I get a ton of questions on JUST circuit components and understanding how current flows. On the MCAT, circuit questions are relatively simple to solve by hand, but many of the underlying mechanics behind circuit behavior are quite complicated. This guide hopes to illuminate and better explain these concepts. Reach out to me with any questions or comments!

A tool that is often helpful to illustrate these ideas is known as the **water analogy, or pipe analogy**. We use the example of a system of flowing pipes to represent electric flow in a way that's more intuitive. Keep in mind, this model has some limitations, but works well with most purposes. Examples of the water analogy will be given in blue so that you may skip this content if you do not feel like you need to view it.

Current

Current is defined as the movement of charges in circuits. Because electrons are assigned a negative charge, positive current is actually defined as going *in the opposite direction of physical electron flow*. This seems very counterintuitive, but it's important to understand that this has no effect on our understanding of the topic. The assignment is completely arbitrary; were electrons assigned a positive charge, then we wouldn't have this issue. But they're negative.

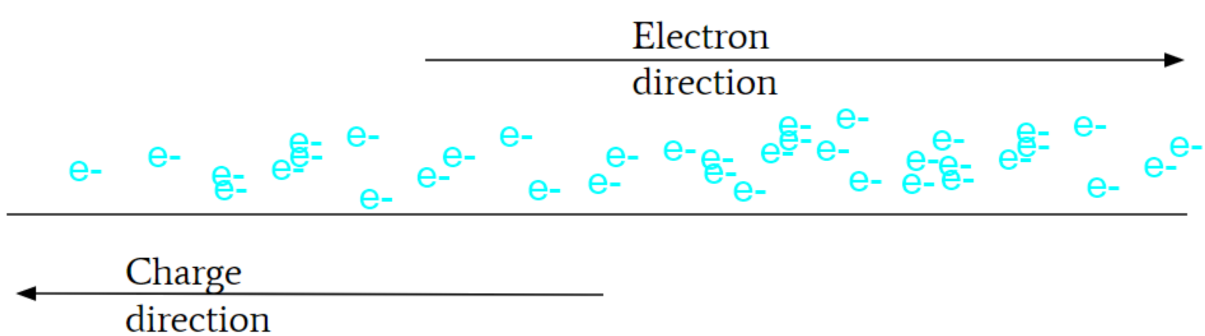


Fig. 1. EEEEEEEEEEEEEEEEEEEEEEEEEEEE

The ability of a material to conduct charge is known as **conductivity.** Electrolytic conductivity relates to that of dissolved salt solutions; what we're more interested in for circuit mechanics is metallic conductivity. Conductivity is a fundamental property, and is assigned its own unit, the **siemens (s).** It is defined as the reciprocal of resistivity, which becomes a much more important concept in a few pages.

The basic unit for current is defined as the **ampere: a movement of 1 Coulomb of charge per second.** We abbreviate current as *I*, and define it formally as

$$I = \frac{Q}{\Delta T}$$

where Q represents charge and T represents time. (No, I don't know why the letter Q represents charge.)

Two modalities of current are encountered in circuits: **alternating current** and **direct current**. Direct current is as the name suggests a single flow pattern, whereas alternating current follows a sinusoidal pattern and periodically reverses flow. There are subtle differences in circuit mechanics depending on the type, but the MCAT is only concerned with direct current. Knowing that alternating current exists in opposition to direct current is sufficient.

With regards to the water analogy, current is best described as water flow through a pipe. The greatest issue to first understand is that unlike electric current, water does not carry an intrinsic charge - there is not a great corresponding entity to alternating current, as water flow doesn't really reverse itself that way. Otherwise, our examples work out nicely. The rate of water flow itself can be seen as similar to current (*I, Q/dT).*

Conductivity can be modeled as how clear or open the pipe is - if the pipe is partially blocked or occluded, less water can flow in it compared to a wide open, clean pipe. This works well with conductivity's inverse, resistivity - a more occluded pipe is also more resistant to flow.

Voltage

Voltage is sometimes a difficult concept to define. We sometimes refer to it as **electric potential difference, electric pressure, or electric tension.** Put simply, voltage is best considered as a measurement of how difficult it would be to move a charged particle from one point to the next point. It takes energy to move an electric charge through an electric field - the higher the voltage, the more energy needed to get from point A to point B. It is by definition not an absolute value - you can only have a voltage *relative* to another point. By convention, if we do not provide a reference point, ground (the Earth) is defined as the reference.

