Physics 313 – Analog Electronics

Why study electronics in a physics program?

- Useful skills in science, engineering (while many "bought" circuits, usually some custom jobs
- Almost all measurements are directly or indirectly electronic – good to know how things work to understand limits
- Practice trouble shooting,
- Si revolution – What's inside those black boxes? How does a transistor work?
- Fun

Approach here: as user (not circuit designer or Solid State physicist)

- Basic principles, rules of thumb (practical)

This course will cover mostly analog circuits

Lab with readings. I'll always take questions, talk if necessary but best if you come to class prepared and spend as much of it as possible doing hands-on with the circuits.

You'll probably need 3 hours/day for lab, but generally less work outside of class hours compared to other courses.

There will generally be assignments every day that will be collected and graded. In addition, you will keep a lab notebook which will be collected and graded. There will be two exams each with a written and practical part. The written part will be similar to assignments and the sort of calculations you will do in class. The practical part will be along the lines of "here's a circuit, build it, measure something, and explain". The practical may also include a "here's a broken circuit, diagnose and fix it" part.

Lab book philosophy: Write down enough info so that later you could completely reconstruct what you did without reference to any other documentation. This should always include circuit diagrams, descriptions of what you are doing and why and all raw data and analysis, and summaries.

- Can use lab book for practical part of exams
- Detailed contents of lab book:
  - Date
  - Equipment used (manufacturer, model #s, ID #s - once is enough)
  - Brief description of what you're doing
  - Schematic diagrams of circuits (even if in lab writeup)
  - <u>Raw</u> data, calculations, graphs, results
  - Attach any loose stuff!
  - Units
  - Graph raw data in logbook as you go
    - You can see where things are interesting to take more data (adaptive data taking)
    - See functional relationships

While we're talking about lab:

- Since we have so many in lab, because of the number of you, most will have to pair up, not optimal but necessary, as consequences switch around building circuits so everyone gets experience—remember everyone will be solo on practical exams!
- Also both record everything in both log books as you go.
- No Food/Drink on Lab side of classroom.

Paul Voytas
Physics 313

Basic Relevant E&M Review (e.g. from Physics 218 or equivalent):

Basic physics for Circuits:

Electric field → Force on charge → charges <u>move</u>

Charge [Q] =Coulomb (C)

$e = -1.602 \times 10^{-19}$ C

Current [I] = charge per time q/time <u>through</u>

1 Ampere (or Amp) = 1 C/sec = 6.242×10^{18} e/s

Since an amp is not a ridiculous amount of current, typical lab currents will involve so many elementary charges we treat current as continuous—much like with a fluid flow we usually ignore the fact that it is made up of atoms. (In some cases one has to worry about the discrete charges that make up current flow for further information research "shot noise").

Potential difference → voltage <u>across</u>

1 Volt = 1 Joule/C (NRG/charge)

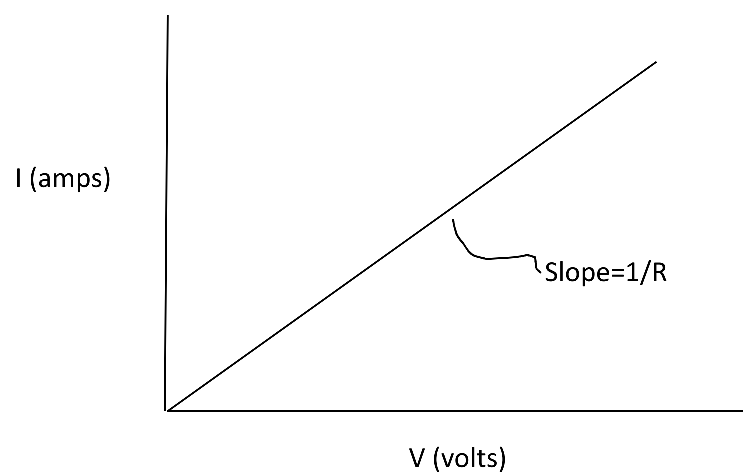
Many sources are sloppy/inconsistent with each other on notation. Some use voltage, some potential difference, some ΔV, some voltage difference. The important thing to remember is that there must be a difference in voltages between two point for a current to flow (except for superconductors…)

Electric field $E_{avg} = \frac{\Delta V}{\Delta r}$ potential differences over a distance

<u>Resistance:</u>

If V exists (with associated E) then current may flow: $\frac{\Delta V}{I} \equiv R$ (definition of resistance). Equivalently: V=IR or ΔV=IR. Units: [R]=Volt/Amp. 1 Volt/Amp ≡ 1Ohm (Ω).

