82K	820K	8.2M	

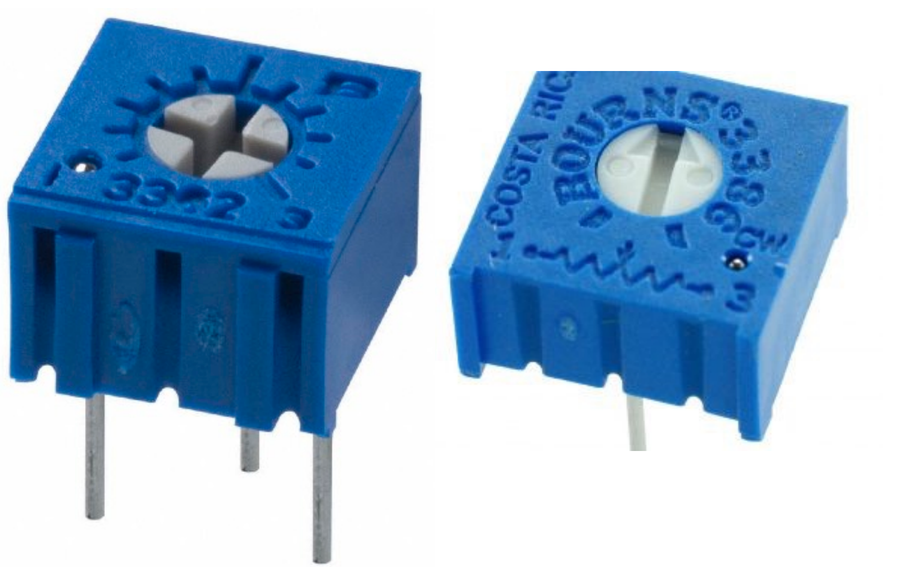
Other values are available but rarer.

Precise values rarely matter in good designs.

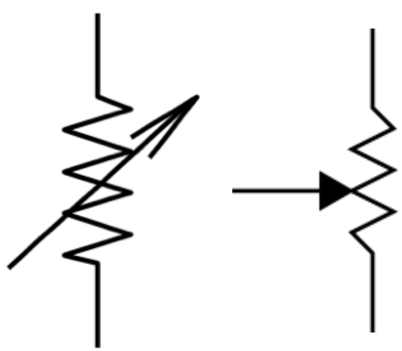
Special resistors

There are some special types of resistors

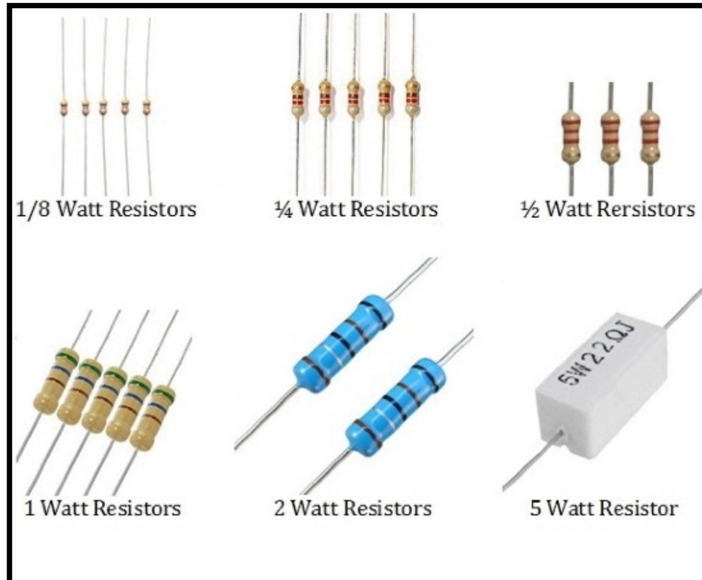
Variable resistors, aka potentiometer or trimpot



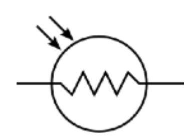
Two common circuit symbols:



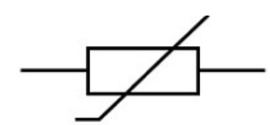
Power resistors



Light Dependent Resistor (LDR)



Thermistor



Ohm’s law

Ohm’s law relates the voltage change across a resistor to the current passing through it.

$$V = I\,R$$

It is not universal; many components have non-linear IV relationships.

In fact this really just defines what we mean by R:

$$R \equiv \frac{dV}{dI}$$

“Resistors have fairly a linear IV relationship, and the slope is what we call the resistance”.

Practically, it means:

A voltage V across R will cause a current I to flow through it, or

a current I through R will cause a voltage drop of V across it.

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Ohm's law

$V = I R$ means:

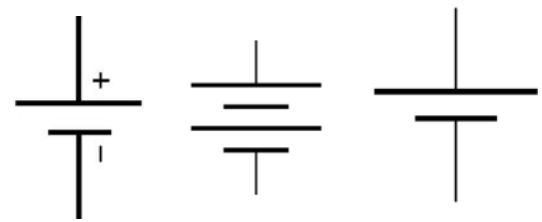
A voltage V *across* R will cause a current I to flow *through* it, or

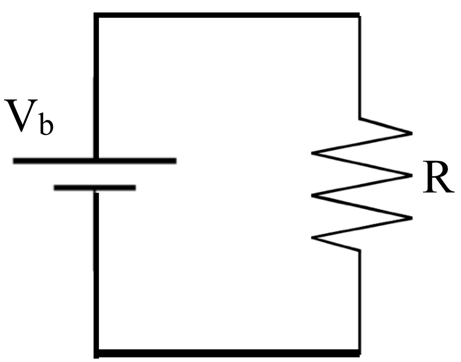
a current I *through* R will cause a voltage drop of V *across* it.

So connect a battery across it.

Several symbols used for batteries.

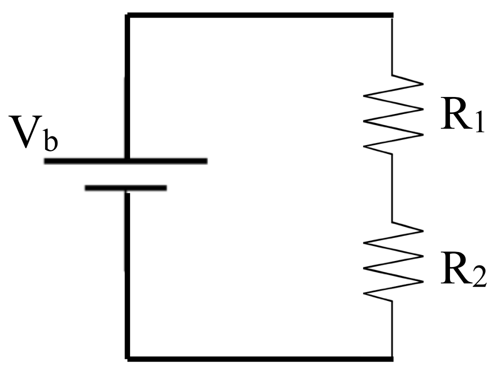
Often labeled with the battery's EMF.





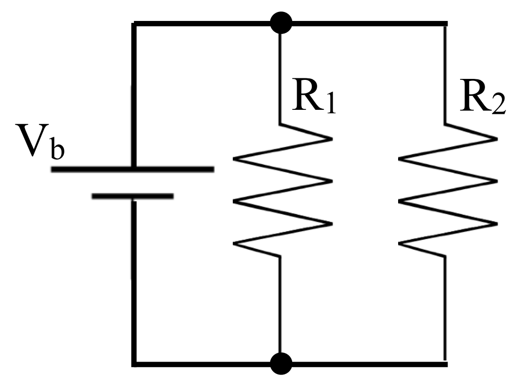
Current through R is

$I = V_b/R$



Current through R_1 is

$I = V_b/(R_1+R_2)$



Current through resistors is

$I_1 = V_b/R_1$ and $I_2 = V_b/R_2$

In series: $R_T = R_1+R_2$. In parallel: $1/R_T = 1/R_1+1/R_2 \Rightarrow R_T = R_1R_2/(R_1+R_2)$

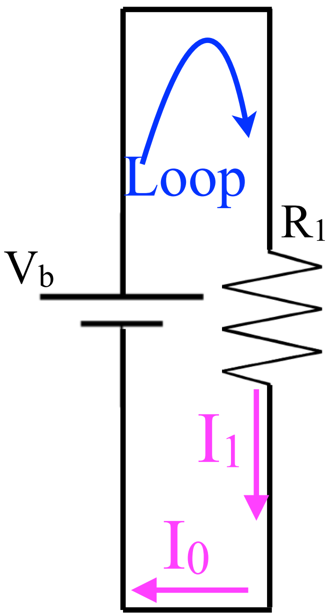
Kirchoff's laws

These are described well in the text and you will have homework on it.

Here, I only want to describe them physically as

Charge conservation, i.e., net current in = net current out at each point

Energy conservation, i.e., voltage increases = voltage drops around loop



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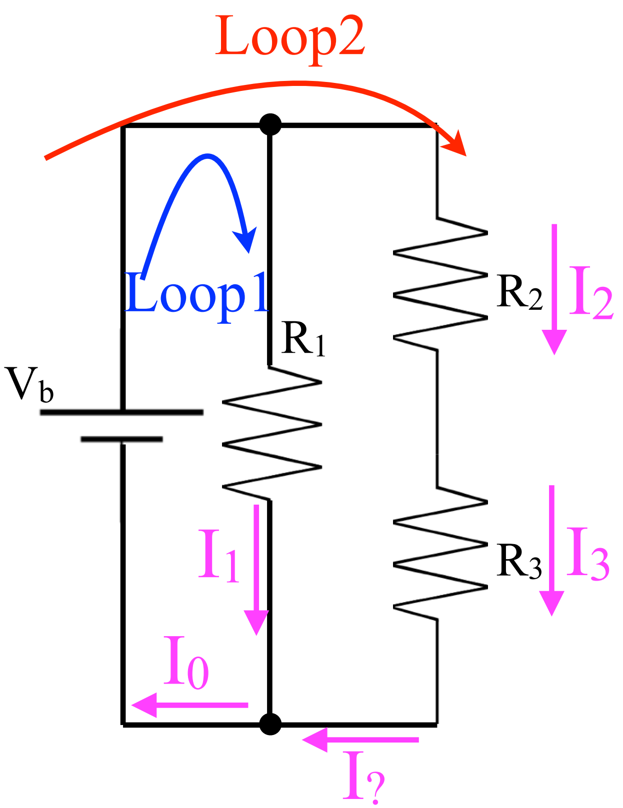
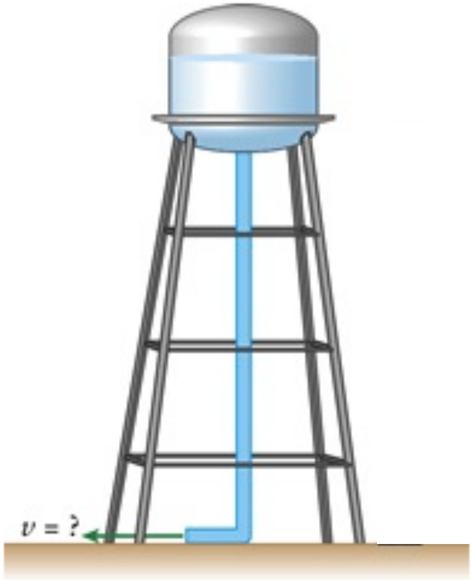


An intuitive model for voltage and current

It is helpful to have an intuitive model for voltage and current, and water flow works pretty well: flow of mass rather than flow of charge.



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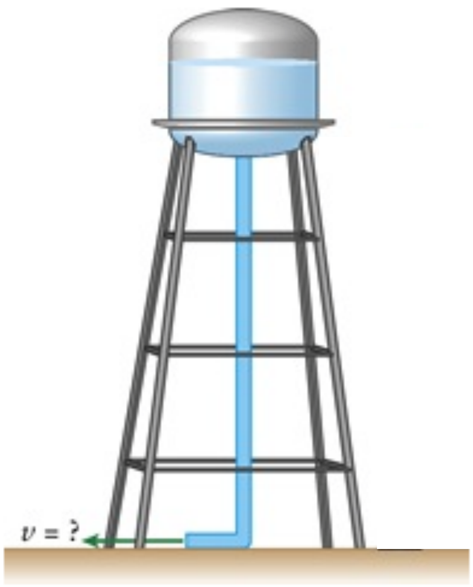

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Potential is the same in tank below water surface due to pressure, but pressure drops while flowing through a "resistive pipe". A battery is like pumping water back up to the tank.

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Current can be described as

$$I = A\,q\,v$$

- v → velocity
- q → charge per carrier
- A → area of “pipe”

$I \propto A \;\Rightarrow$ fatter conducts better

An intuitive model for voltage and current

It is helpful to have an intuitive model for voltage and current, and water flow works pretty well: flow of mass rather than flow of charge.

Current can be described as

$$I = n\,A\,q\,v_d$$

- v_d → drift velocity
- q → charge per carrier
- A → area of "pipe"
- n → number density of charge carriers

$I \propto A \Rightarrow$ fatter conducts better

$I \propto n \Rightarrow$ copper vs glass
will be important with semiconductors later

Resistivity = 1/conductivity

Resistance is a bulk property

Resistance

1 Ohm = 1 Ω = 1 V/A = 1 (J/C)/(C/s)

0.1 ohm for a typical wire
100 ohm is a low resistance
1k - 10k is typical value in our circuits
1M is large
Rarely use values larger than 10M

Common jargon leaves off the Ω; can just say "a 10k resistor".

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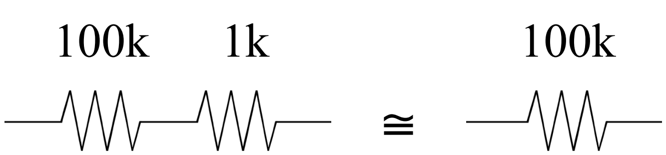
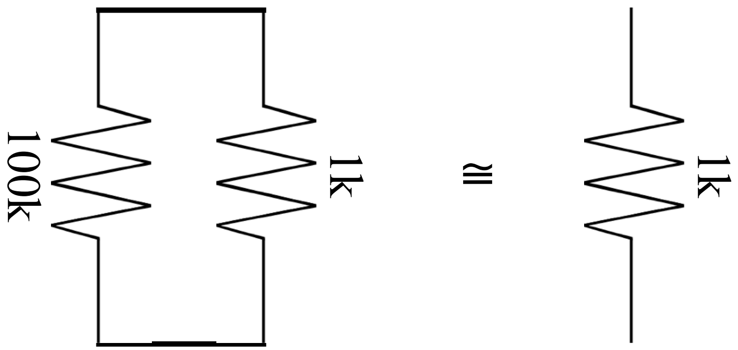
0.1 ohm for a typical wire
100 ohm is a low resistance
1k - 10k is typical value in our circuits
1M is large
Rarely use values larger than 10M

Common jargon leaves off the Ω; can just say "a 10k resistor".
In this course we won't worry about precision more than about 10%.





In series: $R_T = R_1 + R_2$. In parallel: $1/R_T = 1/R_1 + 1/R_2 \Rightarrow R_T = R_1R_2/(R_1+R_2)$

Equivalent Resistance

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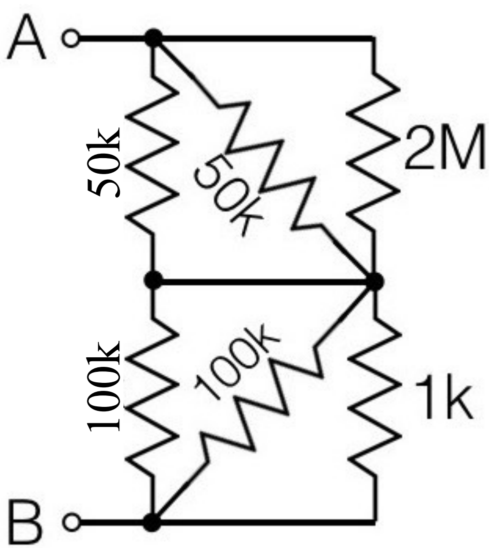

$\cong$?

The open circles indicate terminals of the circuit, ie input/output points.

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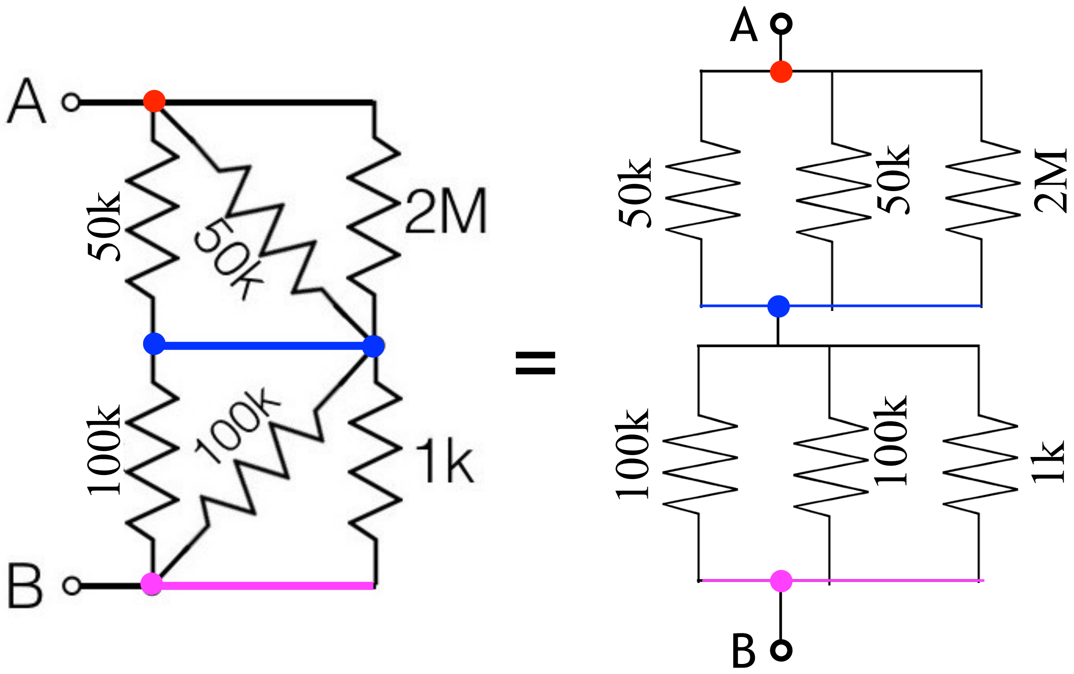

