Electricity and Magnetism
DC Circuits
Resistance-Capacitance Circuits

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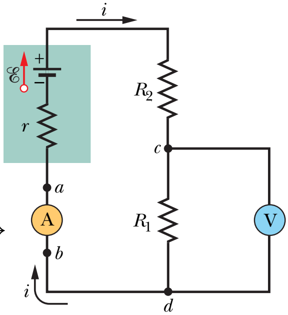
Last time

- emf
- power
- Kirchhoff's laws

Overview

- meters
- Kirchhoff's laws practice
- grounding a circuit
- time-varying circuits

Ammeters and Voltmeters



ammeter → ← voltmeter

Ammeter

A device for measuring **current** in a circuit.

Voltmeter

A device for measuring **potential difference** across a component of a circuit.

Ammeter

For an ammeter to work, the same current that you want to measure must go through the ammeter.

Therefore, it must be connected in series in the part of the circuit where you want to test the current.

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Therefore, it must be connected in series in the part of the circuit where you want to test the current.

Any resistance from the ammeter (r_A) will decrease the current in that part of the circuit.

$$I = \frac{\Delta V}{R + r_A}$$

If $r_A = 0$ the current through that part of the circuit is unchanged.

The current cannot actually be zero, but it needs to be as small as possible for an accurate measurement:

$$r_A << R$$

Voltmeter

For an voltmeter to work, the same potential difference must be across the voltmeter as the part of the circuit to be measured.

This means he voltmeter must be connected in parallel across the component where you wish to measure the potential drop.

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Because this creates another path for the current, the resistance of the voltmeter effects the effective resistance of that part of the circuit:

$$\Delta V = I R_{\text{eq}} = I \left(\frac{R}{R/r_V + 1} \right)$$

If r_V is infinite, the potential difference in that part of the circuit is unchanged.

It cannot actually be infinite, but we need

$$r_V >> R$$

Meters

Some meters can be used either as ammeters or voltmeters with different settings.

These are called **multimeters**.

You have used three different ones already in lab:

- Hewlitt Packard digital multimeter (HP-DMM)
- Extech digital multimeter (hand-held DMM)
- Simpson Volt-Ohm meter (Simpson VOM)

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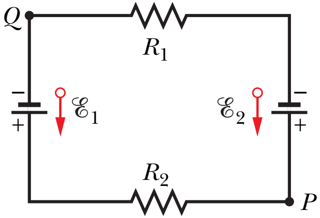
Since the internal resistance must be very much less for an ammeter than a voltmeter it is important to use the meters in the correct mode.

If a meter is in ammeter mode and put in parallel as if it is a voltmeter a very large current may flow through it. This can damage the device. Usually meters are fused in ammeter mode.

Using Kirchhoff's Laws examples

Page 726, #2

•2 In Fig. 27-26, the ideal batteries have emfs $\mathscr{E}_1 = 150$ V and $\mathscr{E}_2 = 50$ V and the resistances are $R_1 = 3.0\ \Omega$ and $R_2 = 2.0\ \Omega$. If the potential at P is 100 V, what is it at Q?



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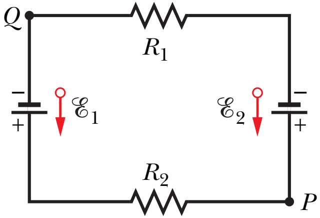
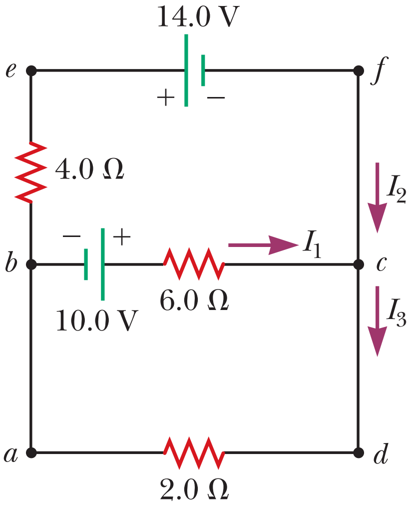


Loop rule: $-\mathcal{E}_2 - IR_2 + \mathcal{E}_1 - IR_1 = 0$, $I = 20$ A.

Potential at $Q = -10$ V.

Example with a Multiloop Circuit

Find the currents I_1, I_2, and I_3 in the circuit.



Suppose the currents flow in the direction shown.