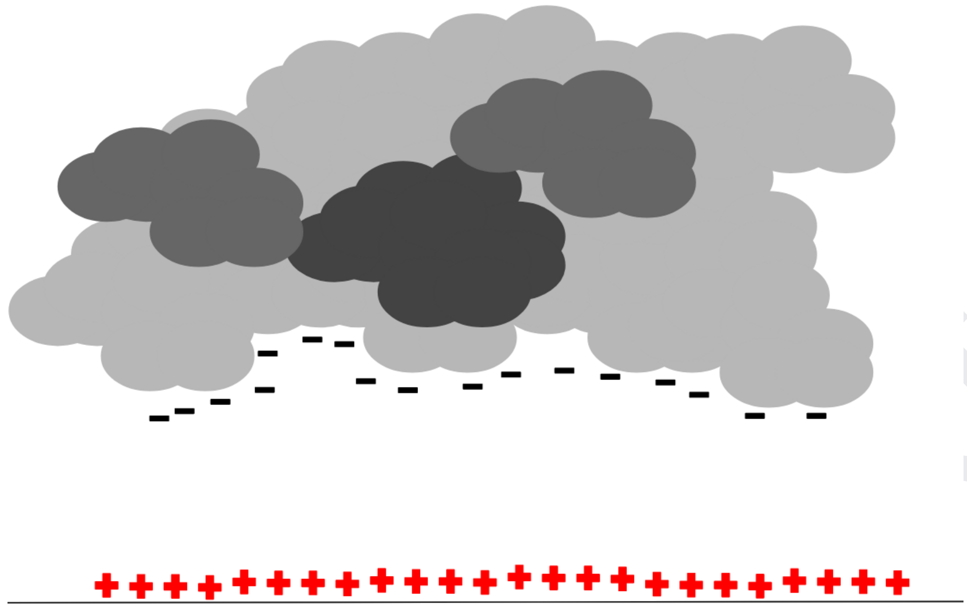


Fig. 2. During thunderstorms, extremely high emf between cloud and ground generates lightning strikes.

If there is no charge moving between the two points, voltage can be referred to as **electromotive force (emf)**. This is not to be confused with an actual force; EMF is simply a voltage. The units of voltage are joules per coulomb ($1V = 1\frac{J}{C}$). In this context, EMF is sometimes thought of as a voltage pressure that elicits charge movement - this view is particularly useful in understanding *induction*, which is a topic out of scope for the MCAT.

Voltage can be thought of as the electrical equivalent to water pressure. Many of the intricacies are preserved - water pressure is always a relative property between two points. If no reference is selected, we would say the water pressure is relative to atmospheric pressure - gauge pressure, in other words. It is easy to understand that water pressure encourages or causes water flow within pipes - similarly, EMF or voltage encourages current in circuits.

Resistance

Resistance is the opposition to charge flow within a material. All materials have some degree of resistance; we make certain assumptions in circuits for the sake of simplicity. Wires, for example, are assumed to have zero resistance. We refer to materials with nearly no resistance as *conductors*. *Insulators,* for the sake of our usage, have very high resistances, to the point of preventing charge flow. Materials that are conductive but provide appreciable resistance are called ***resistors***.

The resistance of a resistor is dependent on its material properties as well as physical dimensions. We can express these metrics with the following relation:

$$R = \frac{\rho L}{A}$$

where R is the resistance, ρ (pronounced "rho") is the resistivity, an intrinsic material property, L is the length of the resistor, and A is its cross sectional area. (We're assuming a cylinder or prism type shape that is constructed such that the cross section doesn't change, because why make life difficult?) The longer a resistor, the greater the length that electrons must pass through the resistive material - therefore, length linearly scales resistance. Cross sectional area will proportionally reduce resistance, since a greater contact area provides more *conduction pathways*, or channels that charge can pass through. For similar reasons, thicker cables can carry a greater amount of current.

We've previously mentioned *conductivity*, which is the inverse of **resistivity**. Our unit for resistivity is the Ohm meter (Ωm). Resistance itself is measured in Ohms, or Ω.