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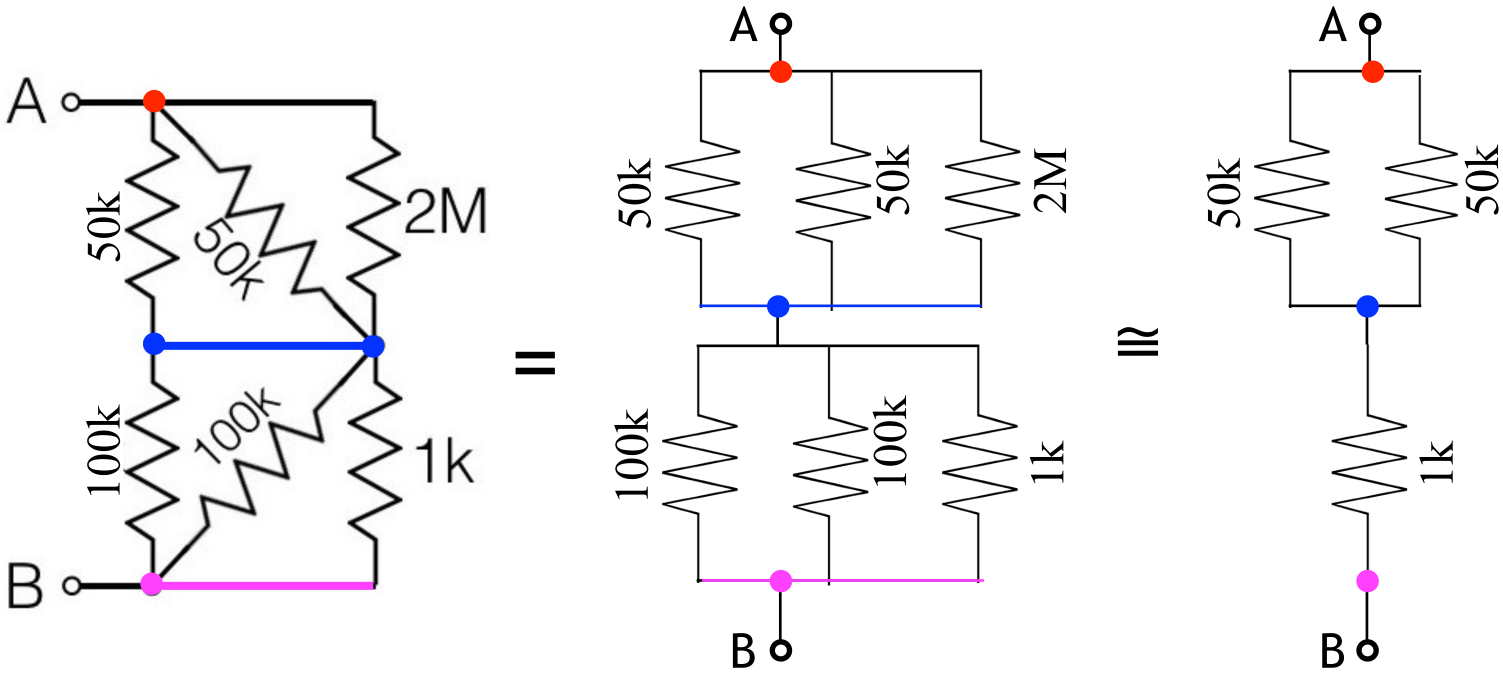

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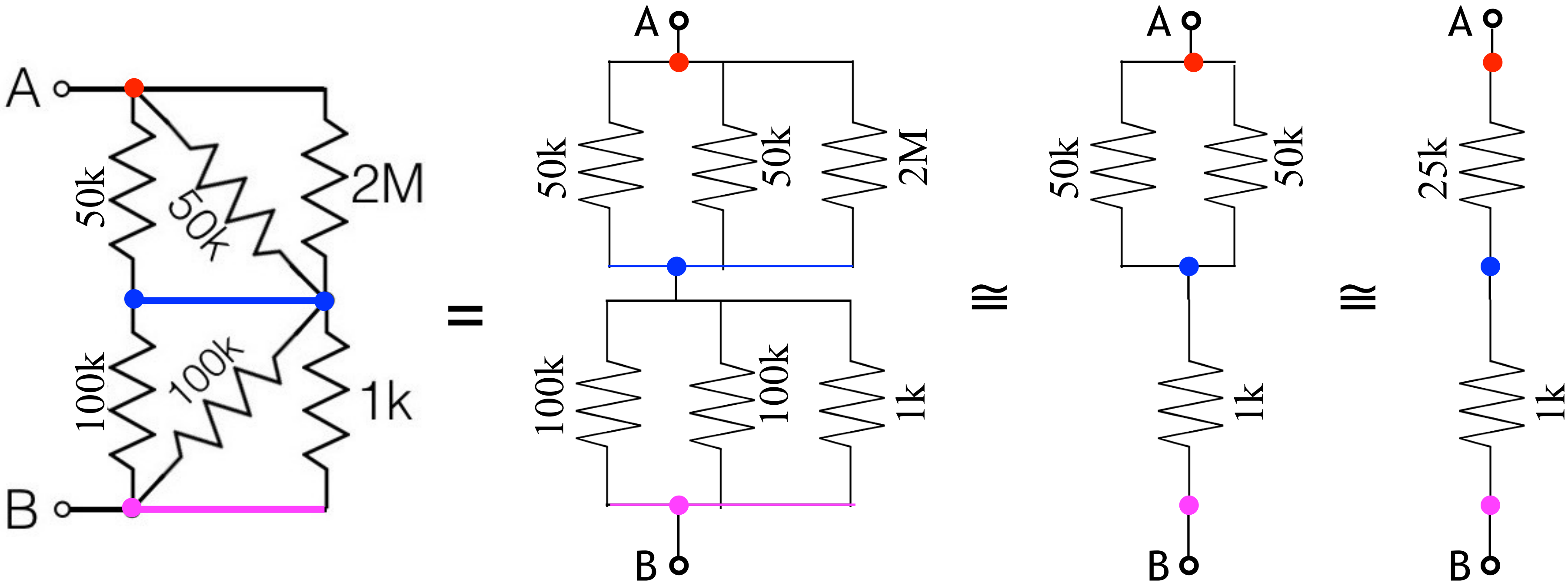

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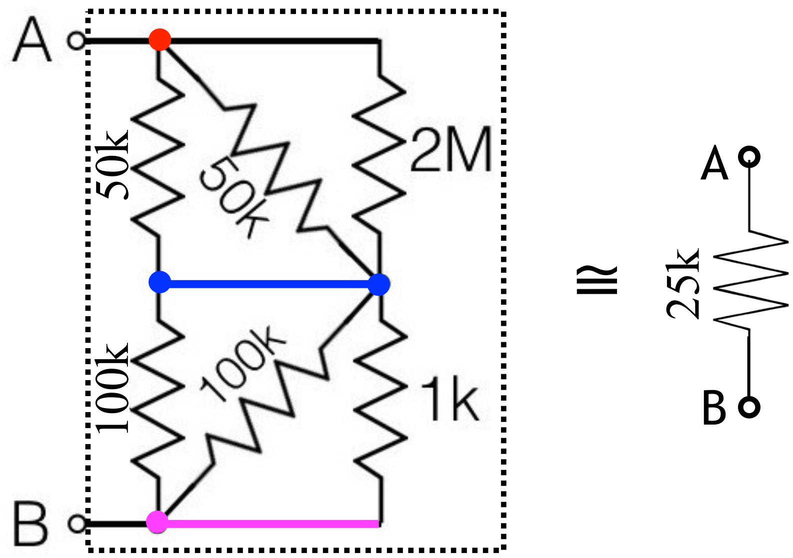
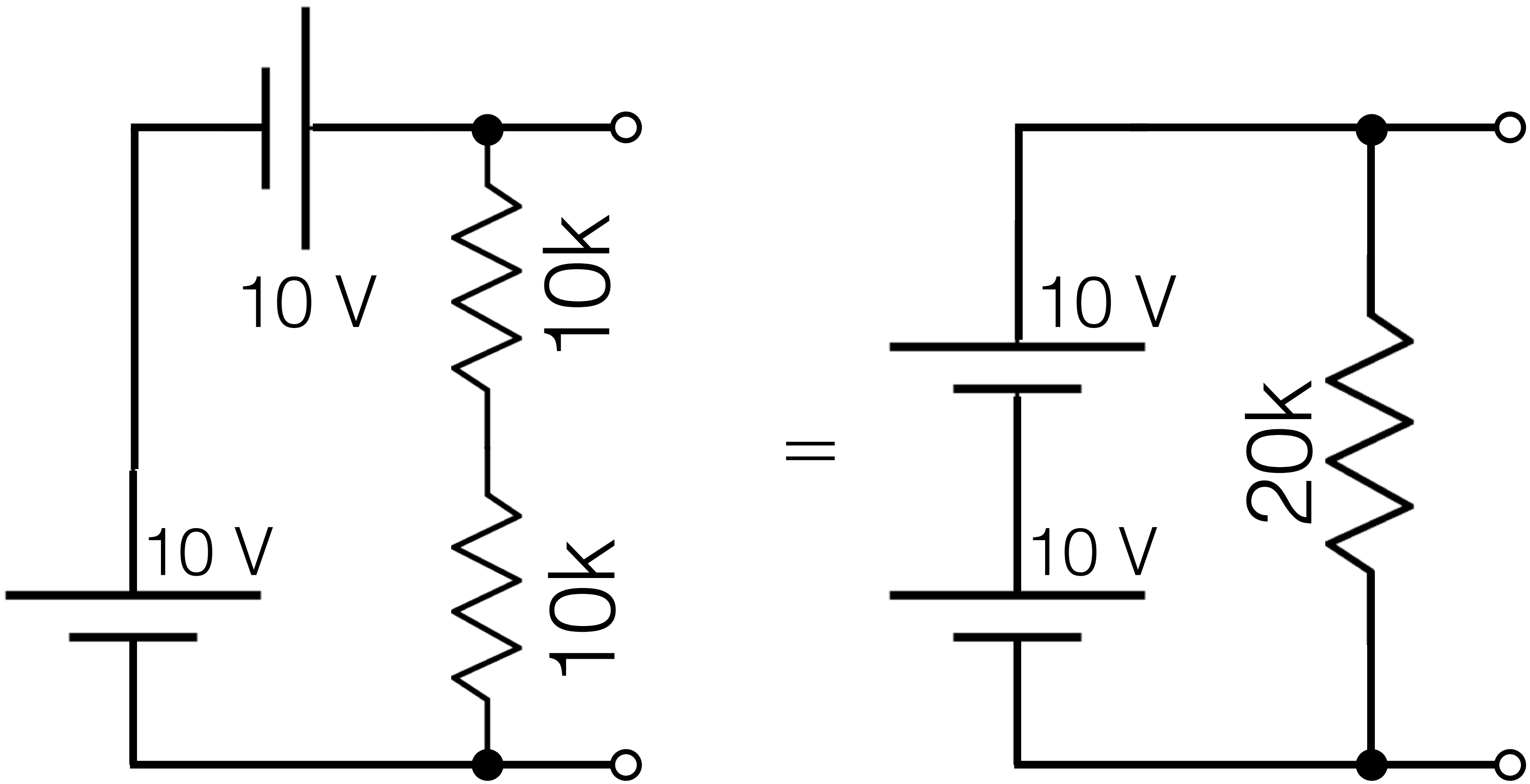


Any complicated mix of resistors can be treated as equivalent to a single resistor, which follows the same V = I R, i.e., the same IV relation.

Equivalent Circuits

You can also find an equivalent circuit if we mix voltage sources and resistors



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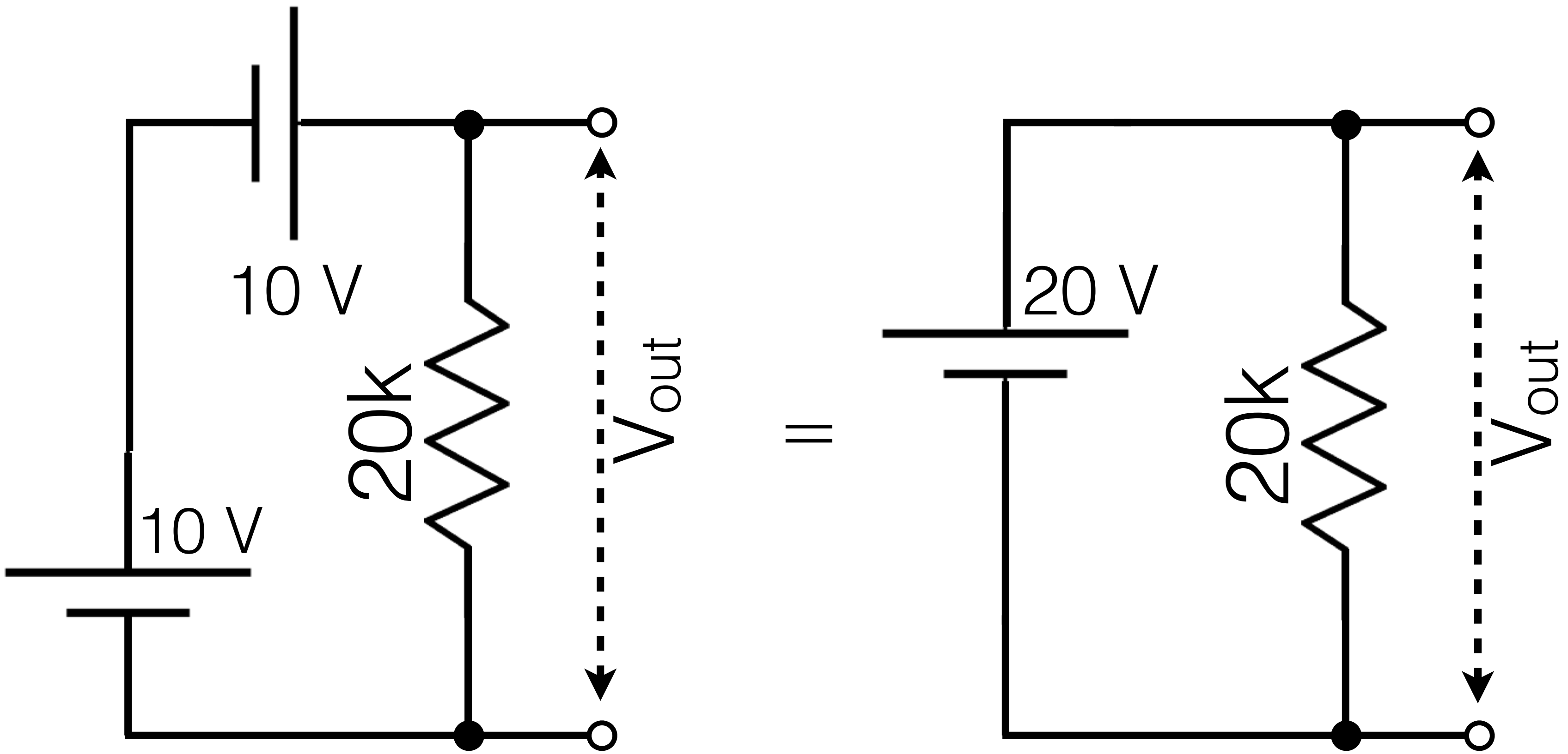
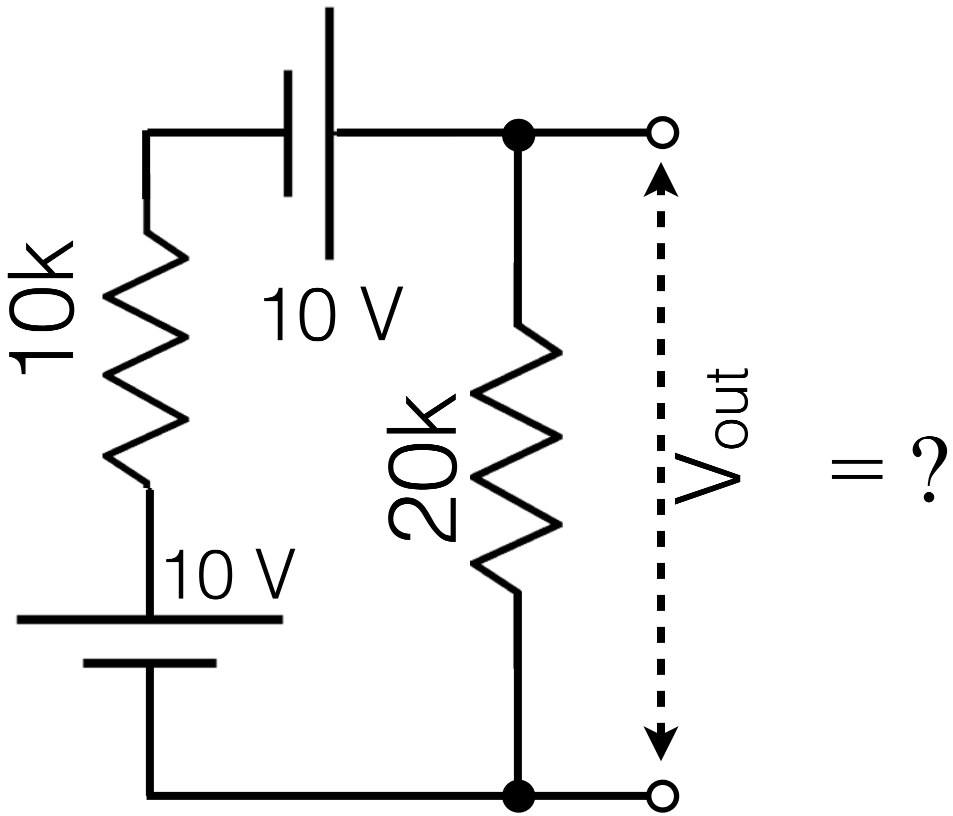


The two circuits behave the same, i.e., the have the same Vout, even if I connect another component or stage across the output. Same I vs V relationship.

Thevenin Equivalent Circuits

You can also find an equivalent circuit if we mix voltage sources and resistors



This is more complicated, not just adding V's and R's, but I can find something with an equivalent IV relationship; still linear but with an offset.