If R = <u>const</u> for all I, this relation is called Ohm's law and the material or object is described as Ohmic. For such a relation, the I-V curve is propotional (linear with intercept of zero) and slope of I vs V is1/ R:

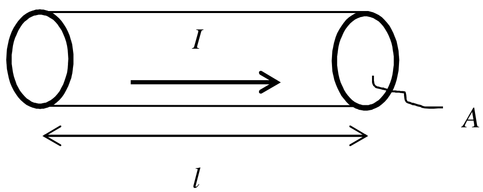


Resistance is extensive property: Depends on specific object: size, shape, etc.

A related property is resistivity (ρ). Resistivity is an intensive property. It is a property of <u>material</u>, not its geometry or size.

For the common case of current flowing along an ohmic object of uniform cross-section, the relation

$R = \rho\frac{l}{A}$ holds where l is length of the object (along current flow) and A is the cross sectional area. From this we can also see that the units of resistivity are Ohm-m in the SI system.



Note that for a normal conductor, there must be an electric field ***in the material*** for current to flow. Superconductors are the exception—once current started in a superconductor it can in principle flow forever without diminution.

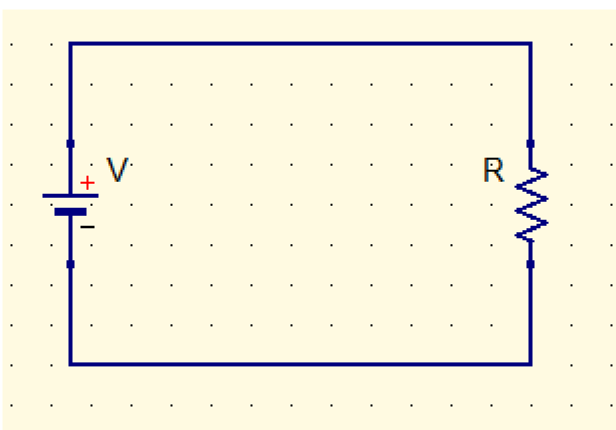
What sorts of values of resistivity are there? There is quite a large range:

Material	Representative Resistivity (Ω-m)
Metal	10^{-8}
Semiconductor	1
Insulator	10^{9}

Resistor: A circuit element designed to have a specific resistance. Symbol is "R" . Why would we *want* to insert resistance? We usually think of resistance as bad, but if we want to control what happens in a circuit it is essential.

We will treat wires as R=0 so we will have $\Delta V = 0$ along wires.

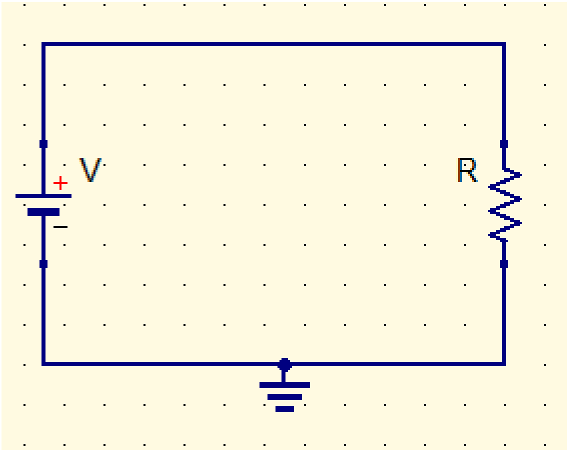
Physics 218 type circuit:

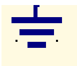
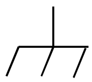


This is pretty cumbersome. Most real circuit diagrams not drawn like this (closed loop showing all wires).