Resistors cause a drop in electric voltage as current passes through them. With voltage, current, and resistance defined, it's time to cover the first of many important equations in circuits: **Ohm's law**. We define it by

$$V = IR$$

where V, I, and R are voltage drop, current, and resistance, respectively. This relation holds for any two set points within the circuit, and shows that the voltage drop is proportional to the current as well as resistance values. Remember: **<u>no charge is lost through a resistor, but voltage may dissipate.</u>**

We've discussed previously how EVERY material has some intrinsic resistance - this even applies to components inside a battery, the typical source of voltage/emf in a circuit. We call this **internal resistance, r_{int}**. This means that the voltage supplied by a battery is slightly lower in practice than the actual rating. We can calculate the true voltage a battery supplies with

$$V = E_{cell} - ir_{int}$$

where V is the real output voltage of the battery, E_{cell} is the theoretical output, i is the current flowing through the cell, and r_{int} is the internal resistance.

A real circuit is often more complicated than a single resistor, however. It is very common for circuits to make use of multiple elements, and exhibit branching. Let's take a look at combining resistors.

Resistors wired in series (or sequentially) will summate resistances one after the other. That is,

$$R_T = R_1 + R_2 + R_3 ...$$

where R_T is total resistance, and R 1, 2, 3...are resistors in series.

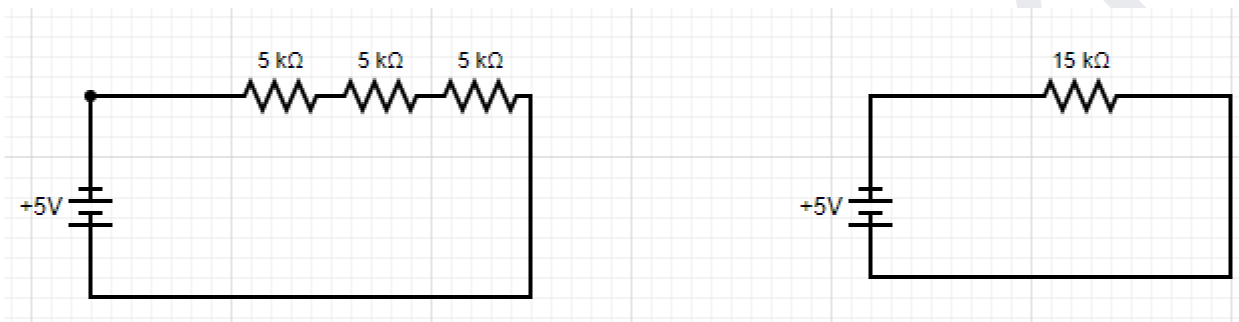


Fig. 3. These two circuits are identical. Resistances add in series directly.

Contrary to popular belief, electricity does not only take the path of "least resistance". It is true that a greater amount of current flows in paths with less resistance, but the current is proportional to the value of resistance. There will still be flow in multiple branches! Resistance along different branches in the same circuit will also combine, but in a different way. If arranged *in parallel*, as shown below, resistances will add reciprocally. That is,

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} ...$$

This may seem counterintuitive, but recall that we mentioned increasing the number of conduction paths will reduce resistance. Providing multiple branches with resistors offers a greater number of conduction paths, and therefore drops resistance.