$V_{out} = I(R+R_{offset}) + V_{offset}$

Thevenin Equivalent Circuits

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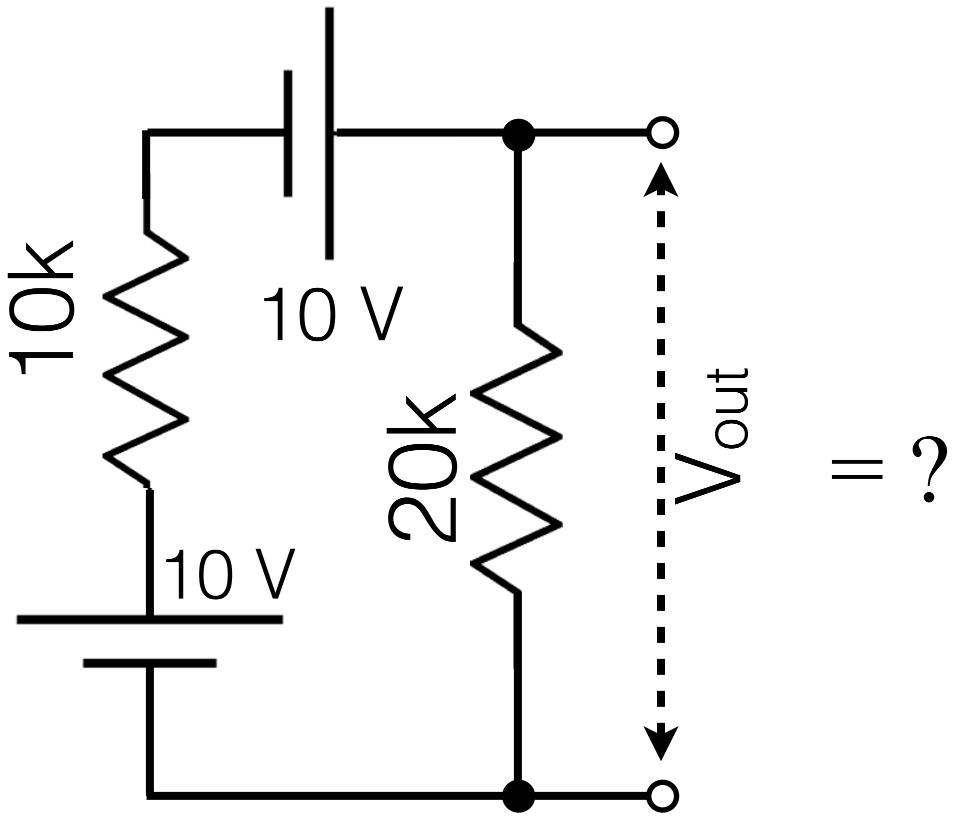

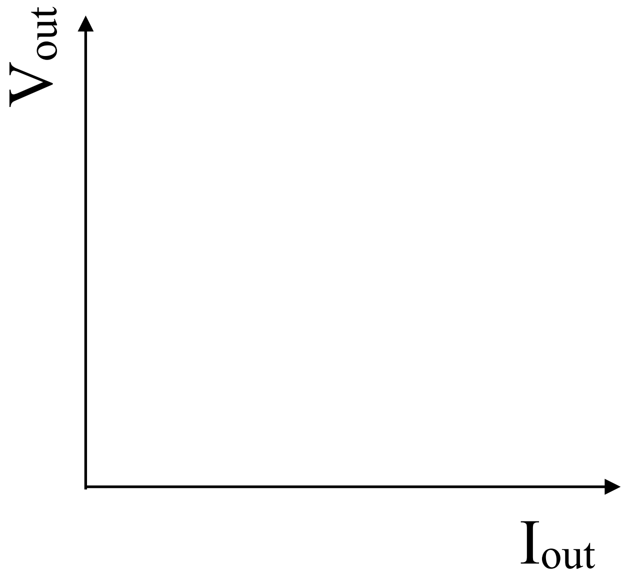

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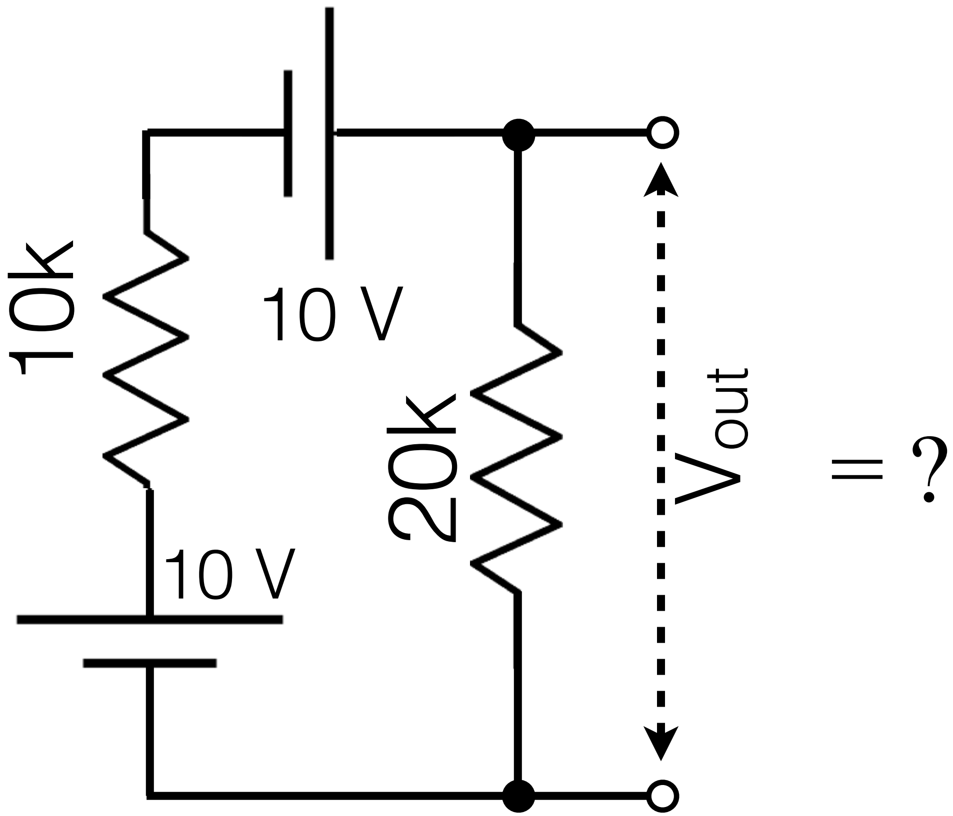

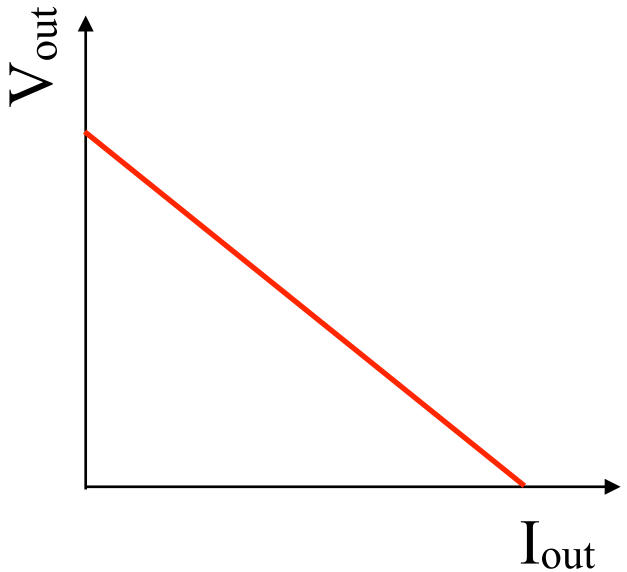

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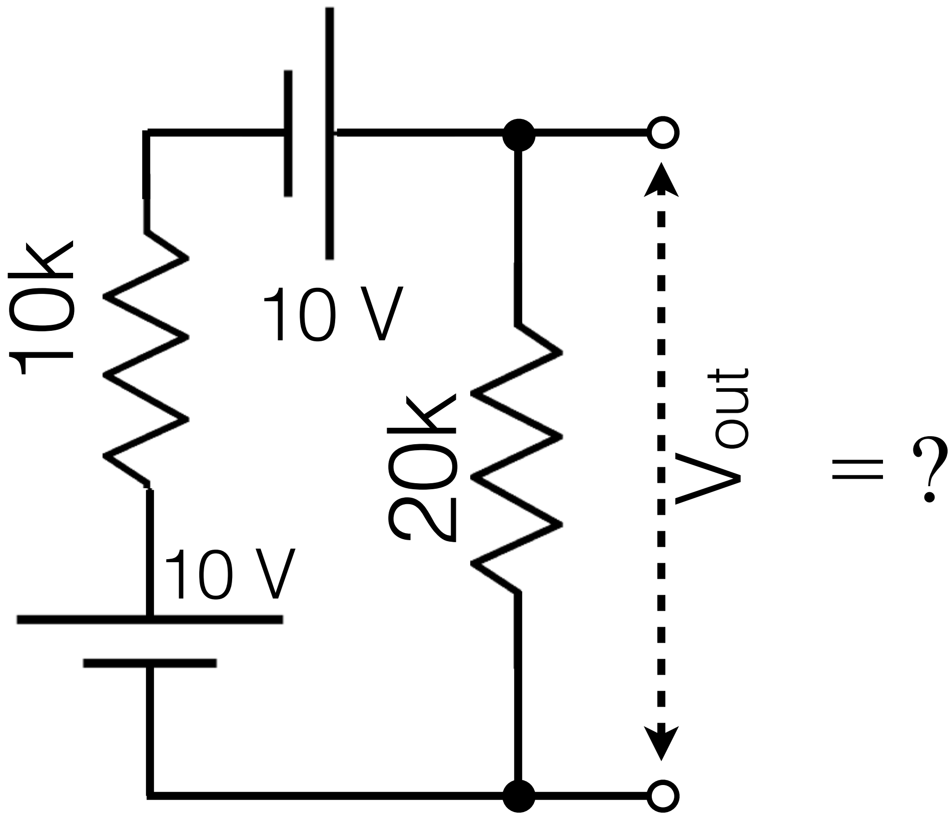

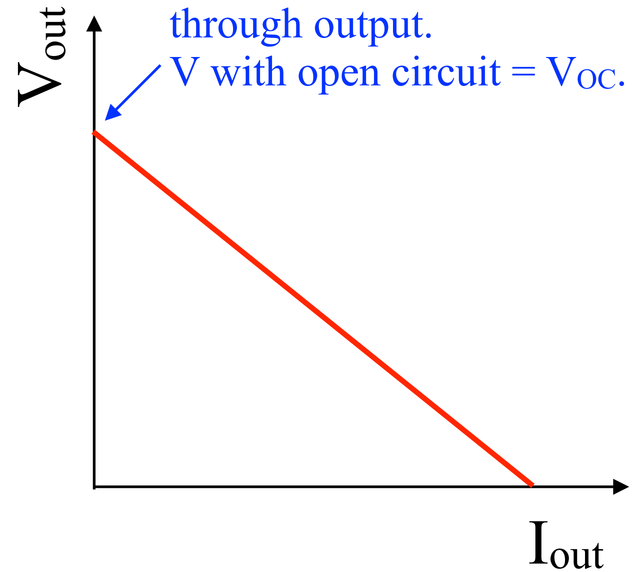

Have output voltage even with no current flowing through output.
V with open circuit = V_{OC}.

This is more complicated, not just adding V's and R's, but I can find something with an equivalent IV relationship; still linear but with an offset.

$V_{out} = I(R+R_{offset}) + V_{offset}$

Thevenin Equivalent Circuits

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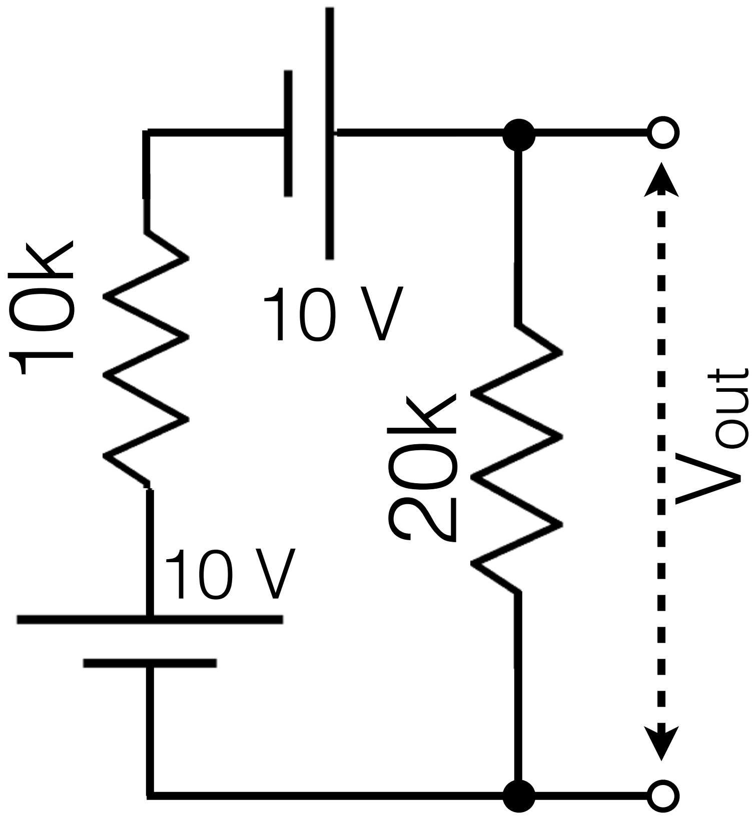

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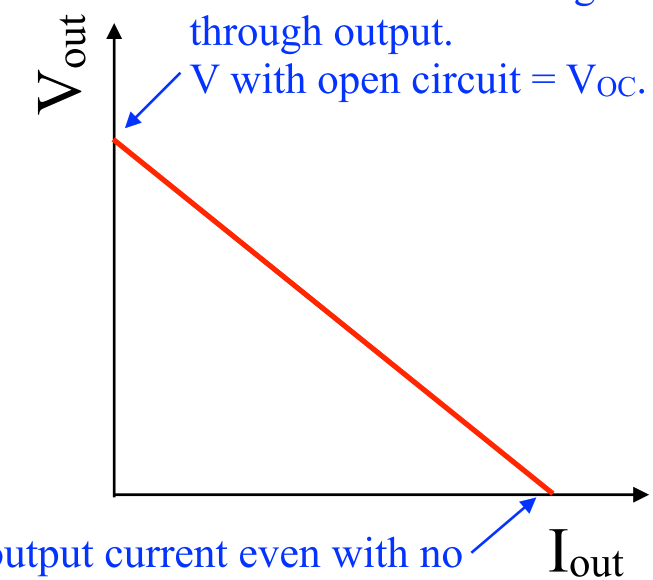

Have output current even with no output voltage, i.e., with the output connected to a short circuit.
I with short circuit = I_{SC}.

This is more complicated, not just adding V's and R's, but I can find something with an equivalent IV relationship; still linear but with an offset.

$V_{out} = I(R+R_{offset}) + V_{offset}$

Thevenin Equivalent Circuits

You can also find an equivalent circuit if we mix voltage sources and resistors

= ?

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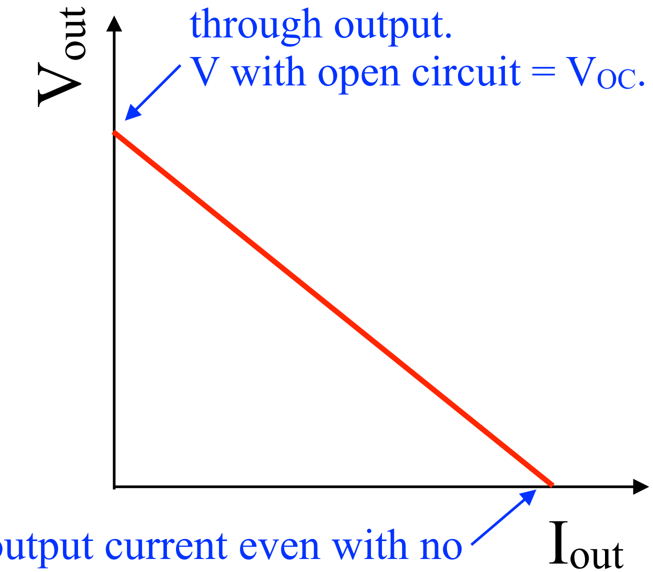
V with open circuit = V_{OC}.



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Thevenin Equivalent Circuits

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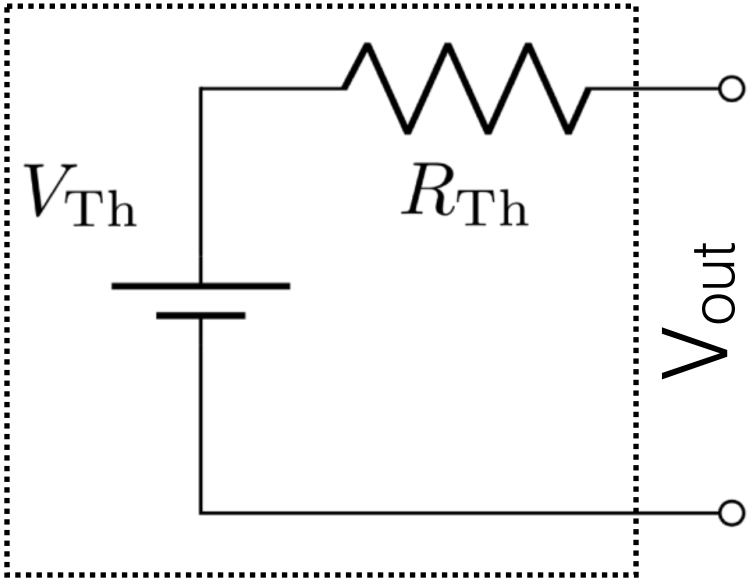

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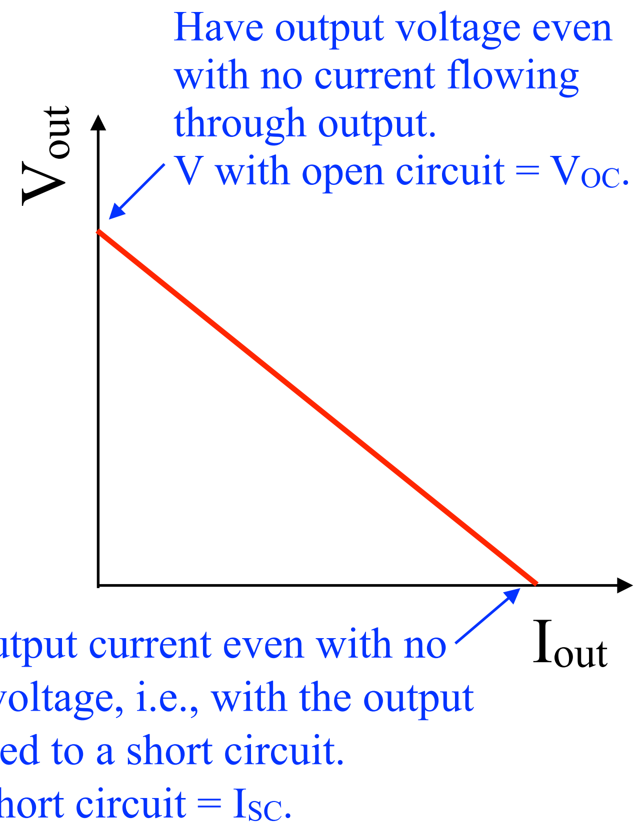

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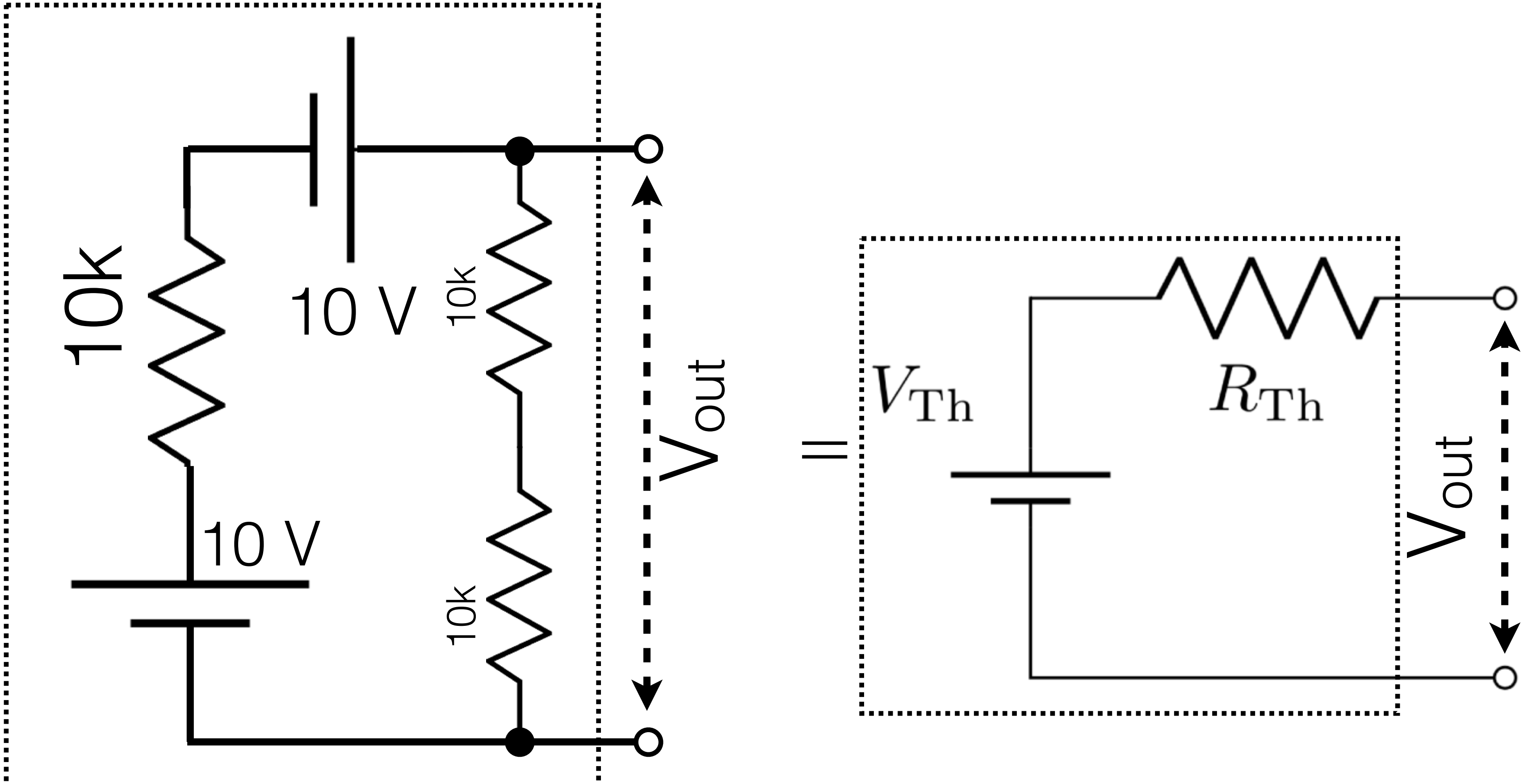
$V_{out} = I(R+R_{offset}) + V_{offset}$