More common is to define a common reference potential (=common, ground, earth, chassis ground)

For this circuit, you might call the bottom wire ground (remember, we treat a wire as R=0, so it is <u>all</u> at the same potential):

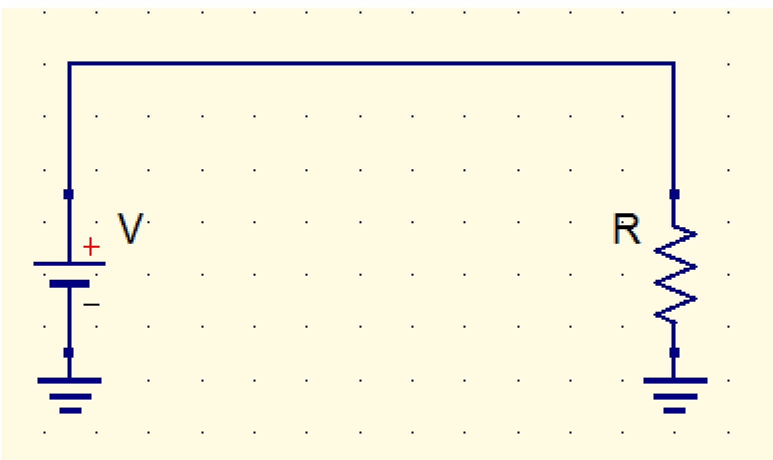


Where  is a common symbol for ground. Sometimes you will also see it as:  . More rarely, or referring to "chassis" ground is: 

(Chassis refers so an electronic device construction technique where the circuits were laid out on a common metal frame (chassis) that was also used as an electrical circuit ground reference).

The idea of having a common labeled reference is that we can then eliminate the <u>lines</u> for many of the wires in a circuit and just put the ground symbols where we need them.

The equivalent circuit using this approach is then:



As we'll see, this becomes more and more helpful in complicated circuits where many crossing wires can be eliminated. Note that since the ground symbol more nearly represents "tying all points labeled ground together", current can enter or leave ground.

<u>Series and Parallel combinations of resistors (Equivalent Resistance)</u>

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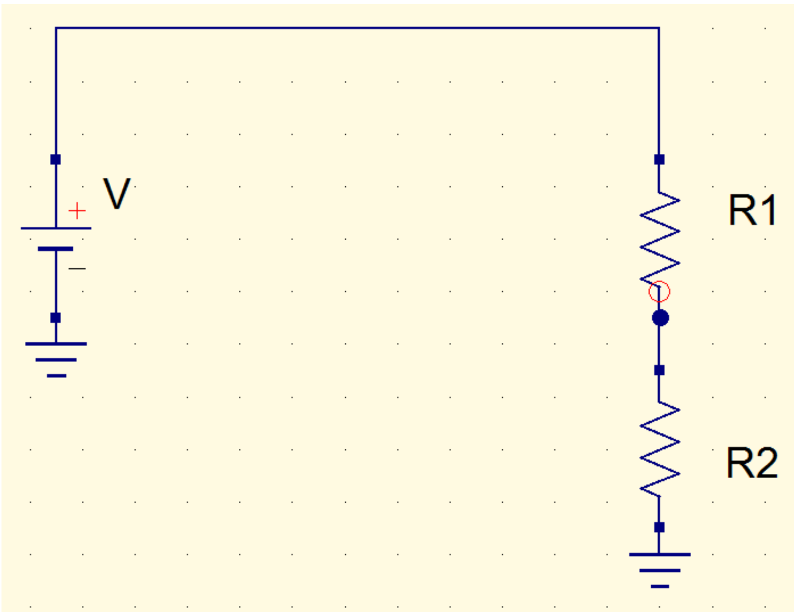
Physics 313

Recall Kirchoff's loop law from Electricity and Magnetism course? It says if you step around a circuit in steady state and add up all the potential changes ("potential drops" even though they aren't all decreases) around a circuit and come back to the starting point, the sum must be zero.



In steady state, charge isn't building up anywhere in circuit so Iin=Iout≡I, and we have:

$$V = \Delta V_1 + \Delta V_2$$

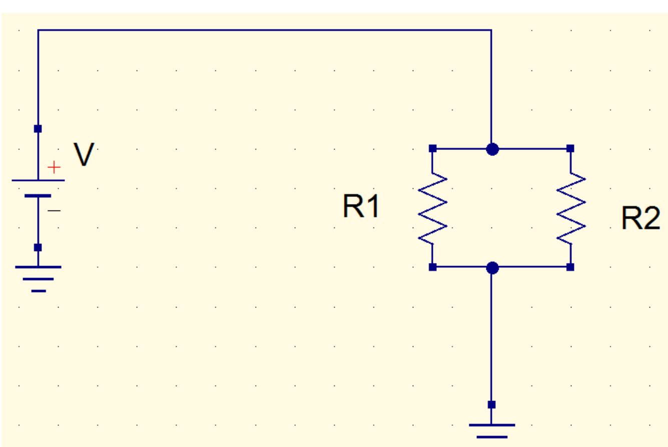
$$IV = I_1R_1 + I_2R_2 = I(R_1 + R_2)$$

$$R_{eq} = R_1 + R_2$$

Note also that $\Delta V_2 = R_2I = R_2\frac{V}{R_{eq}} = \frac{R_2}{R_1+R_2}V$. We call this a voltage divider and we'll use it a lot.