Example with a Multiloop Circuit

Junction rule:

$$I_1 + I_2 = I_3 \tag{1}$$

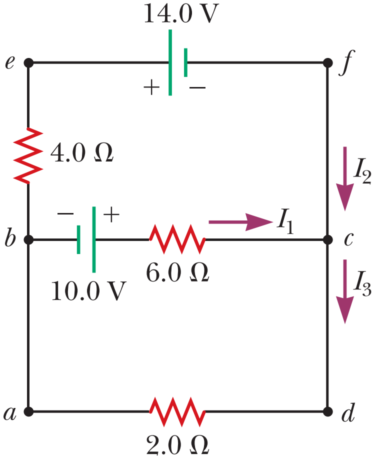
Loops:

$$10\text{V} - (6\Omega)I_1 + (2\Omega)I_3 = 0 \tag{2}$$

$$-14\text{V} + (6\Omega)I_1 - 10V - (4\Omega)I_2 = 0 \tag{3}$$

$$-14\text{V} - (2\Omega)I_3 - (4\Omega)I_2 = 0 \tag{4}$$

Example with a Multiloop Circuit



$I_1 = +2.0$ A $\;\; I_2 = -3.0$ A $\;\; I_3 = -1.0$ A

Time Varying Circuits

In circuits charge is not static, but moving.

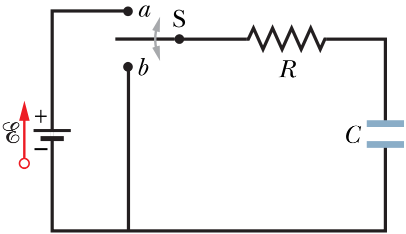
Current does not necessarily have to remain constant in time.

Capacitors take some time to charge and discharge, as you saw in the lab.

Other components also cause current to behave differently at different times, but for now, we will concentrate on circuits with resistors and capacitors.

RC Circuits

Circuits with resistors and capacitors are called “RC circuits.”



Charging a Capacitor

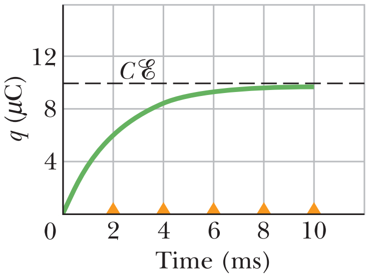
When an uncharged capacitor is first connected to an electrical potential difference, a current will flow.

Once the capacitor is fully charged however, $q = C\,(\Delta V)$, current has no where to flow and stops.

The capacitor gently "switches off" the current.

Charge varies with time

The charge on the capacitor changes with time.



It is possible to determine how if changes by considering the loop rule for a resistor in series with a capacitor:

$$\mathcal{E} - IR - \frac{q}{C} = 0$$

Current is the rate of charge flow with time: $I = \frac{\Delta q}{\Delta t}$.

Formally, this is actually the derivative $I = \frac{\mathrm{dq}}{\mathrm{dt}}$.

RC Circuits: Charging Capacitor

If we replace I in our equation with the derivative:

$$\mathcal{E} - R\,\frac{\mathrm{dq}}{\mathrm{dt}} - \frac{q}{C} = 0$$

This is a differential equation. There is a way to solve such equations to find solutions for how q depends on time. (You do not need to know them.)

The solution is:

$$q = C\mathcal{E}\left(1 - e^{-t/RC}\right)$$

RC Circuits: Charging Capacitor

Using the equation for q, an equation for current can also be found:

$$I = \left(\frac{\mathcal{E}}{R}\right) e^{-t/RC}$$

Using $\Delta V_C = q/C$, we can also get the potential difference across the capacitor:

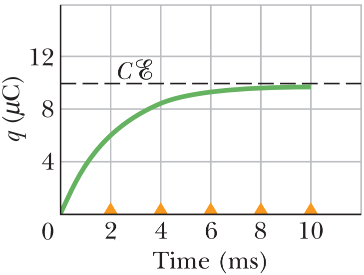
$$|\Delta V_C| = \mathcal{E}(1 - e^{-t/RC})$$

RC Circuits: Charging Capacitor

How the solutions appear with time:

Charge:

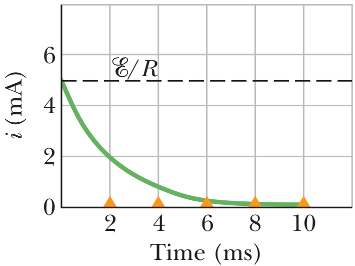
$q = q_0\,(1 - e^{-t/RC})$



where for this circuit $q_0 = C\mathcal{E}$

Current:

$I = I_0\,e^{-t/RC}$



where for this circuit $I_0 = \frac{\mathcal{E}}{R}$

RC Circuits: Time Constant

$$\tau = RC$$

τ is called the **time constant** of the circuit.