Thevenin Equivalent Circuits

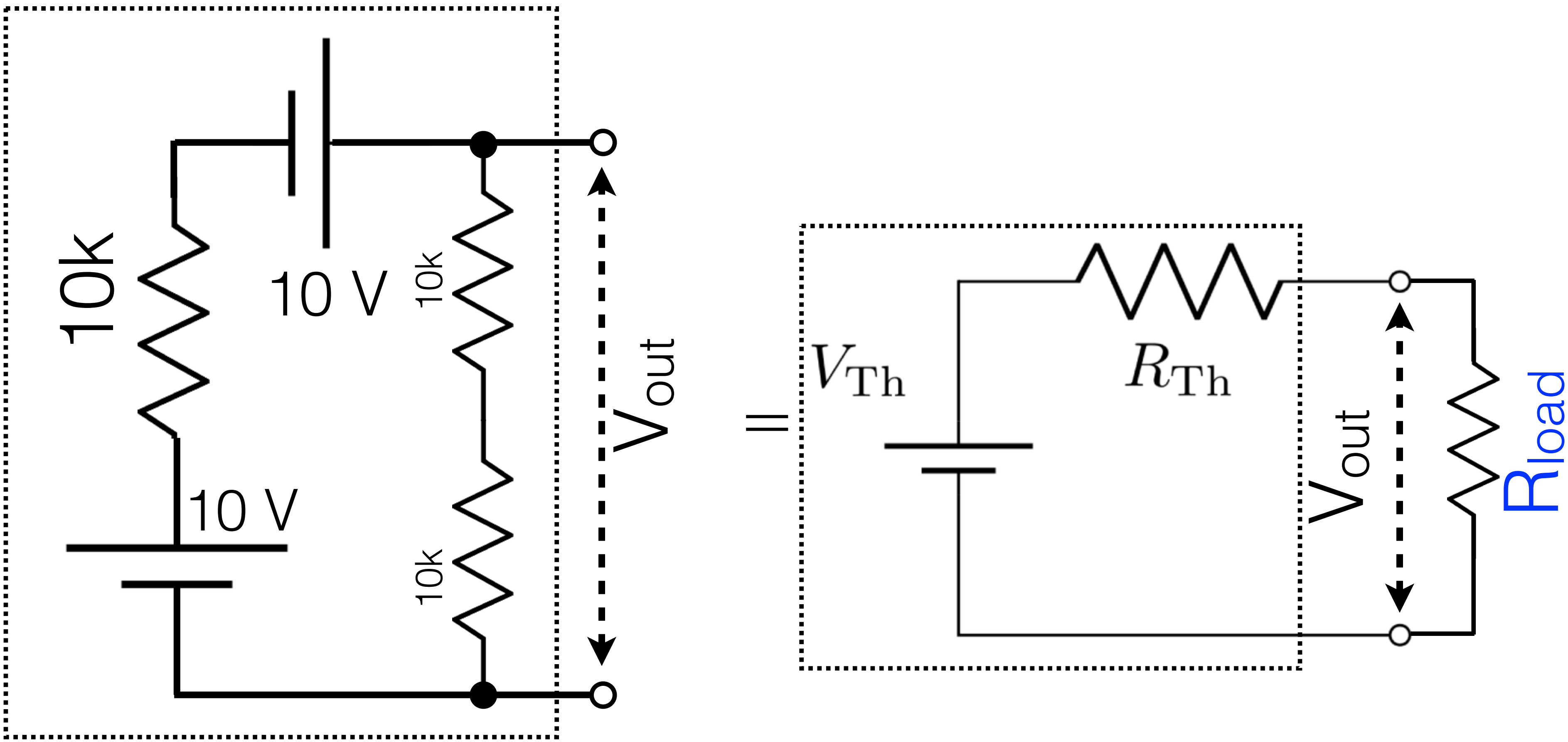
You can also find an equivalent circuit if we mix voltage sources and resistors



Any complicated mix of voltage sources & resistors can be treated as equivalent to this Thevenin equivalent circuit, i.e., it follows the same IV relation.

Thevenin Equivalent Circuits

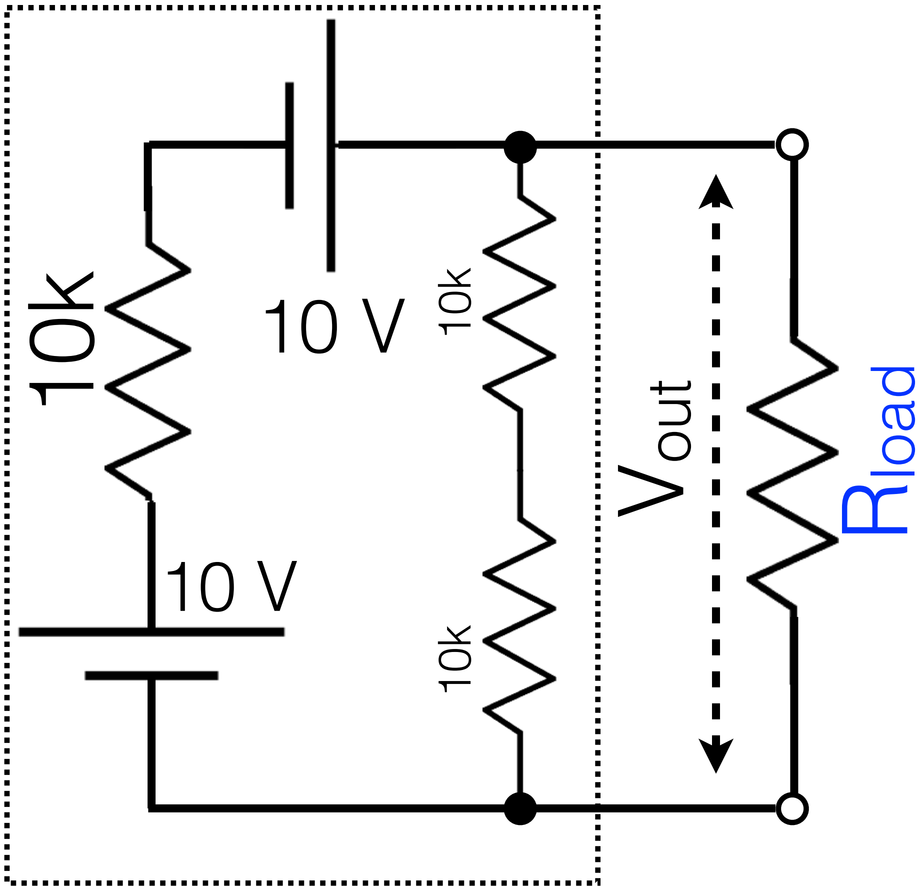
You can also find an equivalent circuit if we mix voltage sources and resistors



Any complicated mix of voltage sources & resistors can be treated as equivalent to this Thevenin equivalent circuit, i.e., it follows the same IV relation.
That means if I attach *any value* of load resistor, R_{Load}, across the terminals, the V_{out} and I_{out} will be the same between the two circuits, i.e., they're equivalent.

Thevenin Equivalent Circuits

Calculate V_{Th} and R_{Th} by making the IV relationships match. Use extremes.



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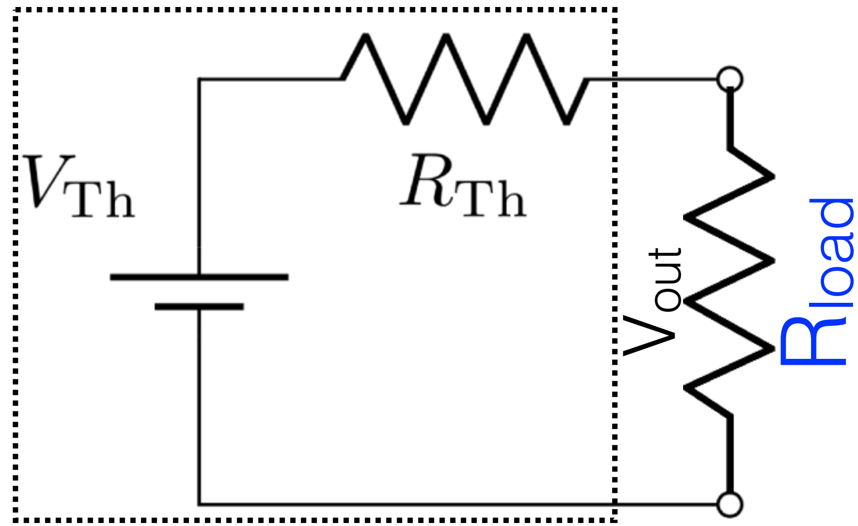
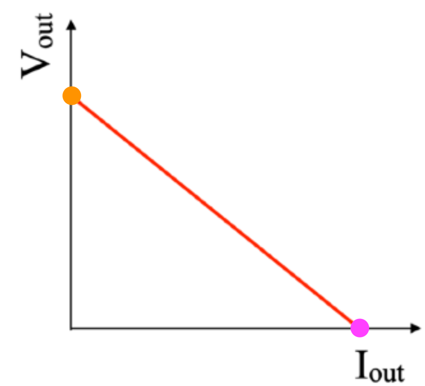


Response must be linear, so we only need the two numbers, V_{Th} and R_{Th} for $0 \leq R_{Load} < \infty$

Pick the extremes: $R_{Load} = 0$ is a "short circuit" and $R_{Load} = \infty$ is an "open circuit".



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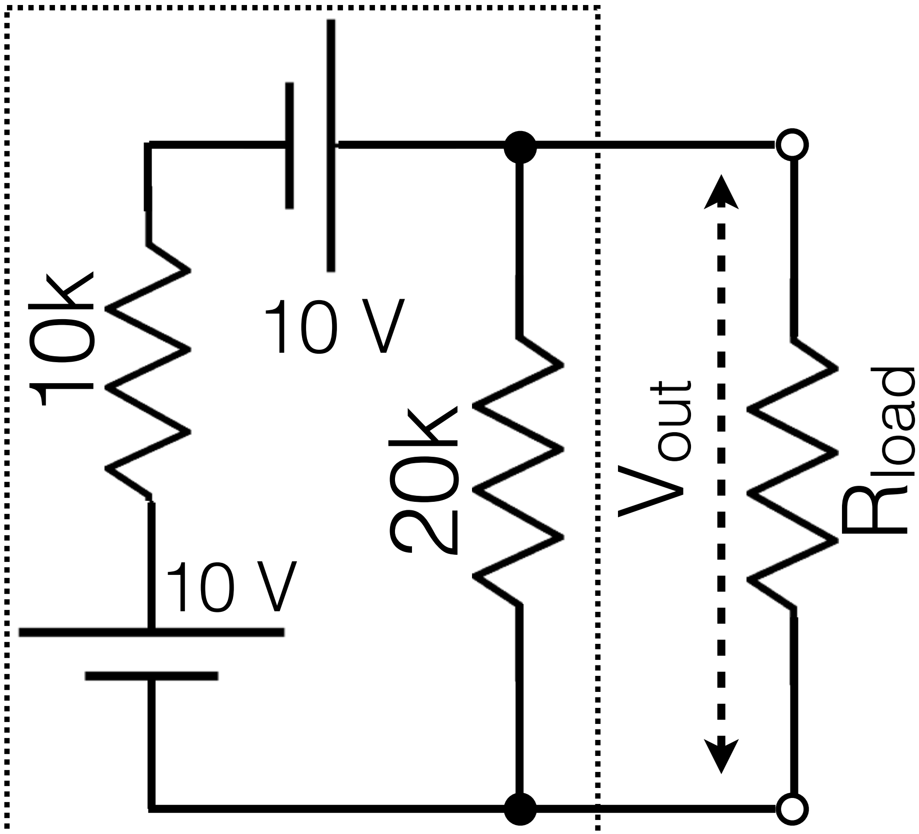

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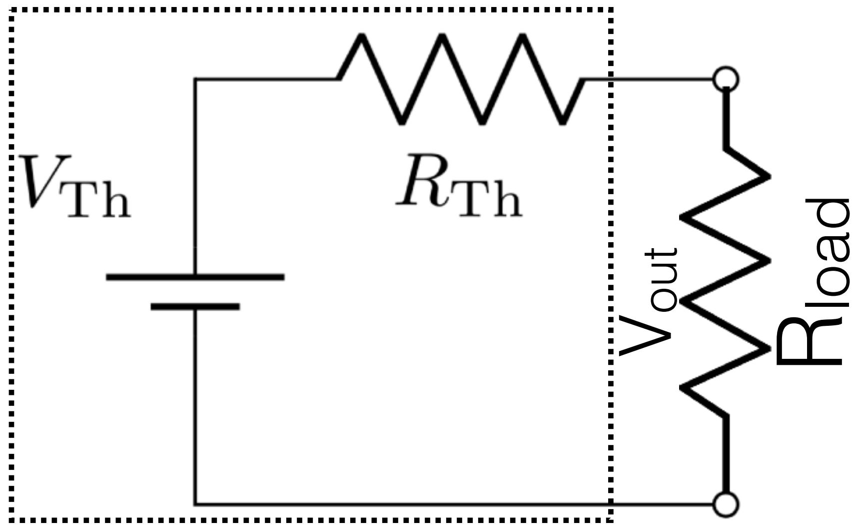

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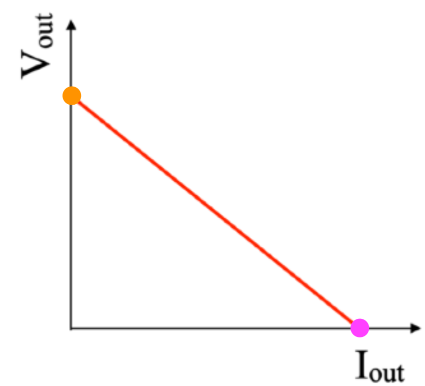

$V_{SC} = ?$ and $I_{SC} = ?$

$V_{OC} = ?$ and $I_{OC} = ?$

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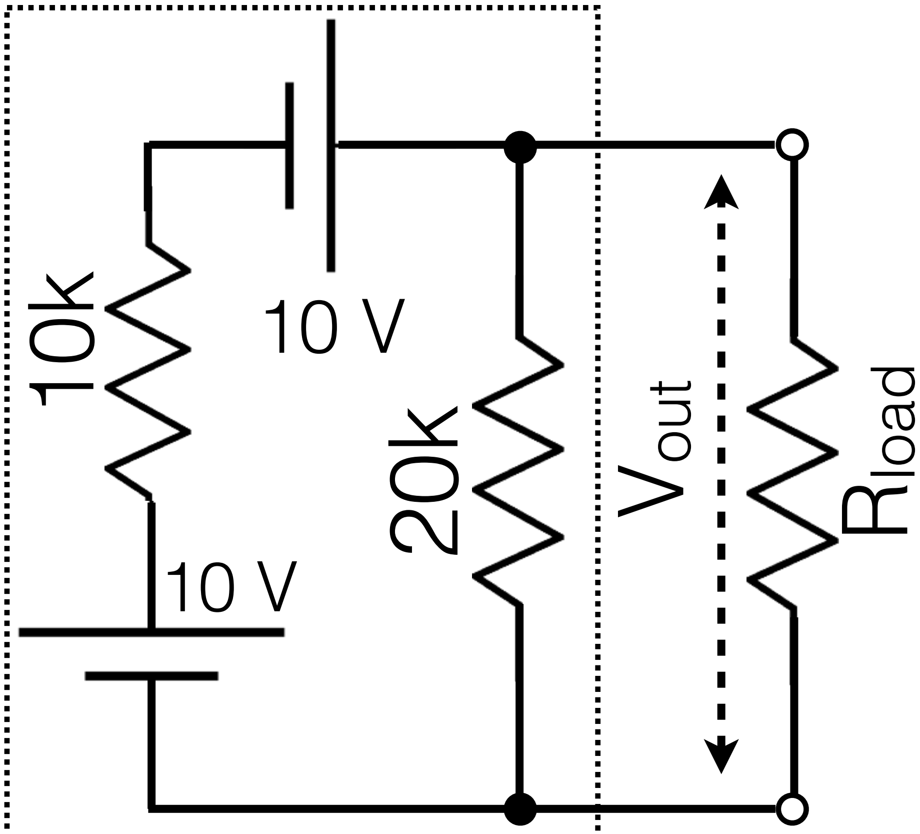

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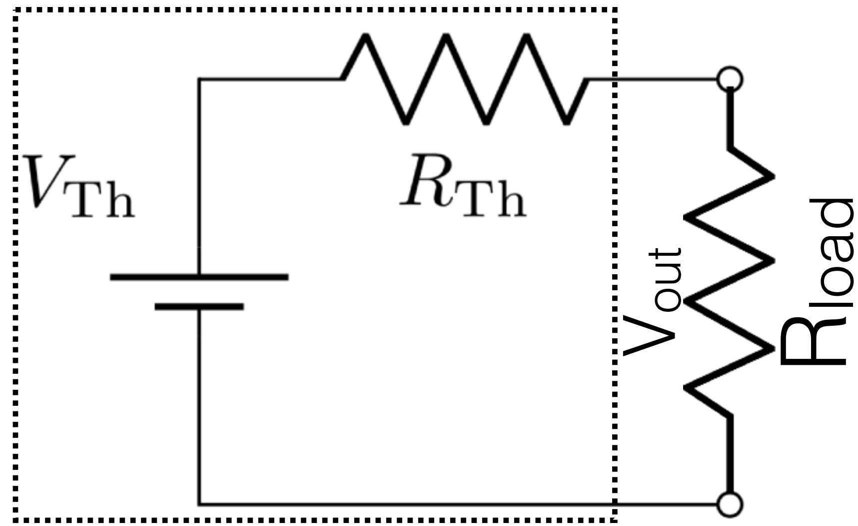

$V_{SC} = 0$ and $I_{SC} = ?$

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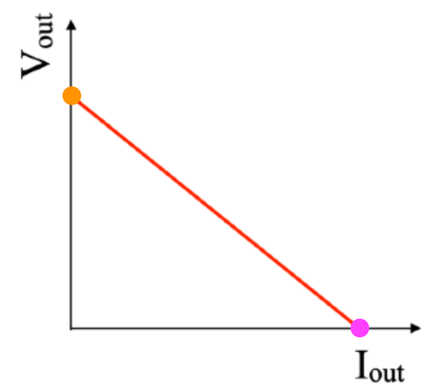

