## Electrical measurements:

Last time we saw that we could define circuits though: current, voltage and impedance.

Where the impedance of an element related the voltage to the current:

$$V = IZ$$

This is Ohm's law.

We saw that the voltage was like a pressure and current was a flow. From this we realized that the sum of currents into and out of any point must be 0 in steady state:

$$\sum_n I_n = 0$$

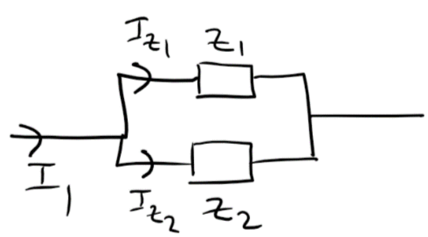
This is KCL.

And that the voltages around any loop in a circuit must be zero:

$$\sum_n V_n = 0$$

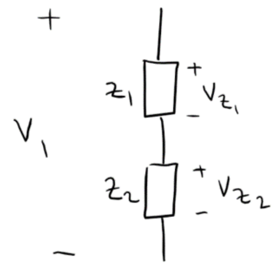
This is KVL.

From these rules we saw that there were a few handy rules for elements connected in series and parallel. For elements in parallel we found that the current divides between them with more of it going to the branch with the lower impedance (bigger pipe):




$$I_{Z1} = \frac{I_1 Z_2}{Z_1 + Z_2}$$

For element in series we found that the voltage divides between them with the larger voltage drop of the element proportional to the impedance of that element:




$$V_{Z1} = \frac{V_1 Z_1}{Z_1 + Z_2}$$

This all seems reasonable. But electricity is still largely invisible, how do we measure these quantities in the lab? How do we use this theory to create models of systems?

The elements that we have talked about mathematically are ideal. Today we will see that we can use the ideal to model the real. We will also see how we might think about measuring these quantities and how they are measured in practice.

We would like to measure both current and voltage. How can we do this?

**Measuring current:**

Consider the inductor, its terminal relationship is:

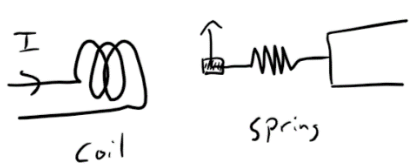
$$\Phi = LI$$

This states that the magnetic flux density is equal to the inductance multiplied by the current.

Meanwhile there is a magnetic force created between any two objects with a magnetic field.

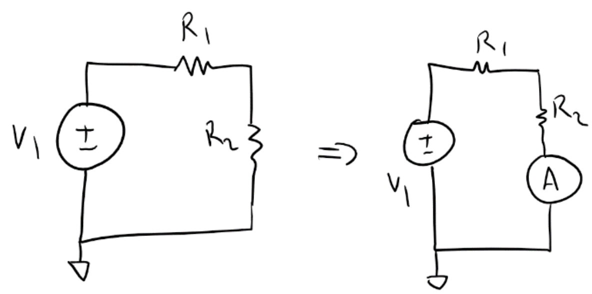
We can measure the magnetic force by measuring it against a spring or against gravity or anything else known. (Electromagnet demo).

Therefore one way to determine the current in a circuit would be to create a “standard” coil. We will give this coil’s inductance a name: 1 Henry. Then we measure the force using a spring and create a ruler to mark off how much current is flowing!



This is exactly how the panel meter works in this power supply. It has a very small spring and an electromagnet tugging on a ferromagnetic material and it is all balanced just so to allow it to move the needle to what the current is on the gauge.

So what do we do if we want to measure the current in a random circuit?




Well we must place the meter into the path of the current. If the current does not flow through our meter then it will not create the magnetic field we need.

Now you might say: ah, by putting the meter into the circuit we have changed the circuit, and you would be right. The meter is an inductor in this case and it is made of some wire so it must have some resistance. So it *will* change the circuit.

To not disturb our system the meter should have zero resistance and zero inductance. In other words it should just be a short circuit. In practice such a measurement is *impossible* and we must take this into account when understanding what we have measured.

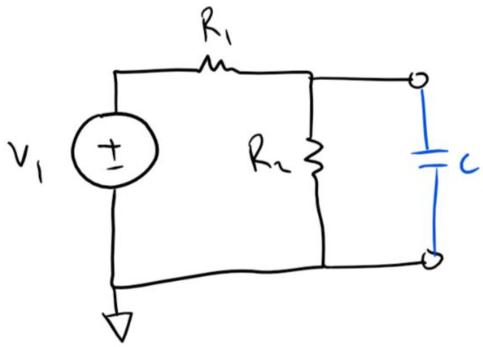
Although analog panel meters have largely stopped being used in measurement, current measurements though magnetic sensing continue in industrial applications through the use of clamps that measure the stray magnetic field from wiring.

**Measuring voltage:**

Voltage being a pressure we might think we should measure how fast our electrons are going. This is a reasonable idea in principle but in practice it might be hard to do.

Instead let’s consider how we might use our handy current meter to measure what voltage something is.

What if I had an ideal capacitor, and I hooked it up in parallel with the element I wanted to measure the voltage of.




A capacitor is like a water tank and so when I first insert it next to the element in the circuit it will suck up all of the current but as the charge on the capacitor increases the current is requires will drop to 0.

When this happens it is as if the capacitor is not in the circuit.