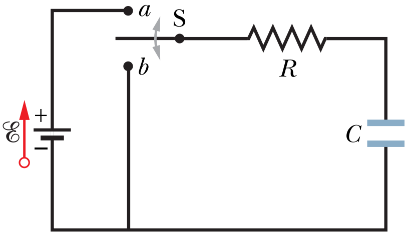
This gives the time for the current in the circuit to fall to $1/e$ of its initial value.

It is useful for comparing the "relaxation time" of different RC-circuits.

RC Circuits: Discharging Capacitor

Imagine that we have charged up the capacitor, so that the charge on it is q_0.

Now we flip the switch, the battery is disconnected, but charge flows off the capacitor, creating a current:



RC Circuits: Discharging Capacitor

What happens to the charge on the capacitor?

$$q = q_0 \, e^{-t/RC}$$

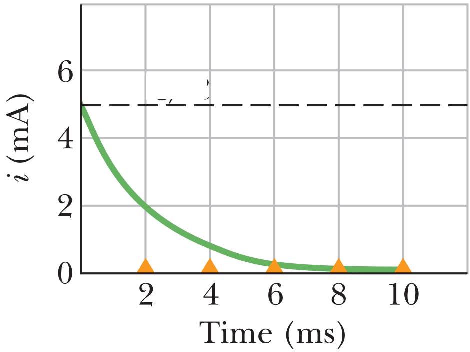
It decreases exponentially with time: you will see this in a lab!

RC Circuits: Discharging Capacitor

What happens to the current?

$$I = I_0\, e^{-t/RC}$$

where $I_0 = \frac{q_0}{RC}$.



RC Circuits: Discharging Capacitor

Multiplying the current by the resistance R gives the potential difference across the resistor:

$$|\Delta V_R(t)| = (\Delta V)_i \, e^{-t/RC}$$

The same expression describes the potential difference across the capacitor!

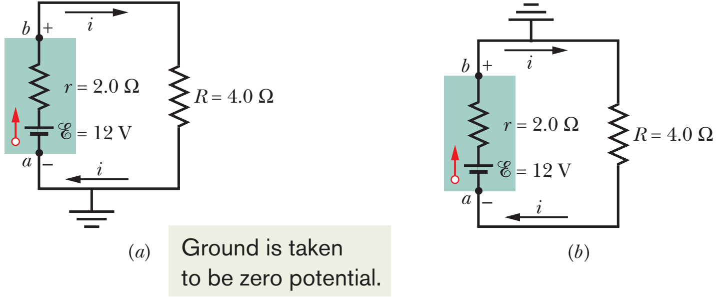
$$|\Delta V_C(t)| = (\Delta V)_i \, e^{-t/RC}$$

where $(\Delta V)_0 = I_0 R = \frac{q_0}{C}$.

Grounding a circuit

A circuit can be "grounded", that is connected to the Earth. This should drain any built-up charge off of that part of the circuit.

By convention, we label the potential at this point $V = 0$. This gives us an absolute scale for potential, rather that simply speaking of potential differences.

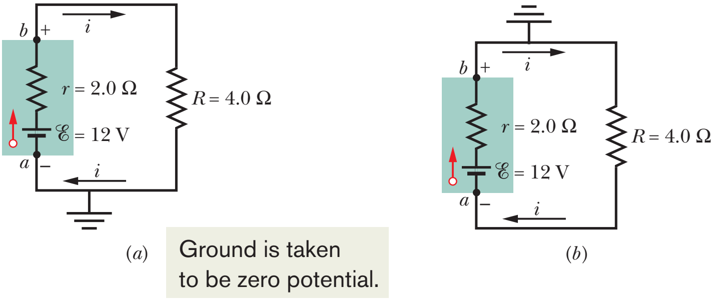


Grounding a circuit is represented with a three-line symbol.

Grounding a circuit and changes in potential

What is happening to charges in the circuit?

Grounding a circuit



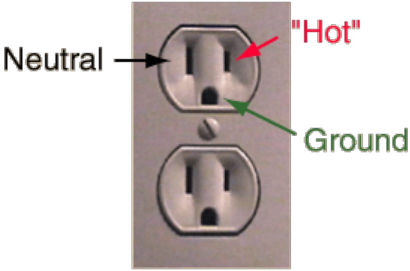
In (a), the potential at a, $V_a = 0$ V and at b, $V_b = 8$ V.