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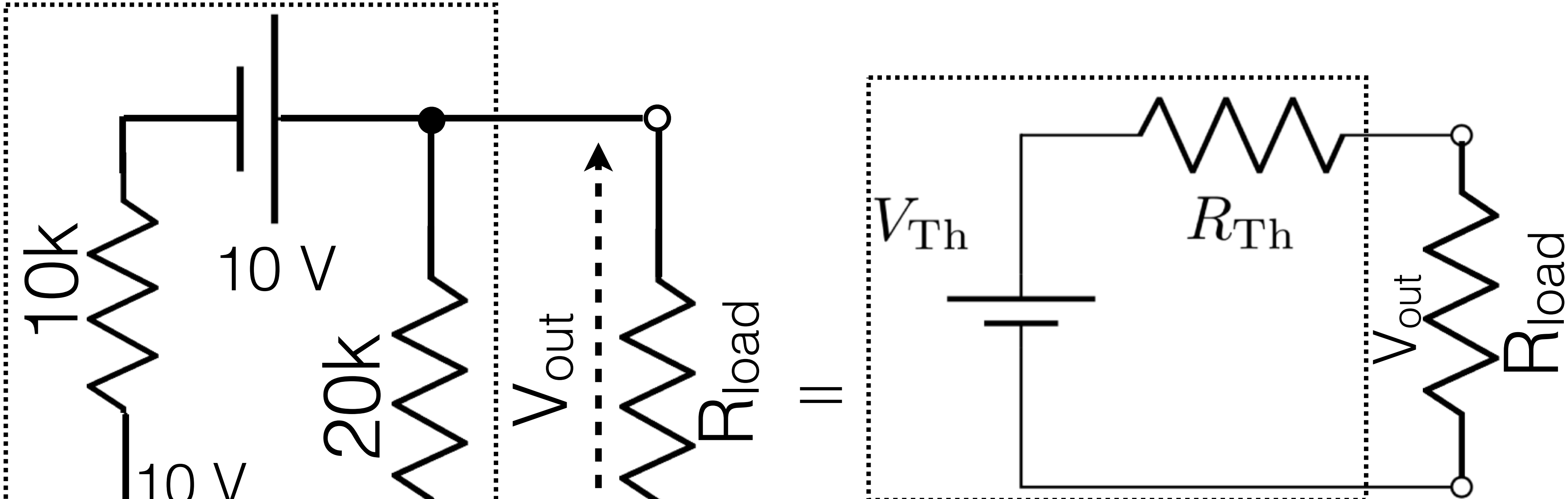

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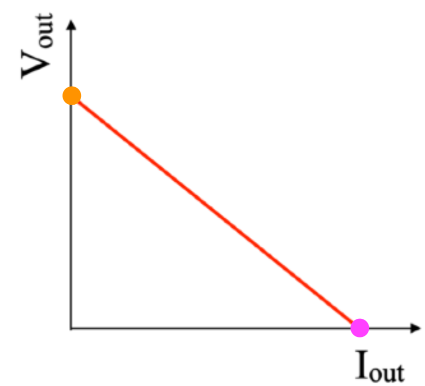
Pick the extremes: $R_{Load} = 0$ is a "short circuit" and $R_{Load} = \infty$ is an "open circuit".

$V_{SC} = 0$ and $I_{SC} = V_{Th}/R_{Th}$

$V_{OC} = V_{Th} - I_{OC}R_{Th} = V_{Th}$ and $I_{OC} = 0$



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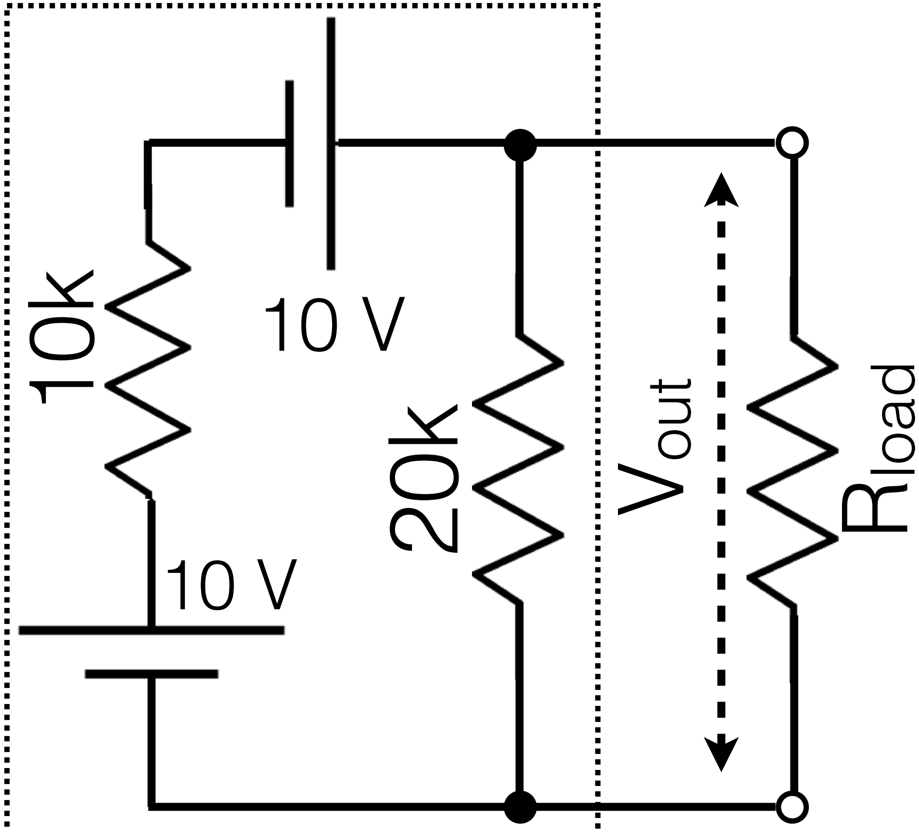

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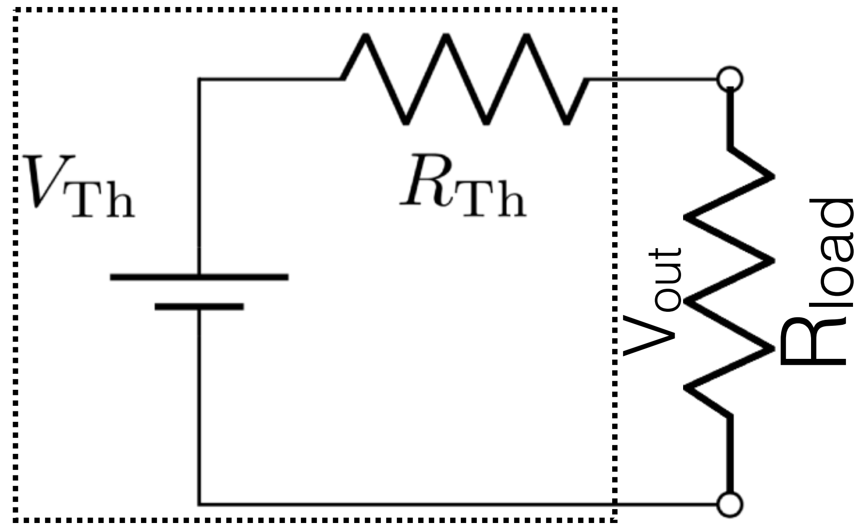

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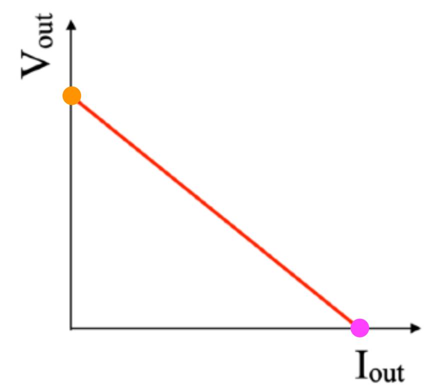


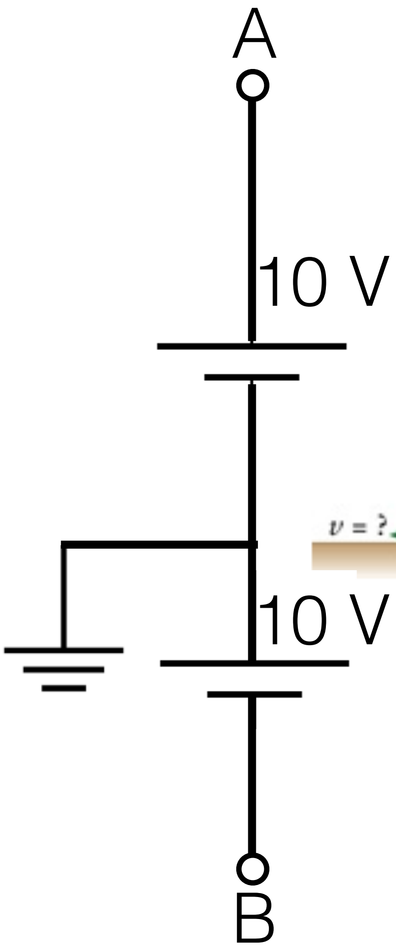
$V_{SC} = 0$ and $I_{SC} = V_{Th}/R_{Th}$

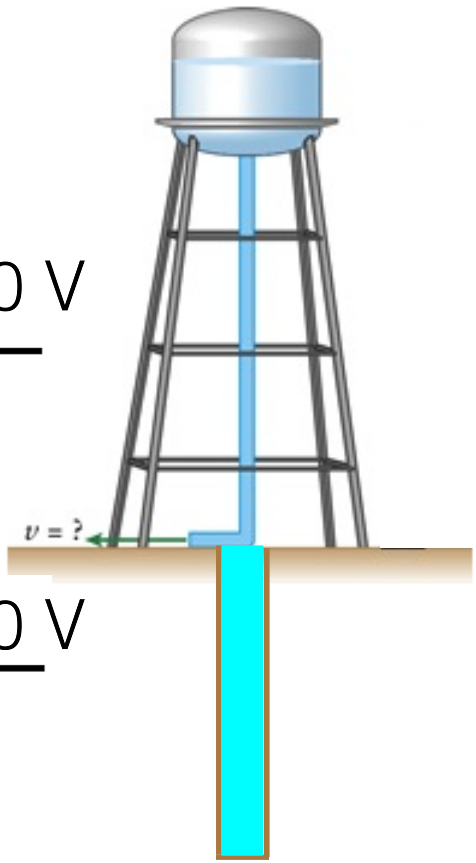
$V_{OC} = V_{Th} - I_{OC}R_{Th} = V_{Th}$ and $I_{OC} = 0$

Find V_{OC} and I_{SC} for the left hand circuit
and you can calculate both V_{Th} and R_{Th} that are equivalent.

A handy simplification in drawing circuits

Now is a good time to introduce the concept of "ground".





The idea of ground is to define a "zero point" of voltage for your circuit.
This is arbitrary, but so it calling the ground's gravitational potential zero in U = mgh
All that matters for energy is potential differences.
All that matters for voltage is potential differences.
So, pick a zero point for convenience.

$V_{AB} = 20$ V
$V_A = +10$ V
$V_B = -10$ V

Two subscripts means between two points, while one subscript means wrt ground.

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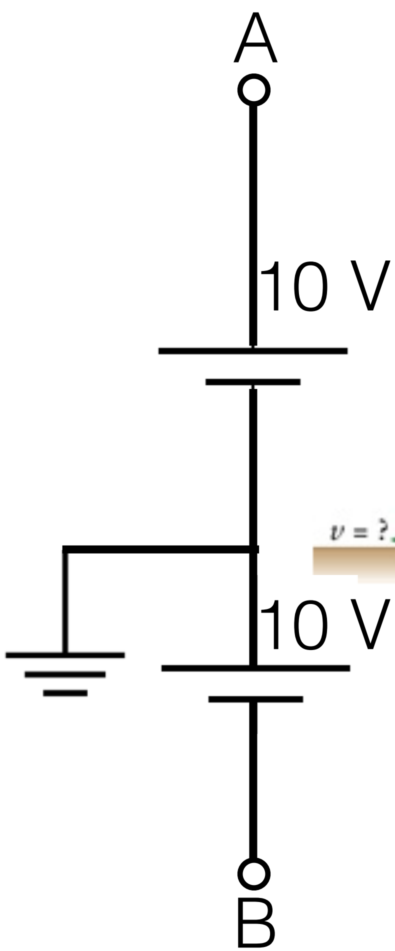

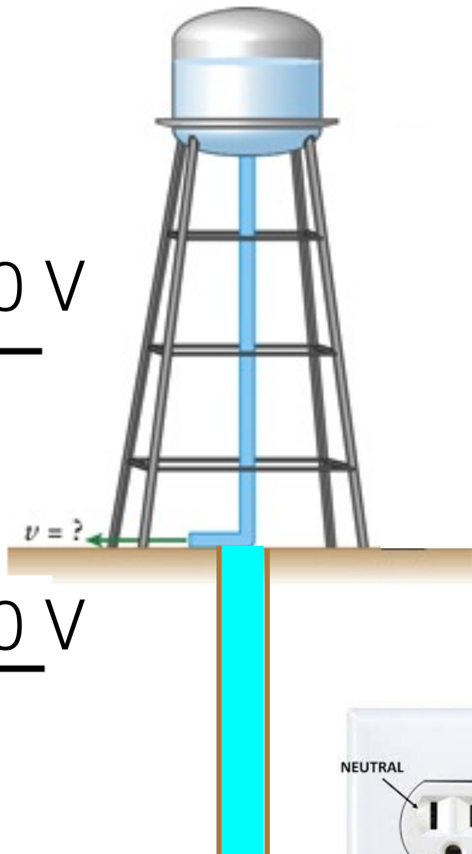

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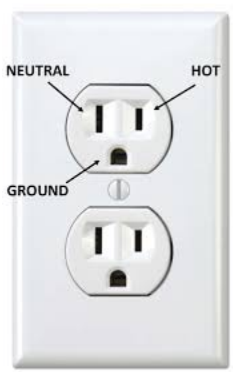
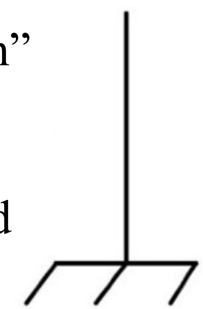


A separate symbol is used for "earth"
Which is the building's common potential, connected to the dirt through rebar, plumbing, or a buried metal "fork".

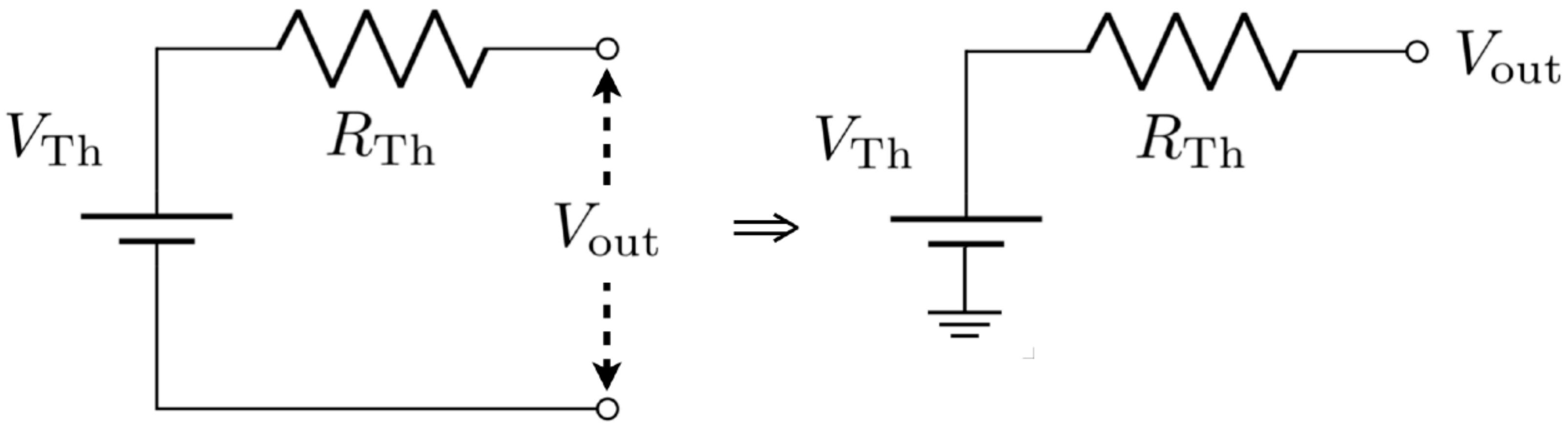


A handy simplification in drawing circuits

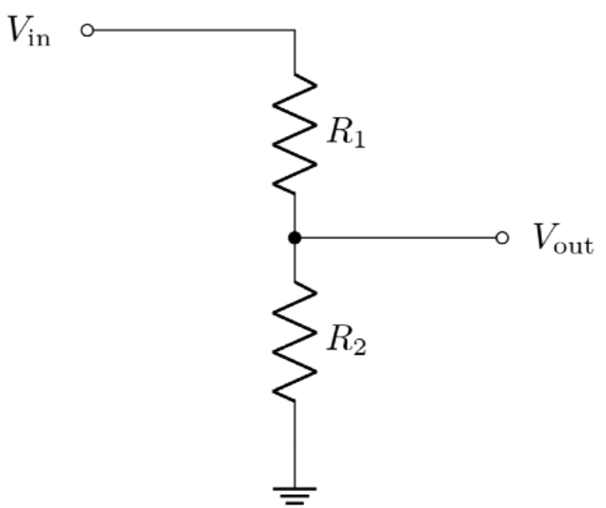
It is not the potential that transfers energy, it is the potential *difference*.

Thevenin Equivalent Circuits

So we can draw the Thevenin equivalent as



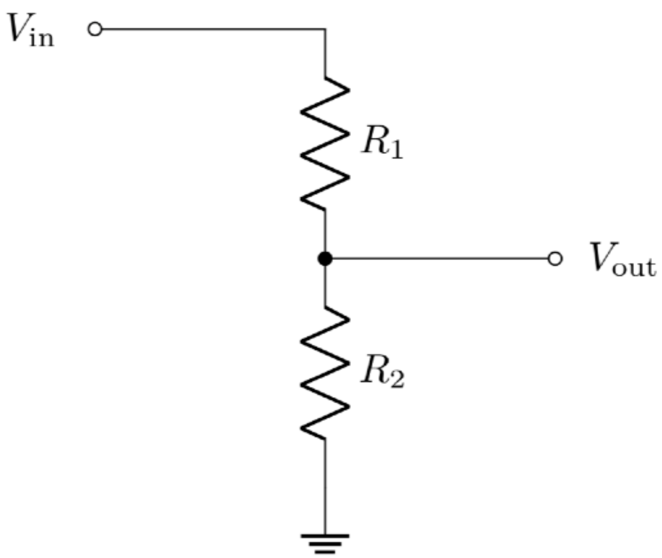
V_{out} is understood to be relative to ground.
We can do the same with a V_{in} which is a signal, not just a battery.



You should be able to calculate the Thevenin equivalent circuit for this.

Voltage divider

This circuit is a voltage divider. We'll use this a lot, and generalize it.