Important to note: I chose R_2 since the lower end of it was at ground (0V) so the voltage drop across it is just V_2. This then also helps remember how it works: the V_2 term is in the numerator on the left (denominator is one) and in the numerator on the right has a factor of R_2. Note that this will occur so frequently it is useful to remember.

Parallel combinations can be similarly analyzed.



In this case since both ends of both resistors are connected together, the potential drop across each must be the same. So then we have:

$$V = I_1R_1 = I_2R_2$$

$$I_1 = \frac{V}{R_1}\ ;\ I_2 = \frac{V}{R_2}$$

Since all the current leaving the battery must go through R_1 or R_2 we must have $I=I_1+I_2$.
So the equivalent resistance has I flowing through it and

$I = \frac{V}{R_{eq}} = I_1 + I_2 = \frac{V}{R_1} + \frac{V}{R_2}$ or, looking at second and fourth terms:
$\frac{V}{R_{eq}} = \frac{V}{R_1} + \frac{V}{R_2}$ which is $\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2}$. Equivalently: $R_{eq} = \frac{R_1 R_2}{R_1+R_2}$.

Again note that $I_1 = \frac{V}{R_1} = \frac{IR_{eq}}{R_1} = I\frac{R_2}{R_1+R_2}$ and similarly $I_2 = I\frac{R_1}{R_1+R_2}$. This tells us how the current splits in a parallel combination, which is also called a current divider. Note that in this case, the subscripts in the numerators are complementary: 1 goes with 2 and vice versa.

How do we measure these quantities?
In old meters a current in a coil interacts with a magnetic field, usually from a permanent magnet. Resulting torque causes the coil and attached meter to rotate with a coil spring opposing the rotaion. Can design this so that deflection is proportional to the current. This basic device is a galvanometer (specifically a D'Arsonval galvanometer). Different configurations of this basic device can measure current or voltage.

Modern digital meters measure ΔV across a known $R_{internal}$ to get $I_{external}$.

Power dissipated by R

$$P = I\Delta V \; ; \; \Delta V = IR$$
$$\text{so } P = I^2 R \text{ or } P = \frac{\Delta V^2}{R}$$

Power supplied by battery?

$$P = I\Delta V$$

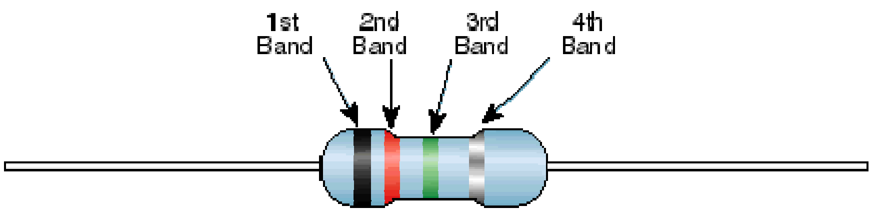
Real resistors come in many values. We'll be using resistors that look like this:
A configuration of discrete (individual) resistor components common in prototyping and small production work. More mass produced cicruits make use of surface mount packages which are small and designed for machine placement. They look more like this:

For the cylindrical bodied ones we'll be using, the color bands all around the cylindrical body of resistor encode the R value. This scheme is compact and readable from any orientation. The code identifies R value and "tolerance" reflecting a percentage range around the coded value the component is assured of having. Standard resistors have 4 bands. High precision version may have 5 band code. Power dissipation is also a relevant parameter: How much power can be dissipated in a resistor without damaging it? Physical size is one significant factor in determining power rating: small sized resistor=small power rating. Typical values: 1/8 Watt, ¼ W, ½ W, 1 W. For larger power ratings, package is less standardized and usually rating is printed on the package. Also, they are now big enough to be able to read printing on them.