In (b), the potential at b, $V_b = 0$ V and at a, $V_a = -8$ V.

Household Wiring

Electricity is delivered to your house in two line or “live” wires, each at 120V (rms), but with different polarities.

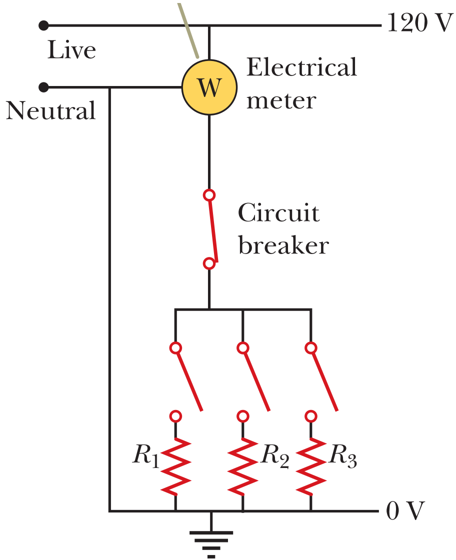
These wires are then split and power runs to sockets with one line wire and one neutral wire.



The neutral wire is supposed to be at 0V, but in practice charge can build up.

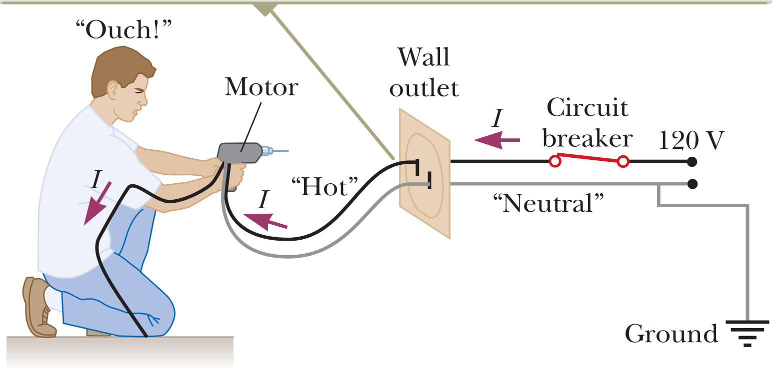
It is best to treat is as also “live”.

Household Wiring



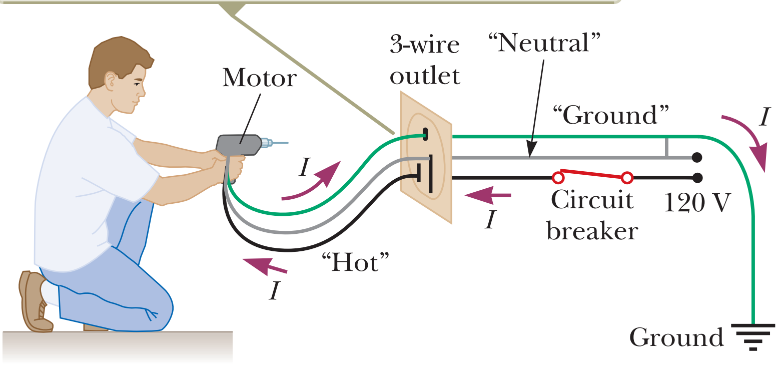
Safety and Grounding

In the situation shown, the live wire has come into contact with the drill case. As a result, the person holding the drill acts as a current path to ground and receives an electric shock.



Safety and Grounding

In this situation, the drill case remains at ground potential and no current exists in the person.



More exotic conducting materials

So far, we have talked about conductors and insulators.

However, there are materials that behave in ways quite different from the conductors and insulators we have investigated so far. They are:

- semiconductors
- superconductors

Semiconductors

Semiconductors have resistivities between those of conductors and insulators.

However, their resistivities can be controlled by several different means (depending on the type of semiconductor):

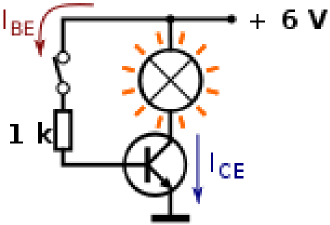
- by adding impurities during manufacture
- by electric fields
- by light

This allows for many new kinds of components in circuits: ones that amplify currents, emit light, are light sensitive, implement switching, *etc.*

Semiconductors

LED (light emitting diodes) are one application of semiconductors.