$V_{out} = ?$

Voltage divider

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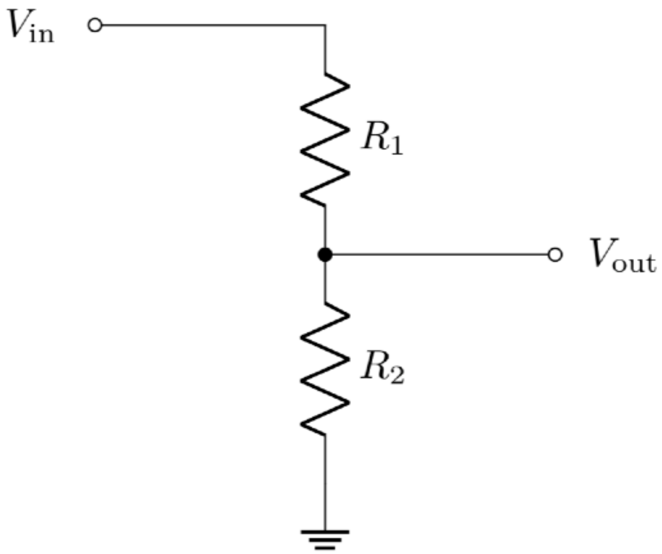

$V_{out} = IR_2 = [V_{in}/(R_1+R_2)]\ R_2$

If $R_1 = R_2$ then $V_{out} = ½V_{in}$

If $R_2 = 10\ R_1$ then $V_{out} \cong$?

Voltage divider

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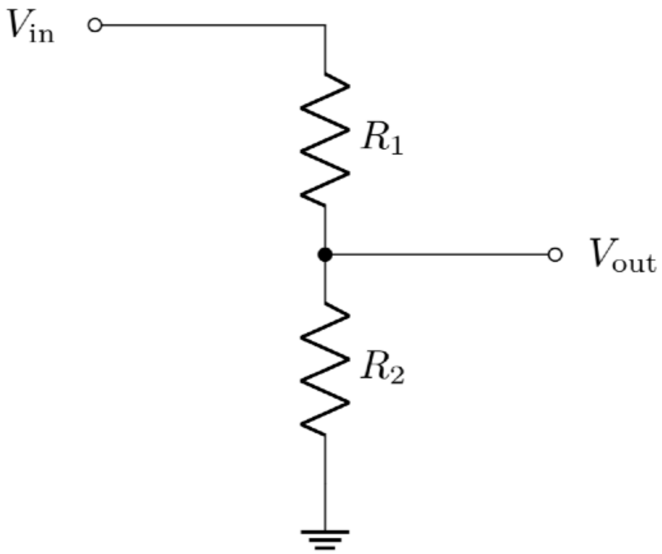


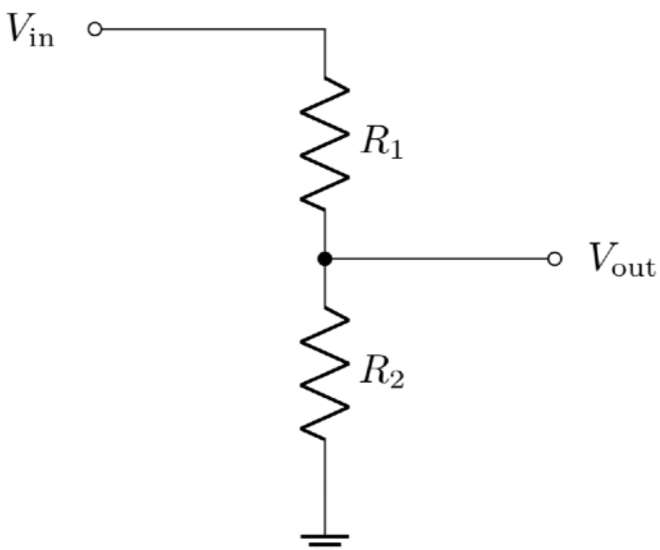
$V_{out} = IR_2 = [V_{in}/(R_1+R_2)]\ R_2$

If $R_1 = R_2$ then $V_{out} = \frac{1}{2} V_{in}$

If $R_2 = 10\ R_1$ then $V_{out} \cong 0.9\ V_{in}$ which is close enough.

Voltage divider

This circuit is a voltage divider. We'll use this a lot, and generalize it.



$V_{out} = IR_2 = [V_{in}/(R_1+R_2)]\ R_2$

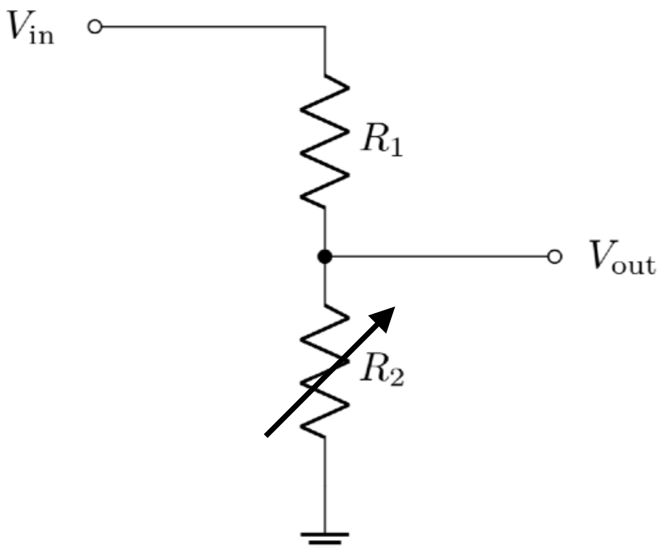
If $R_1 = R_2$ then $V_{out} = ½V_{in}$

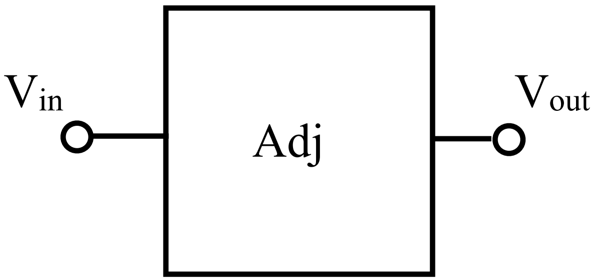
If $R_2 = 10\ R_1$ then $V_{out} \cong 0.9\ V_{in}$ which is close enough.

Trimpots used frequently for this to get an adjustable voltage.

An example circuit stage

So we could use a voltage divider as a circuit stage that outputs an adjustable voltage. This could be the dimmer switch on a lamp.





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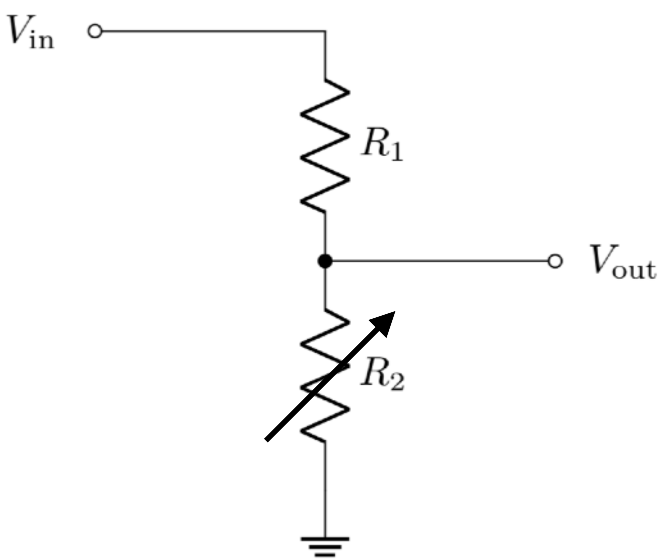

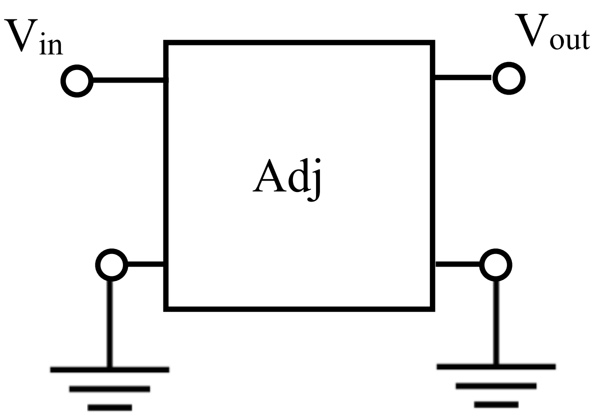

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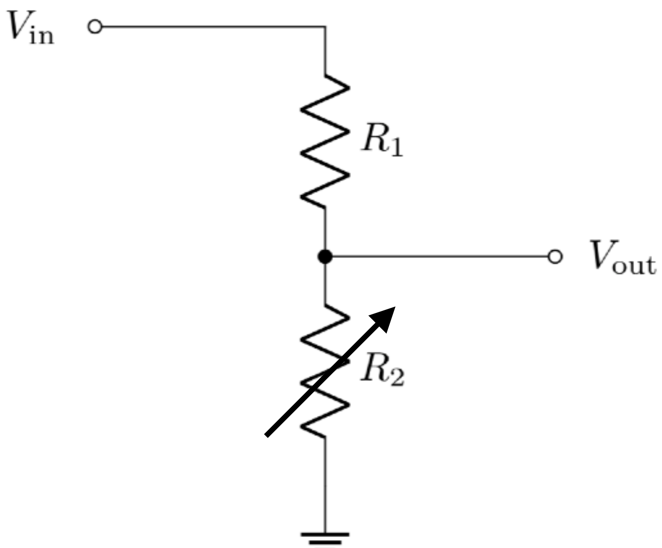

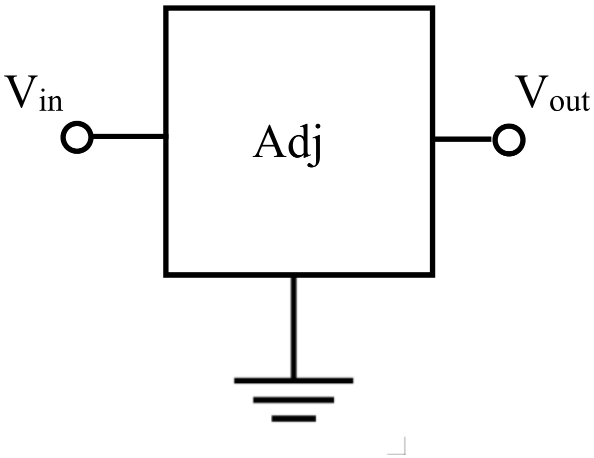

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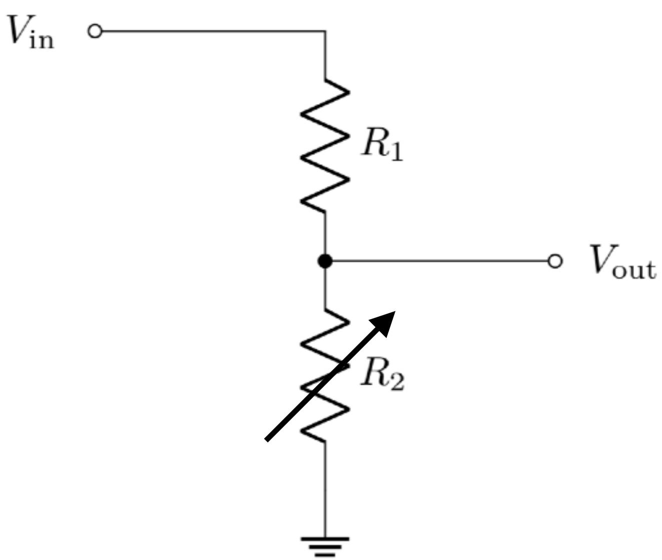

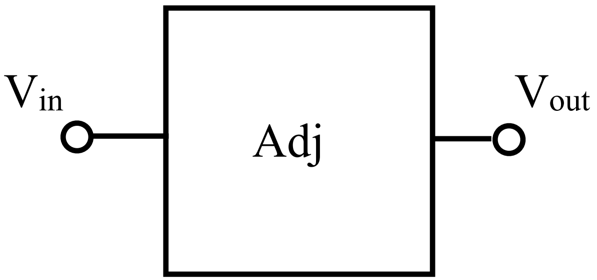

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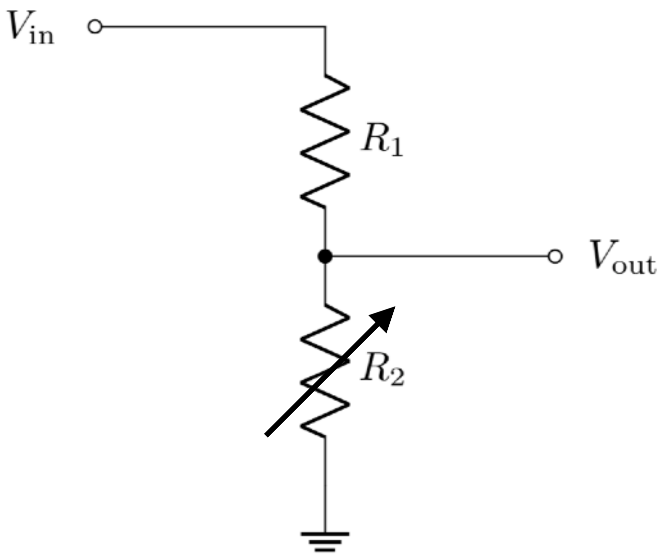

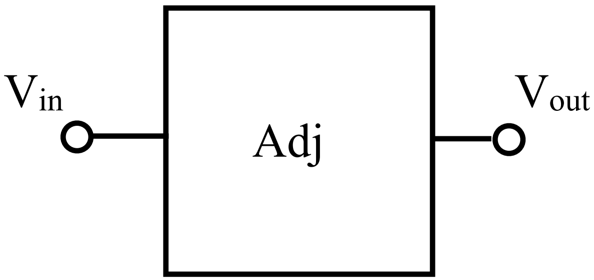

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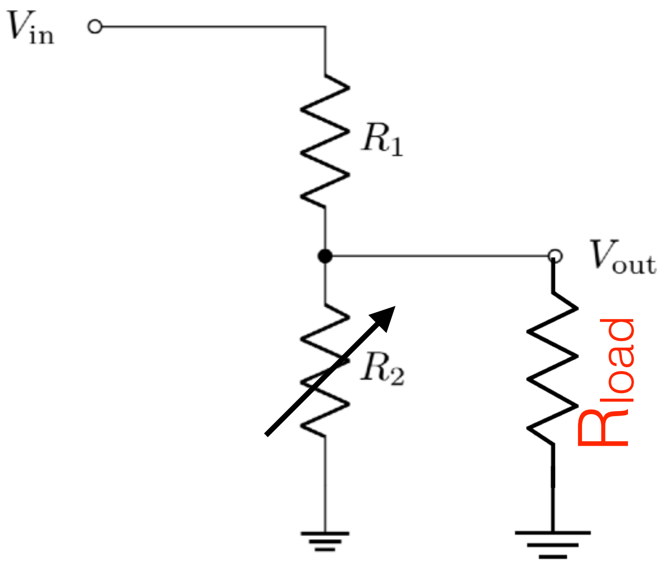

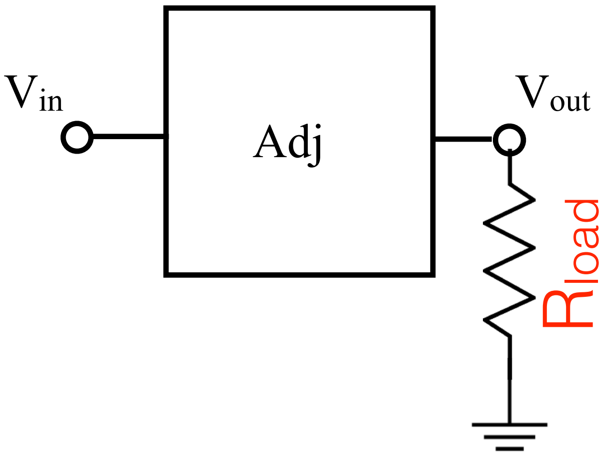

$$V_{out} = IR_2 = V_{in}\frac{R_2}{R_1+R_2} = V_{in}\frac{R_2R_{Load}/(R_{Load}+R_2)}{R_1+R_2R_{Load}/(R_{Load}+R_2)} = V_{in}\frac{R_2}{R_1+R_2 + R_1R_2/R_{Load}}$$

But, suppose I now connect this stage to the next stage in my circuit. In this case, it would be a lamp. That is the load.

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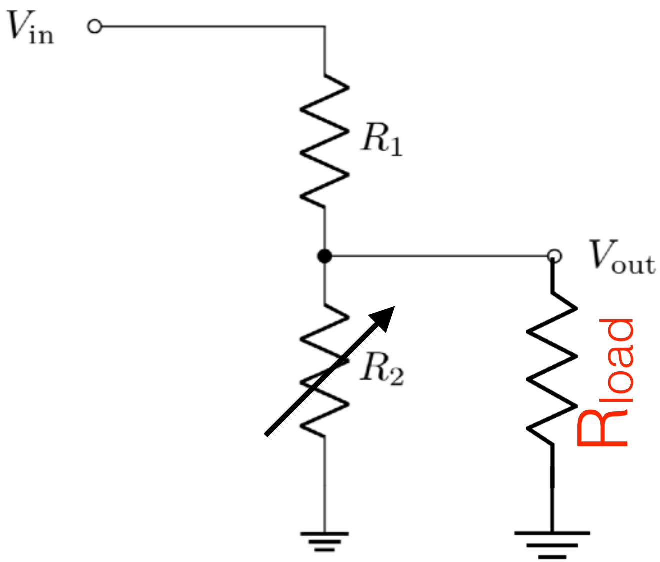

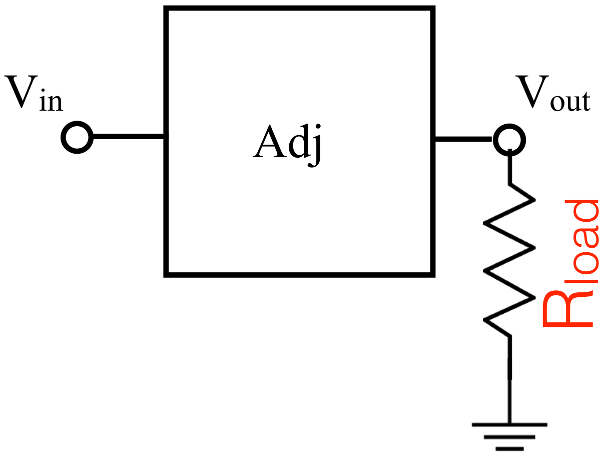

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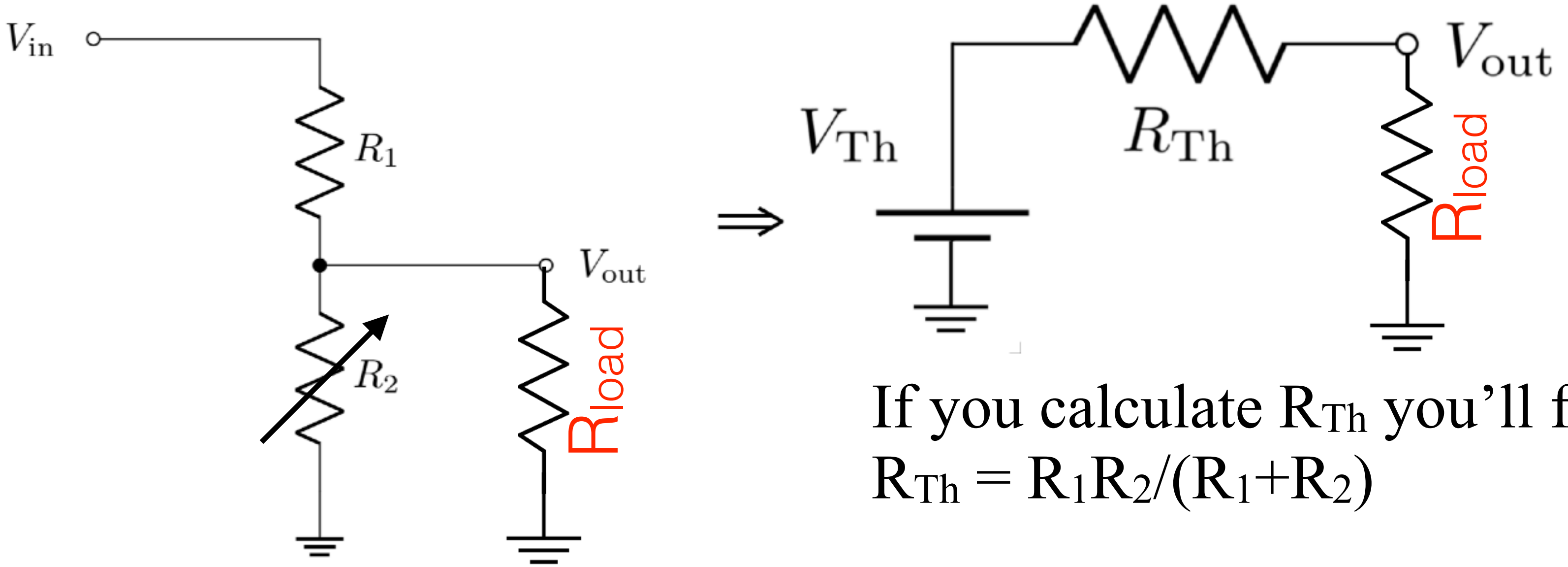

If you calculate R_{Th} you'll find
$R_{Th} = R_1R_2/(R_1+R_2)$

In general, the load causes negligible change to V_{out} wrt the stage's unloaded behavior **only if** $R_{Load} \gg R_{Th}$.