From Mr. Varistor's Fun Page: http://www.marvac.com/fun/resistor4band.aspx

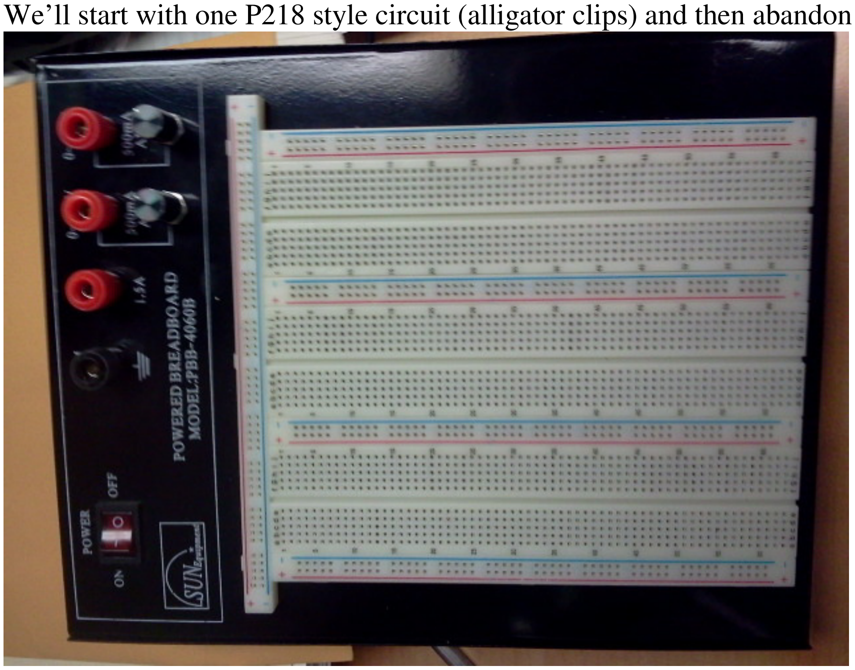
XICON™ **Passive Components**

Standard EIA Color Code Table 4 Band: ±2%, ±5%, and ±10%



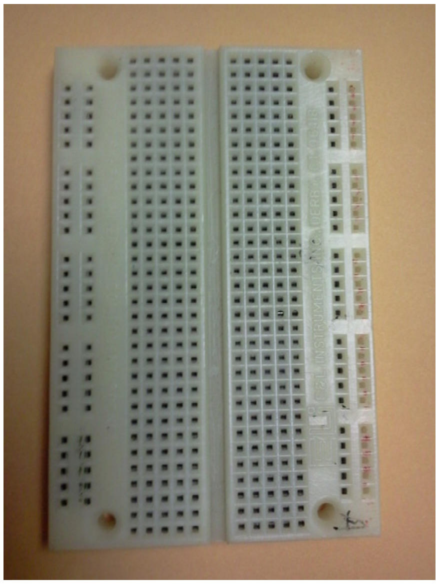
Color	1st Band (1st figure)	2nd Band (2nd figure)	3rd Band (multiplier)	4th Band (tolerance)
Black	0	0	10^0	
Brown	1	1	10^1	
Red	2	2	10^2	±2%
Orange	3	3	10^3	
Yellow	4	4	10^4	
Green	5	5	10^5	
Blue	6	6	10^6	
Violet	7	7	10^7	
Gray	8	8	10^8	
White	9	9	10^9	
Gold			10^{-1}	±5%
Silver			10^{-2}	±10%

We'll start with one P218 style circuit (alligator clips) and then abandon them for breadboard layout:



The breadboard system is

- Quick, compact, organized way to lay out charts, especially for developing
- Wires inserted into the holes can be used to build up circuits. Some of the holes are connected together electrically on the backside:




Comparing the left (top view) and right (bottom view) shows how the connections work. The short horizontal rows of 5 holes are electrically connected. The “trench” down the middle is designed for use with a common type of integrated circuit package that we will see later in the course.

The vertical columns along the egdes are connected as well. In longer breadboards the vertical columns are sometimes split in the middle electrically, so you can have independent circuits on the two halves. As we will see, sometimes we want to deliver a common voltage (+15 V, -15V, 0V) to different parts of a circuit. The vertical columns are ideal for this distribution. A system that distributes power (or a common signal) to many points is called a *bus*.

Good practice:
- turn off power while setting up
- Keep leads short and ***neat***: finding and fixing mistakes is much easier with neatly wired circuits
- Use busses
- Color code wires, especially for power. Conventions vary but a common one is red=+voltage, black=-voltage (or ground, if there’s no voltage below ground), green=ground.