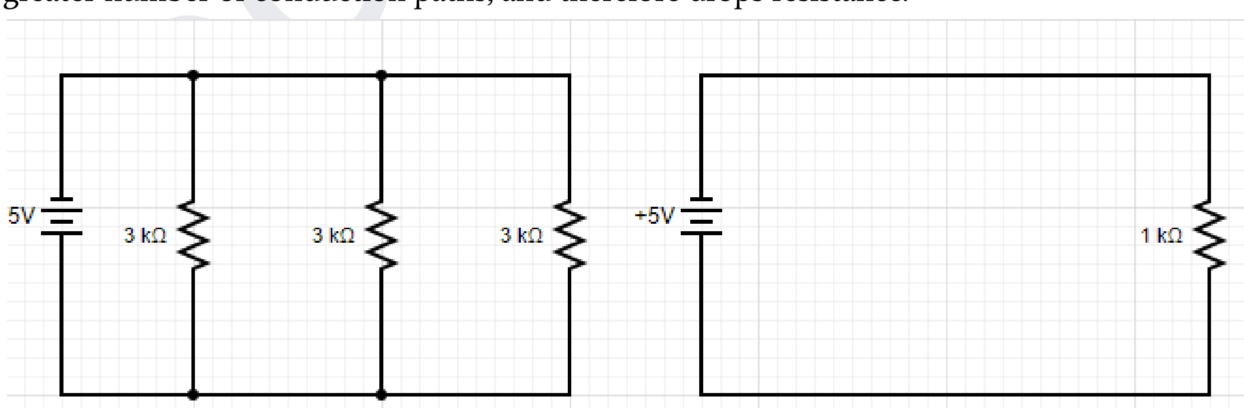
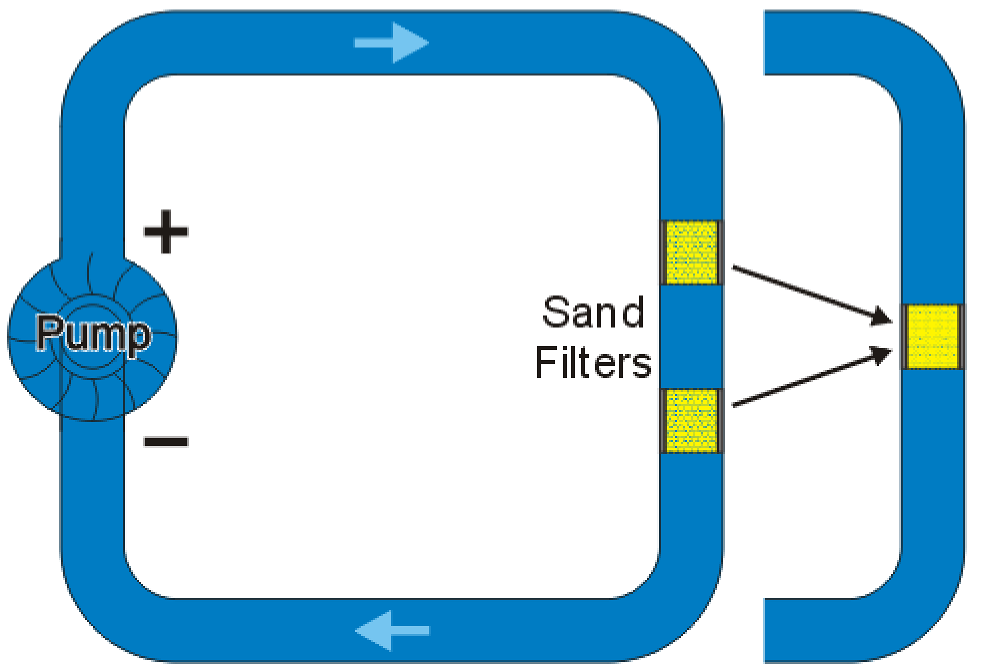


Fig. 3. These two circuits are identical. Resistances add in parallel in reciprocal.

In the water analogy, resistors are often represented as sand filters or sand traps in pipelines. Alternatively, they're represented by narrowing of pipes. These filters will permit some amount of water to seep through, but cause a drop in pressure after the water leaves, similar to the voltage drop across a resistor. The properties of a water filter are also similar to the dimensional properties of a resistor - the longer the filter, the more the pressure drops. The wider the filter, the more room there is for flow to find a way, and the less the pressure drops.

In series, additional filters together represent a large blockage in the pipe, dropping pressure further. In parallel, more channels for the water to pass through have less of an effect on pressure, since there are more pathways for the water to pass.



Subfig. 1. In the water analogy, sand filters can also be combined in series to summate resistance.

Let's consider for a second that the circuits we commonly think of in our everyday lives perform useful tasks for us, whether it's lighting up a room, powering our computers, or brewing coffee. We know that energy is conserved - we can't simply poof it out of nothing - so we know that this energy must come from the electrons flowing through our devices. For that reason, we will take a look at