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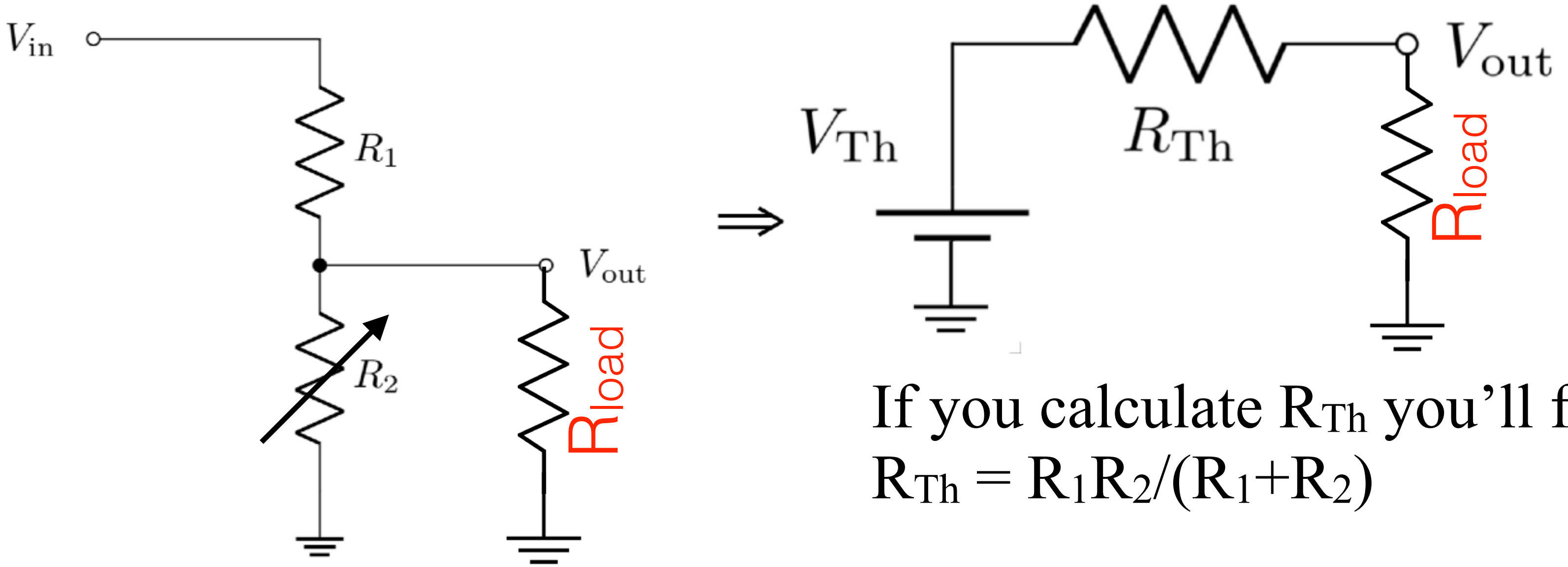

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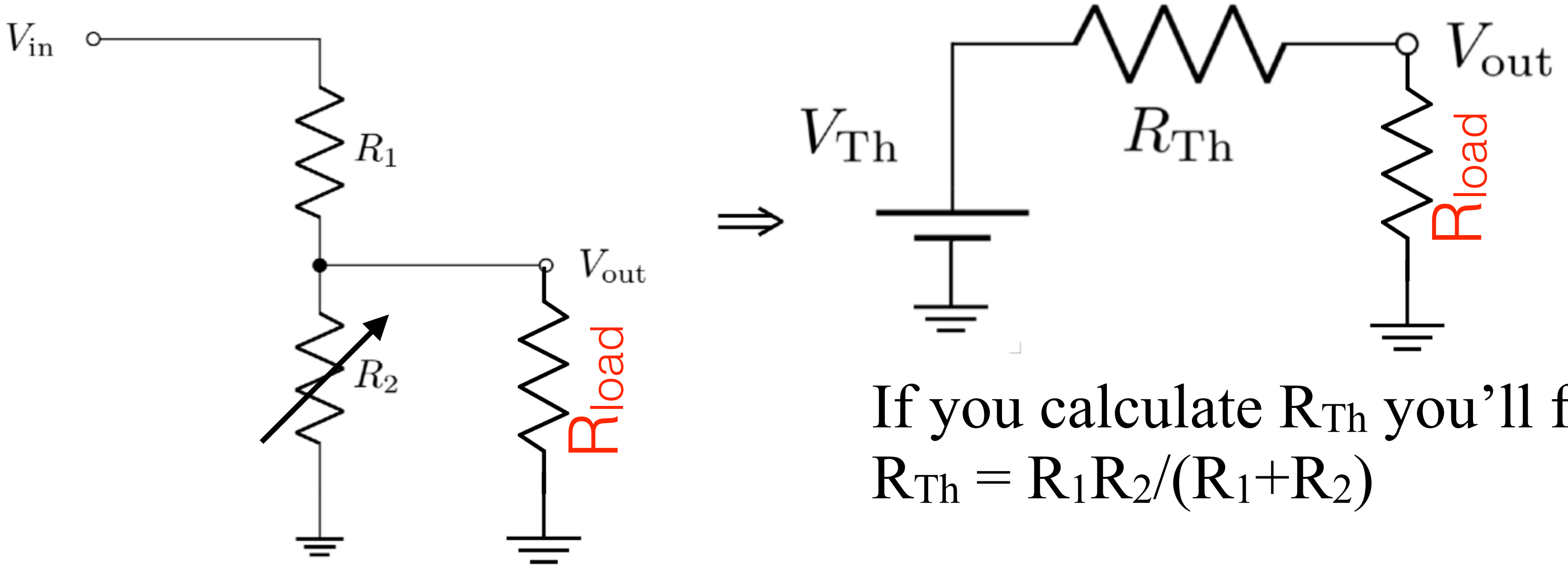

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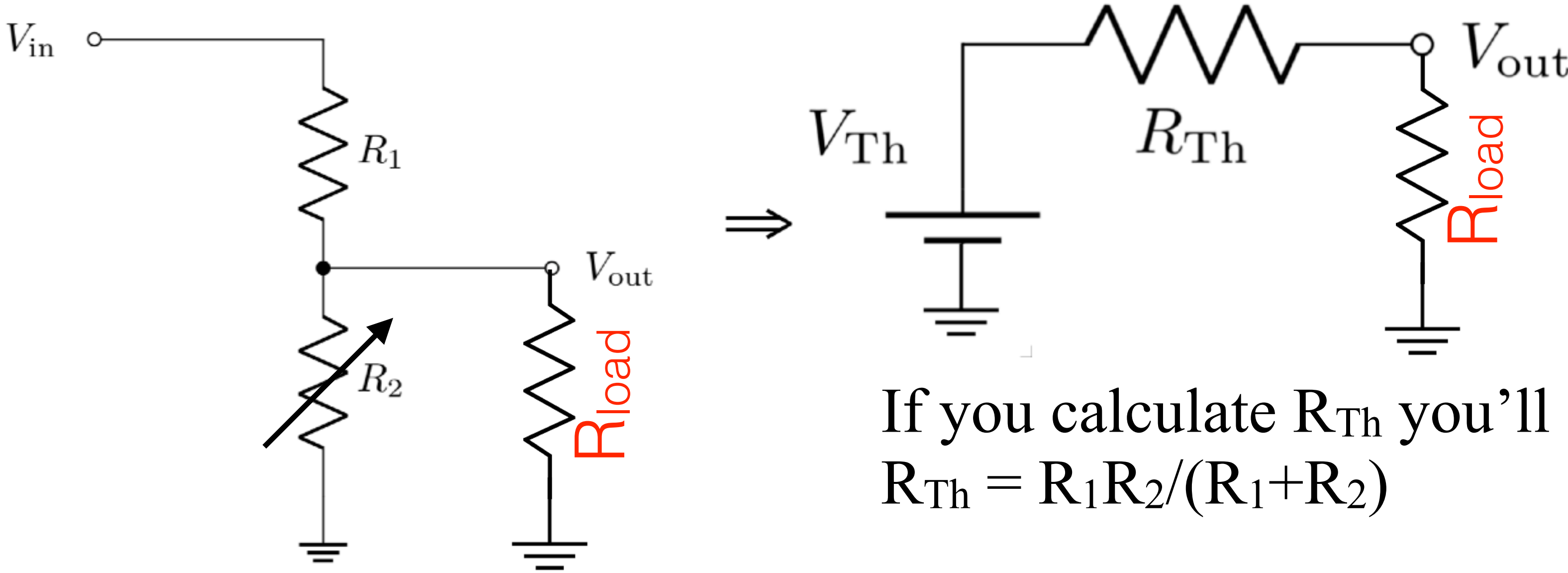

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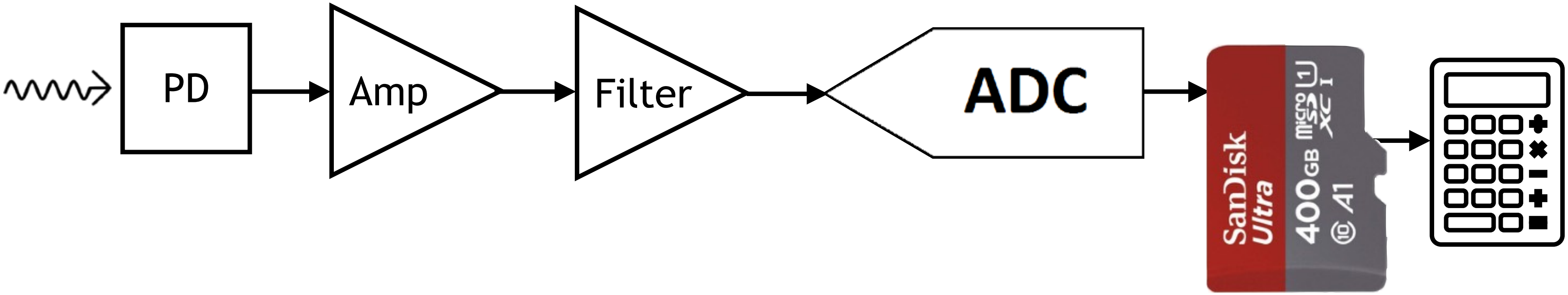
Even more generally, we want the input resistance of the next stage to be much larger than the output resistance of this stage.

Each stage should have large input <u>impedance</u> & small output <u>impedance</u>.

Chaining together stages for a measurement

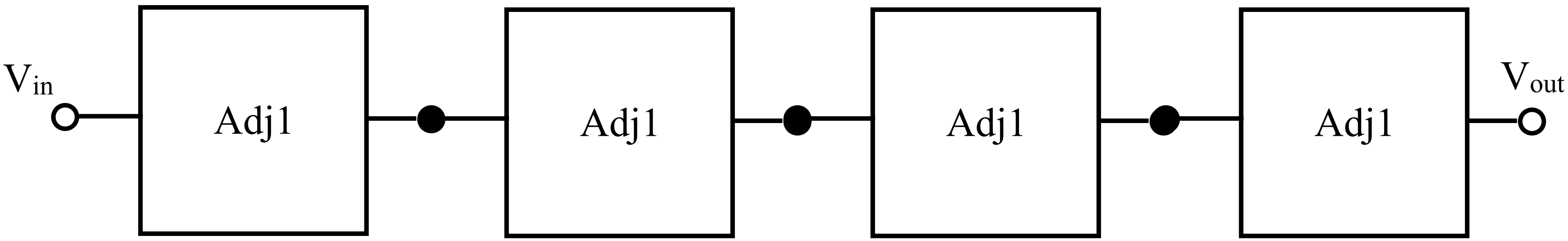
Each one of these stages should satisfy this rule, so I can chain them together without have any one affect the performance of its predecessor or successor.

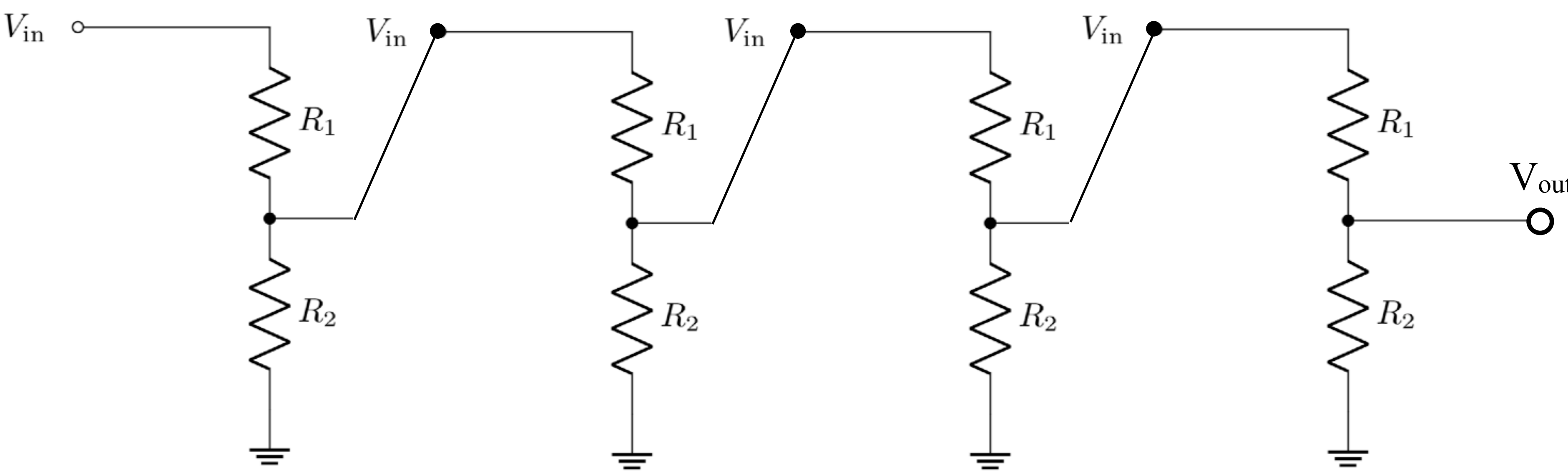


We need each stage to have high input impedance and low output impedance to easily chain together multiple stages.

x10 rule

That looks hard with multiple stages.





I'd need each stage to have resistors 10 times as big as previous stage.

That consumes high power in the early stages; $P = V^2/R$.

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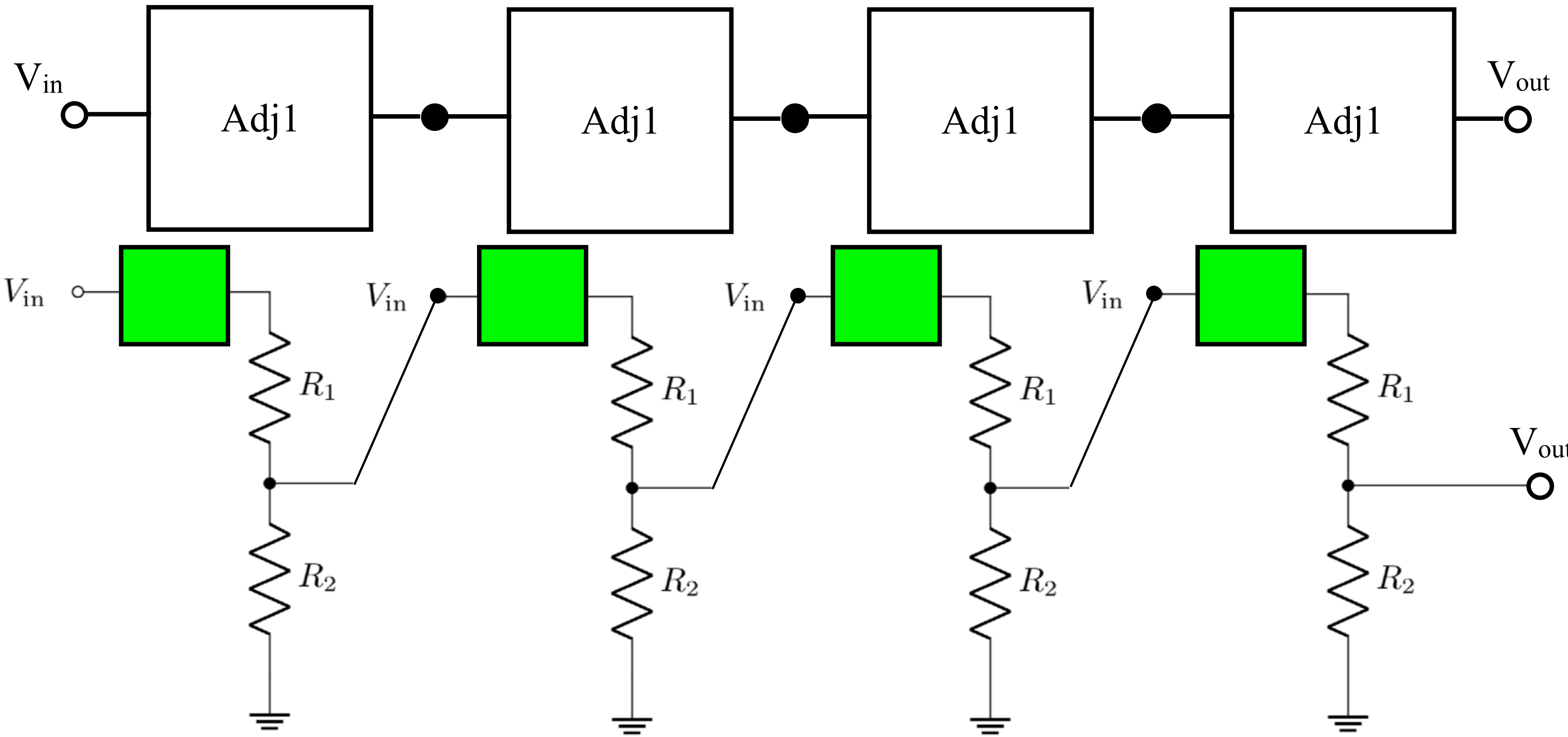
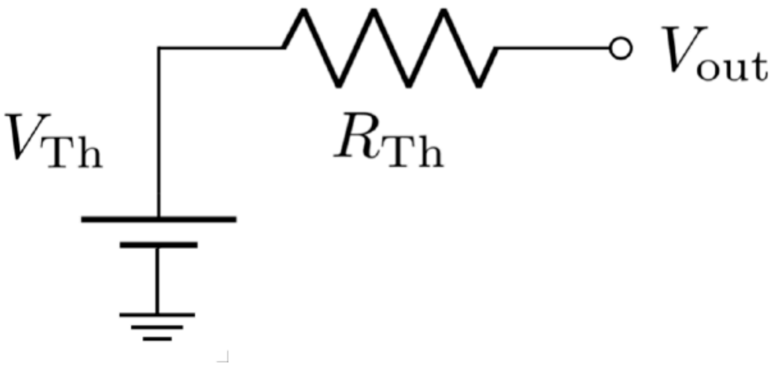