Now I have a tank with a terminal relationship of:

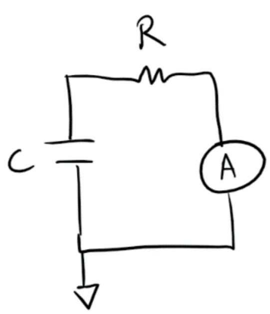
$$Q = CV$$

Again if I defined how big this capacitor was let’s say as 1 Farad. Then if I could measure all of the charge in it, I would know what the voltage was on it at the start.

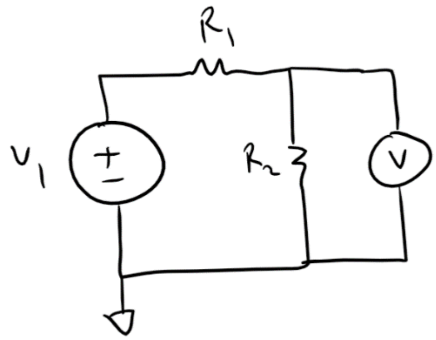
Luckily:

$$I = \frac{dQ}{dt}$$

So all I need to do is integrate the current (which I can measure) from discharging the capacitor. I can do this very well because I can put a resistor in series with the capacitor and use my current meter. Even if it is not a perfect current meter I will get a very good answer because I can choose R to be large when it discharges.




This obviously is not a practical way of measuring voltages but it does illustrate the key properties of a good voltage meter: it goes in parallel with the voltage being measured and it draws no current. Yes our capacitor did draw some current at the start but when it got up to the full voltage it did not.




**Recap:**

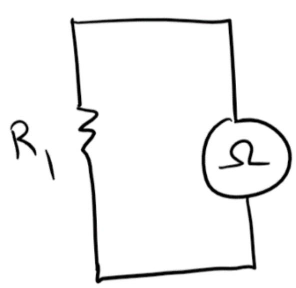
A current meter has to go in series with the element whose current you want to measure. Ideally it looks like a short circuit.

A voltage meter has to go in parallel with the element whose current you want to measure. Ideally it looks like an open circuit.

**Measuring impedance:**

If you want to measure the impedance or resistance of an element simply attach a known voltage across it and measure the current. Dividing the two gives you the impedance.

To measure the impedance of an element remove it from the circuit and place the impedance meter across the element (it is in both series and parallel with the element at once allowing both a current and voltage measurement).




**The multimeter:**

A multimeter is what its name suggest multiple meters in one, most can measure voltage, resistance and current. Some can measure even more things.

Multimeters are mostly based on measuring voltages these days. They have a reference in them at a known voltage based on semiconductor physics and they have a device that can compare two voltages indicating which is greater.

Effectively they can then create a variable voltage divider and measure the point at which the voltages are equal to determine the unknown voltage.

To measure current they generally use a small known value of resistance and measure the voltage drop across it to infer the current.

To measure the resistance of another element they replace the fixed resistance they used in the voltage measurement with your test resistance and again effectively sweep the other resistance until they get a known voltage.

These are the ideas behind how the measurements are done but in practice it is significantly more complex to carry out the ideas.

(Demo of measuring an LED circuit)

A diode is an element that allows current to flow in only one direction. It is the electrical equivalent to a check valve in a fluid circuit.

**Component limits:**

What we just saw was an example of the specifications of a component being exceeded. In this case it was that the power through the resistor was greater than the rating.

Power in an electrical circuit is:

$$P = IV$$

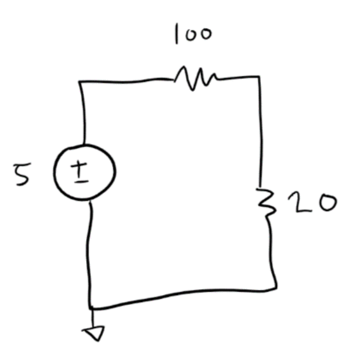
I can trade a lot of current flowing at low speed for less current going faster and still do the same work. The product of the pressure of the fluid and the amount is the power.

Based on this the power in a resistor can be written two ways:

$$P = I^2R = \frac{V^2}{R}$$

A typical though-hole resistor is ¼ Watt.

How much power will each resistor need to dissipate in this circuit if the voltage source is 5V?



$$I = \frac{5}{120} = 0.042\ A$$

$$P_{R1} = I^2 R_1 = 0.176\ W$$
$$P_{R2} = I^2 R_2 = 0.035\ W$$

Capacitors and inductor have limits too.

Capacitors have a maximum voltage and inductors a maximum current. Above these limits they will fail. Inductors will melt together normally, perhaps then catching on fire. Capacitors may fail open or shorted. Capacitors that fail shorted will catch on fire.

You should give good engineering margin to components if you do not want them to fail.

Capacitor can also be polarized. This is because they can work based on electrochemical properties. Using them backwards will cause an electrochemical reaction that will cause an electrolytic capacitor to fail, normally shorted.

(Demo of capacitors failing).

**Modeling non-ideal systems:**

You may have seen a battery based on a potato or other food or chemical items before. The potato battery works for exactly the same reasons that regular batteries work: electrochemistry. The acid in the potato is an electrolyte between two electrodes of different types of metals. These metals have different work functions (how hard it is to get an electron out), and so they exchange electrons via the electrolyte. Zinc and copper are commonly used for this experiment.

A variation on this idea was how the first battery was made by Volta in the 1700s in Italy.

We often draw an ideal voltage source as a battery. But is a battery an ideal voltage source?

(Show that the potato produces a voltage with the multimeter).

How much current should flow out of a voltage source if we put it in series with an ammeter?

Based on this the meter should catch on fire.

(I will measure the short circuit current from the potato).

So our potato had about 0.9 V output but only a small current. How can we model this?