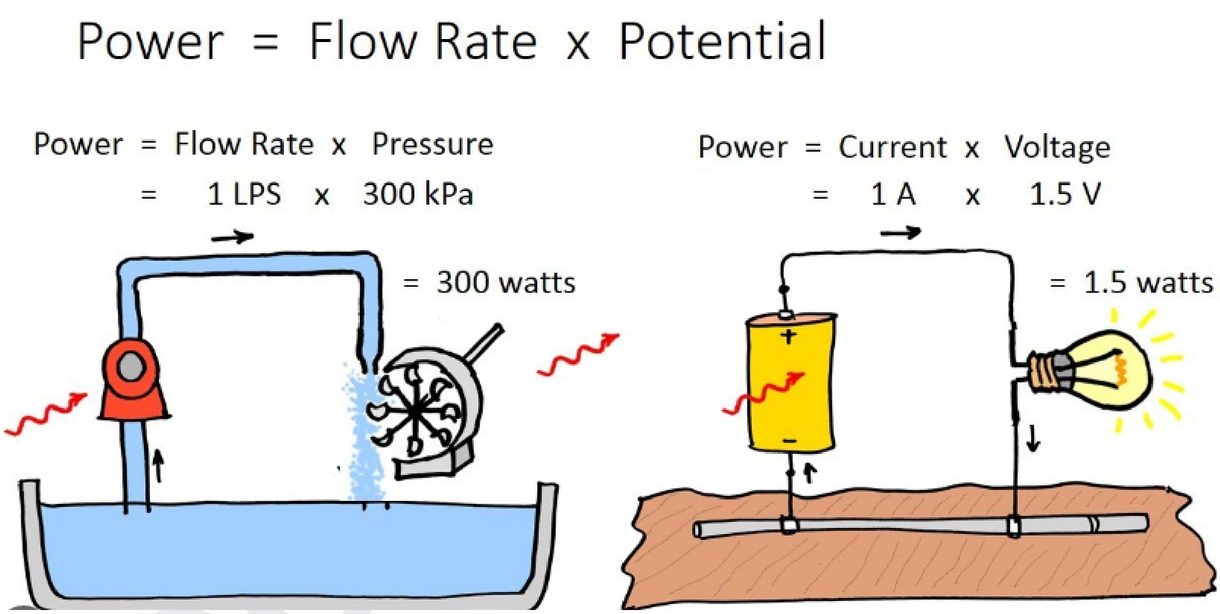
Power

or, more specifically, the rate of conversion of energy over time. We represent devices that convert electrical energy into other forms as resistors. This can be modeled by the following equation:

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

where P is the power (energy over time) dissipated by the resistor.

This one doesn't align well with the analogy because the hydraulic equivalent of an inductor is usually the paddlewheel, but we can double dip to demonstrate. If power in a circuit is current flow times voltage, then power in a flowing set of pipes is water flow rate times pressure.



Subfig. 2. These are all approximations, but in fluid mechanics, flow rate x pressure DOES represent power.

Kirchoff's Laws

Gustav Kirchoff was a 19th century scientist who contributed heavily to our understandings of circuits, thermodynamics, chemistry, life, death, and probably more. Anyways, he wrote two important laws you should know for circuits analysis.

Kirchoff's Junction Law

Also known as the node law. Current flowing into a *node* (any arbitrary point in a circuit, but usually a branching point) must equal the sum of the current flowing out of the node.

Likewise, we can consider the continuity of flow in a water pipe. You can't have more water ENTER a point than water exits, and you can't have more water EXIT than enters.

Kirchoff's Voltage Law

Also known as the loop law. This one is the more elusive of the two for students. Around any closed loop, the sum of voltage sources must always equal the sum of voltage drops.

If we think of the equivalence of water pressure, this means that a closed pipeline requires that the pump pressure is equal to the pressure drops throughout the system. Excess pressure means the pipes would burst over time; not enough pressure means that water doesn't flow and eventually stops!

Keep in mind that this property will hold true for ANY closed loop we draw, even ones that encompass previous loops!