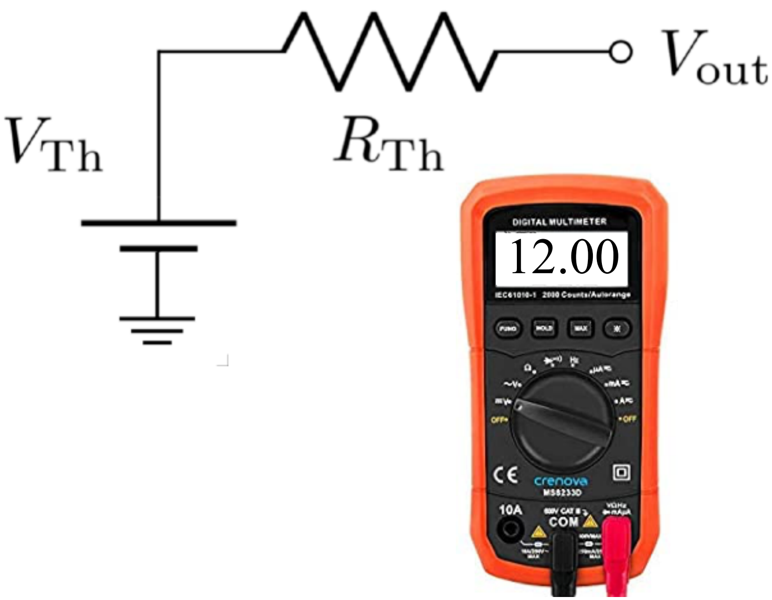
We need an "electromagical" impedance booster at the input of each stage
We'll see how to do this soon, with a transistor.

Ideal voltage and current sources

In the Thevenin equivalent circuit, we treated V_{Th} as a battery.



Batteries have a set EMF.
Ideally a 12V battery will always give 12V output. But what happens when it discharges?



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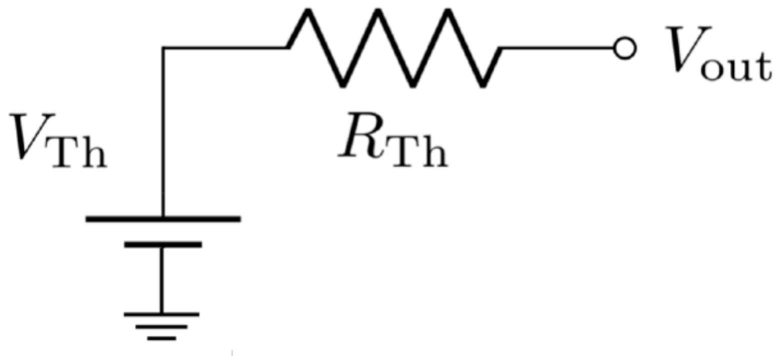

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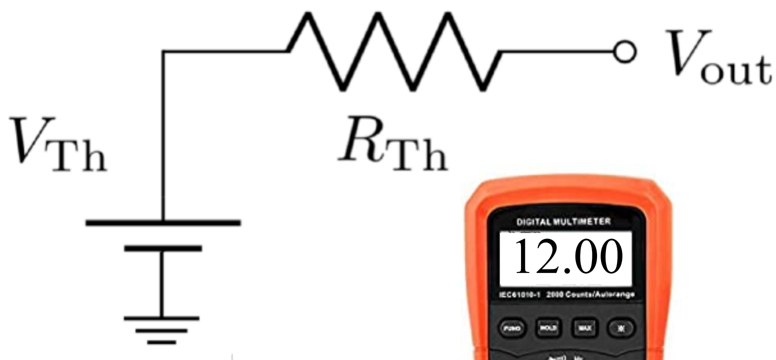

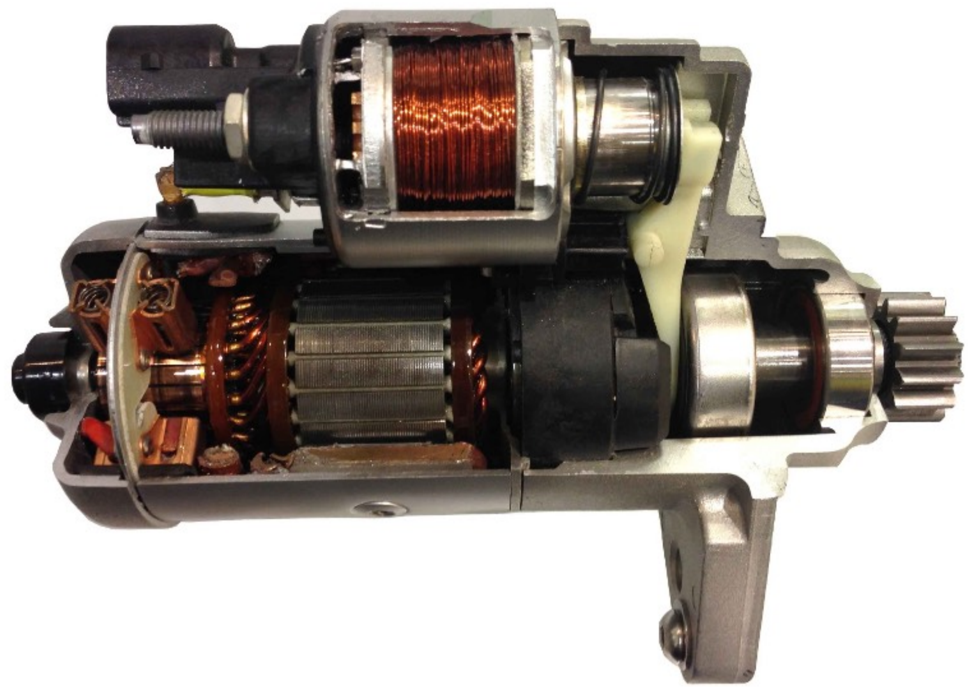

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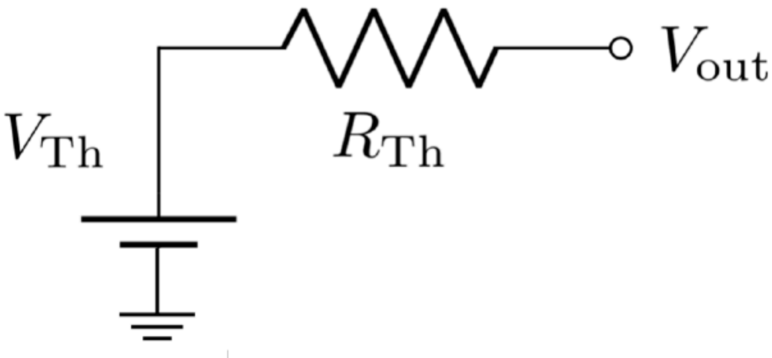

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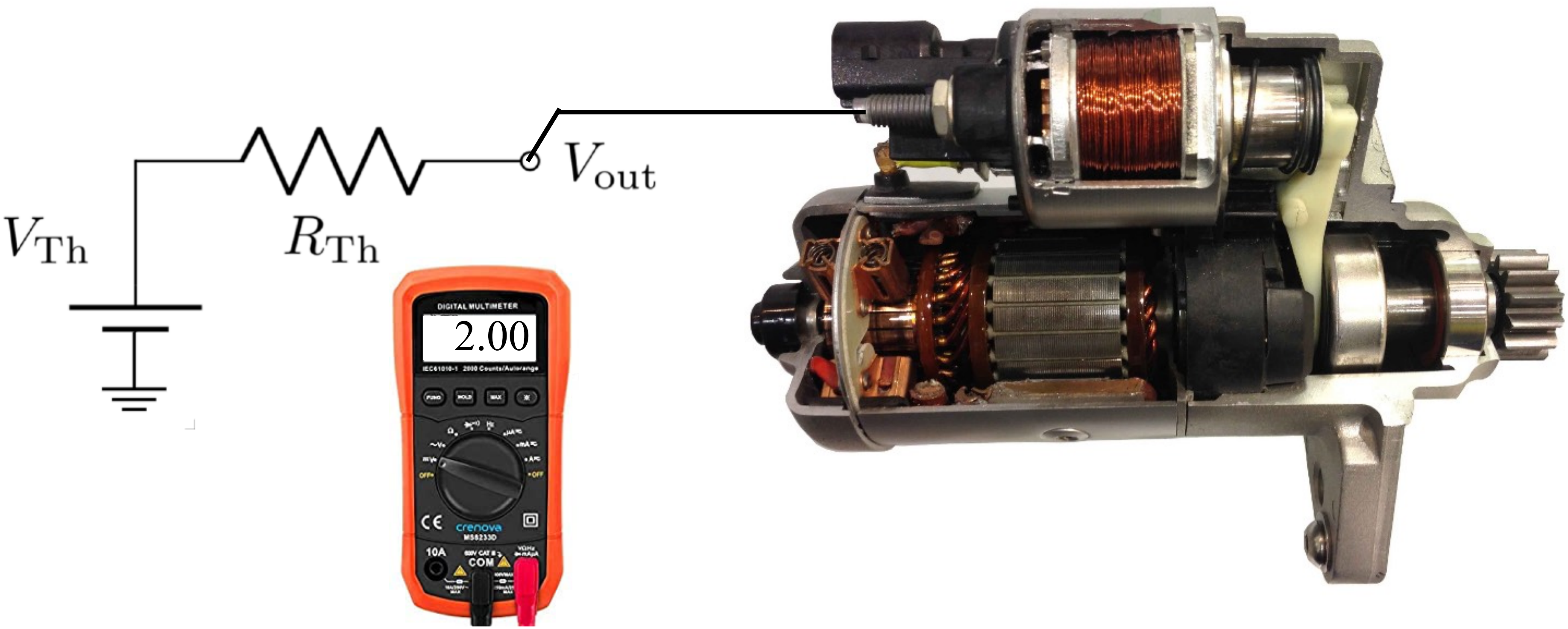

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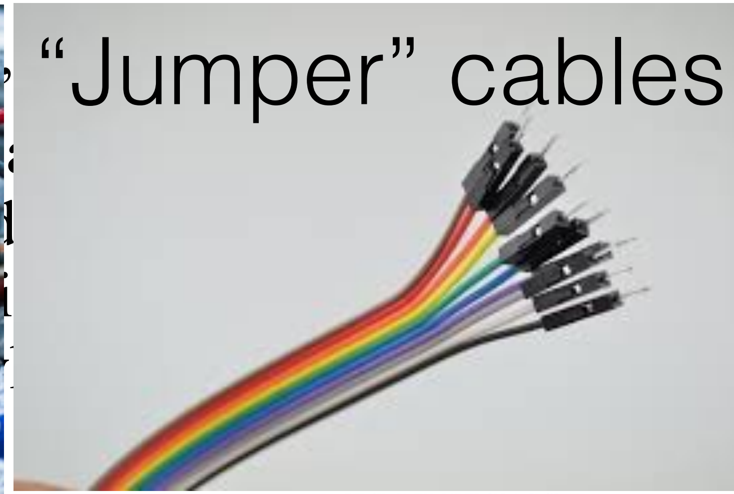
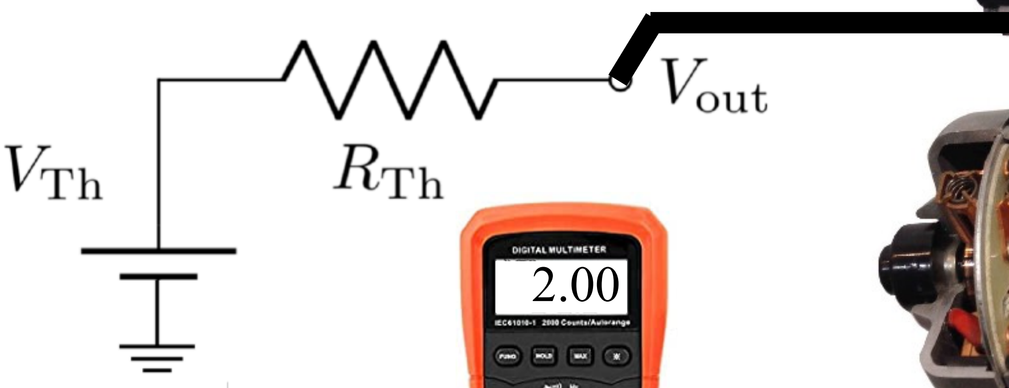
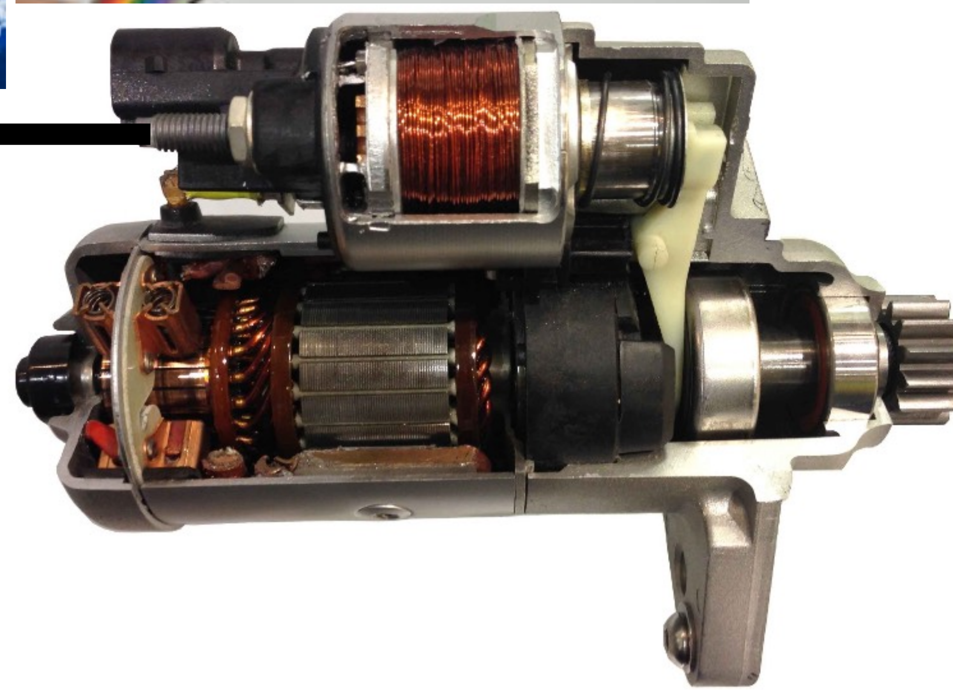
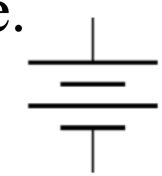




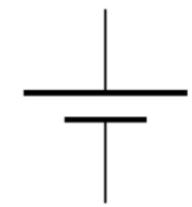


Ideal voltage and current sources

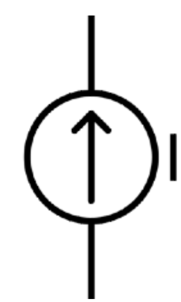
The cell in the battery approximates an ideal voltage source through its chemical potential, but it has an internal resistance in the electrolyte.



Ideal voltage source means constant voltage regardless of current into load, ie for any R_{Load}. The Thevenin equivalent has $R_{Th}=0$.
It is an ideal, but a useful concept for approximation.
Real voltage sources sag when loaded with small R_{Load},
because it can't produce infinite current.

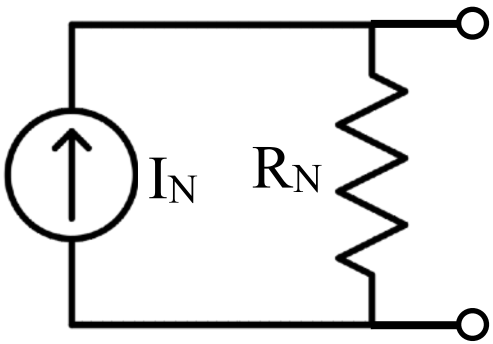


We can also define an ideal current source, which produces a constant current through a load regardless of the load.
It is an ideal, but a useful concept for approximation.
Real current sources sag when loaded with large R_{Load},
because it can't produce infinite voltage.



Norton Equivalent Circuits

Just like any mix of resistors and EMFs can be treated as equivalent to a Thevenin equivalent circuit, with the right V_{Th} and R_{Th}, such circuits can also be treated as equivalent to a Norton equivalent circuit, with the right I_N and R_N.



You would find I_N and R_N just as you found V_{Th} and R_{Th}.
Consider the extreme load resistance options, 0 and infinity, and make sure that you get equivalent V_{out} and I_{out}.

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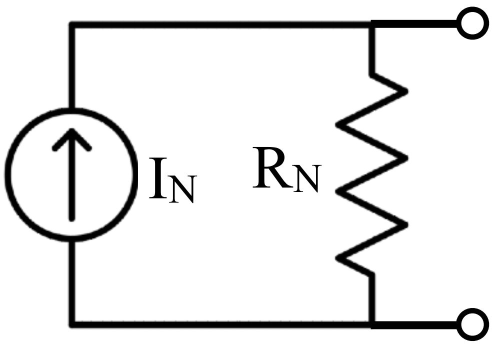
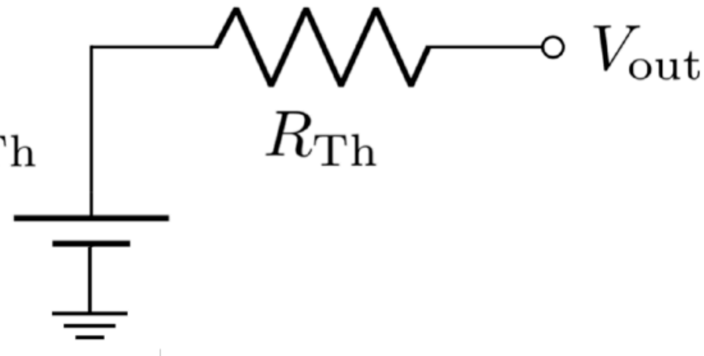


$\Rightarrow$



Exercise: Find I_N and R_N to match V_{Th} and R_{Th}.