Answer all questions asked in lab handout in your lab book. This does not mean “write down the question and supply the answer. The best way is to answer the question in context. So if the question is something like “How does the current in R1 depend on the power supply voltage?” What might appear in your log book would be only: “The current in R1 is seen to increase linearly with the power supply voltage.”

Lab book should be “blog-like” in that it should explain what you are doing and how as well as record data and self-contained analysis. It is not a record of every specific action you took. You will not be writing things like “then we connected a blue wire from point a33 to b52 on the bread board”. You will sketch any circuit you make and describe what measurements you make, how measurements are made, what the result of the measurements are, and what conclusions you come to as a result.

When we don't have simple series or parallel combinations, we have to use Kirchhoff's laws to analyze circuits.

$\sum_{\substack{around\\loop}} \Delta V's = 0$: This is conservation of energy.

$\sum_{at\ a\ juntion} I's = 0$: This is conservation of charge. (assumes steady state=no charge accumulating at junction.

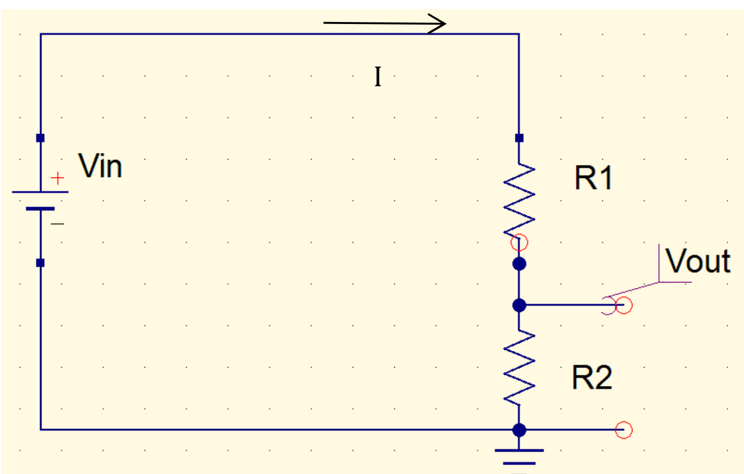
When we simplify circuits (series, parallel) into a single effective resistance, we call that R equivalent (R_{eq}), why equivalent? Because if we apply the same voltage, the same connect flows, so same I-V curve.

When we start chaining circuits together, it's usually easier to do that if we simplify circuits first.

Thevenin (& Norton) Theorems say that any linear circuit of resistors and sources can be replaced with a single voltage (current) source in series (parallel) with one resistor . In general, the source and resistor will not be any of the values in the original circuit. Again, the purpose of this is to make thinking about behavior of the circuit easier and to make it easier to understand what happens when we chain circuits together.

Let's start with a simple example that we already understand to illustrate the ideas and procedures:

Voltage divider



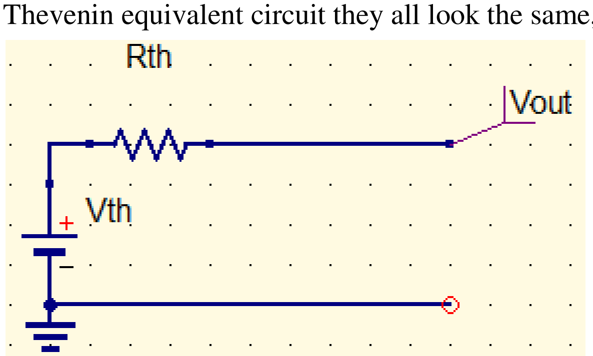
With no load (nothing attached across V_{out}:

$I = \frac{V_{in}}{R_1+R_2}$

$V_{out} = IR_2$

$V_{out} = \frac{V_{in}R_2}{R_1+R_2}$

The Thevenin equivalent of this circuit (*all* Thevenin equivalents look like this—that's the beauty of the Thevenin equivalent circuit they all look the same, just different values) is:



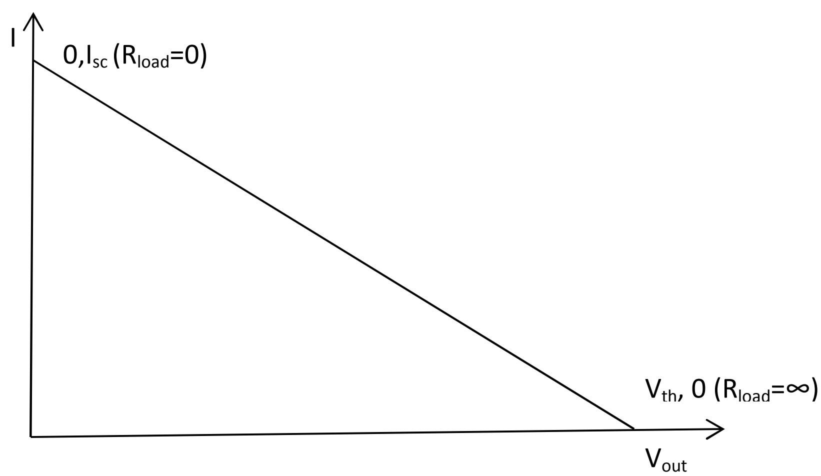
So the idea is that if we a load (some R_{load} , say) across the output terminals of either circuit, the same current would flow—they have the same I-V curve.

But the values of Rth and Vth are not those of the original circuit. What values to use? From the circuit at left, if there's no current flow ($R_{load}=\infty$), $V_{out}=V_{th}$. If the I-V curve is to be the same for this circuit as the original, the unloaded V_{out}'s must be the same also. So if we analyze the original and find V_{out} when $R_{load}=\infty$ (this case is usually called the "open circuit" case since in an open circuit no current flows from the output terminals), this is V_{th}.

Similarly, if $R_{load}=0$ ("short circuit") in the Thevenin equivalent the current is $I_{sc}=V_{th}/R_{th}$. So again, if we set $R_{load}=0$ in the original circuit, the current that flows through it is Isc and since we know V_{th}, we can calculate R_{th}. Note that under the short circuit condition, no current flows through R_2 (see the current divider relation!) so that the short circuit current is just $I_{sc}=V_{in}/R_1$.

So what's the point? The point is that now if we imagine connecting any load up to the Thevenin equivalent circuit, it is easy to determine the current that flows because the load and Rth are in series. Obviously, in the example we just did, it's not that much harder to analyze the original, but because even any complicated circuit can be replaced with a Thevenin equivalent, once we have the equivalent circuit it's easy to see what happens with different loads.

How would you determine the I-V curve? Imagine attaching a variable R_{load} to V_{out}.
At $R_{load}=\infty$, I=0 so $V_{out}=V_{oc}$ so one point on the graph is $I=0, V=V_{oc}=V_{th}$.
At $R_{load}=0$, $I=I_{sc}$ and $V_{out}=0$ (a short has no resistance so no voltage drop) so plot $I=I_{sc}$, V=0.



We'll see that a similar analysis works for AC Circuits.

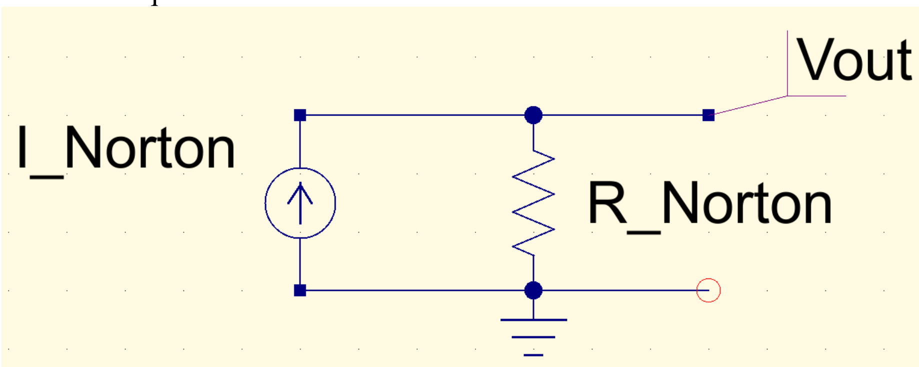
The <u>decrease</u> in Vout as $R_{load} \downarrow$ is called sagging or drooping of Vout.

We say the attached R "loads" the circuit.

This is why we use Thevenin: rather than re-analyzing the circuit for every possible load, find Vth, Rth and we have a <u>simple</u> circuit to deal with.

I mentioned Norton equivalents earlier on. Norton's Theorem is similar to Thevenin's but for constant current sources. It says that any circuit of sources and linear circuit elements can be replaced by one constant current source in They are not as commonly seen (as we'll see because constant current sources aren't as common), but they can be handy in certain circumstances.

So Norton equivalents all look the same:



and you can convince yourself (by analyzing the I-V curve) that $I_{Norton}=I_{sc}$ and that $R_{Norton}=R_{th}$.