Transistors are another. Transistors can act as an amplifier or a switch in a circuit.



[1]Figure by FDominec, on Wikipedia.

Semiconductors

Silicon is perhaps the most famous semiconductor.

Recall that we had a model relating resistivity to temperature:

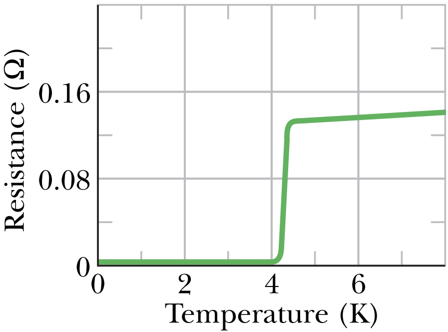
$$\rho - \rho_0 = \rho_0 \alpha (T - T_0)$$

For silicon α is negative! The resistivity decreases as temperature increases.

This is because at higher temperatures more electrons have enough energy to become freely-moving conducting electrons.

Superconductors

Superconducting materials are elements, alloys, or compounds that exhibit a remarkable property: below some *characteristic temperature* the resistivity of the material is effectively zero.



Examples of these materials are mercury and lead. Not all materials do this! Copper does not.

Mercury is superconducting below 4 K. (-269° C)

Superconductors

Before 1986, it seemed we had a good idea about how this happened and why.

Superconductors

Before 1986, it seemed we had a good idea about how this happened and why.

Then "high temperature" superconductors were found.

These are ceramics. One is yttrium barium copper oxide (YBCO).

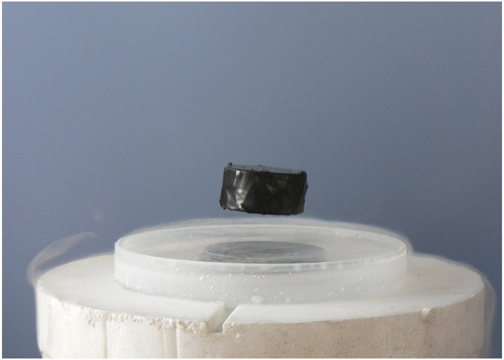
The highest critical temperature found so far is ~ 138 K.

We do not really understand why these ceramics are superconductors.

Superconductors

Superconductors must be cooled to their critical temperature to reveal their superconducting properties.

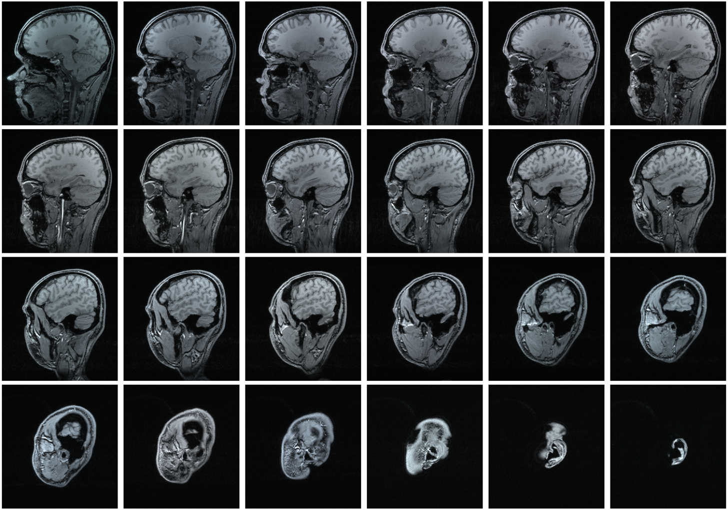
They expel magnetic field lines when cooled below their critical temperature as surface currents cancel out external magnetic fields.



[1] Magnet photo by Mai-Linh Doan, Wikipedia.

Superconductors

Superconductors are used as electromagents in MRI scanners, mass spectrometers, and particle accelerators.



[1]Taken at MPI fuer Biophysikalische Chemie Goettingen, by Daniel Schwen.

Superconductors

Superconductors can also be used very, very sensitive light detectors and for quantum logic circuits.

If a material was found to have a critical temperature above or close to room temperature there would be a huge number of applications for it.

Summary

- meters
- grounding and safety
- RC circuits
- semiconductors
- superconductors

Homework Halliday, Resnick, Walker:

- Look over Chapters 21-27.
- Understand example prob on page 719.
- Ch 27, onward from page 731. Problems: 57, 59