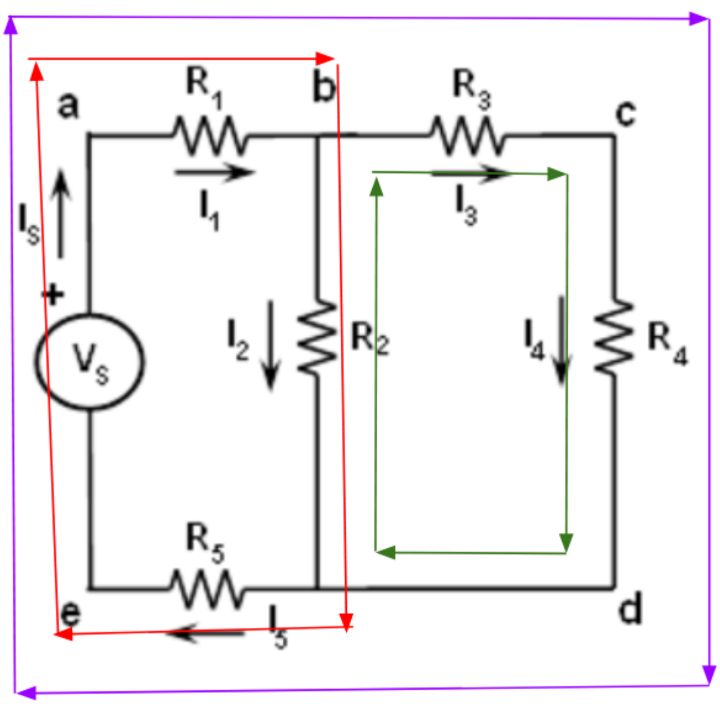
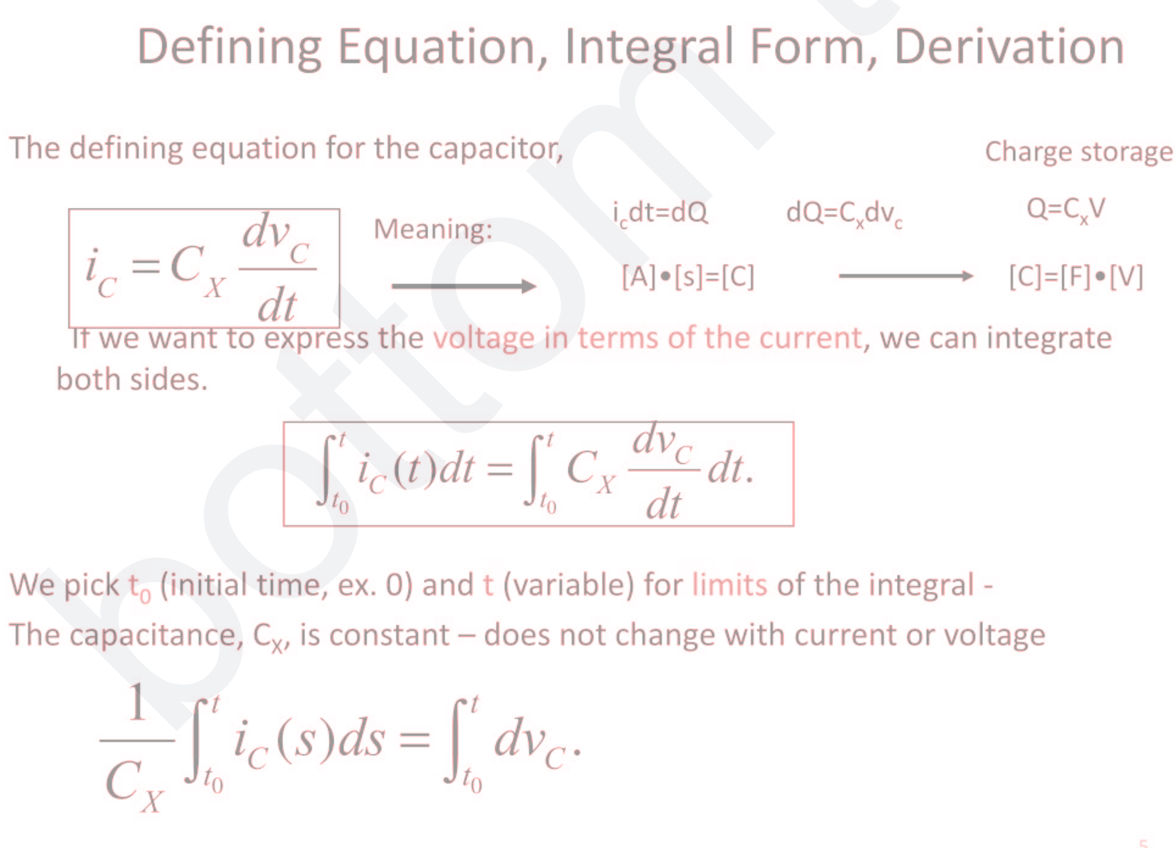


Fig. 4. We can draw loops around resistors 1, 2, and 5; we can ALSO draw a bigger loop around resistor 1, 3, 4, and 5; AND we can draw a loop around just resistor 2, 3, and 4!

Note that we would have to invert the sign of the voltage drop over R2 as the current flows in the opposite direction of the current flow in R3 and R4. All voltage drops and sources should sum to zero.

Capacitors

Capacitors are the final circuit topic featured on the MCAT. A **capacitor** is an electronic circuit component that can hold charge, but not necessarily create a voltage in a circuit. Capacitors are famously used in defibrillators to release their stored charge in one quick burst - a process called **discharge**. (Fun fact: older capacitors really did produce a charging whine. While newer devices no longer create this sound naturally, many defibrillators will STILL simulate the charging noise since providers have grown accustomed to it!) We will focus on one formulation of this device - the parallel plate capacitor. Capacitor discharge mechanics will not be covered on the MCAT. The reason is because it looks like this:



Needless to say, you will not have a calculator to figure this one out.

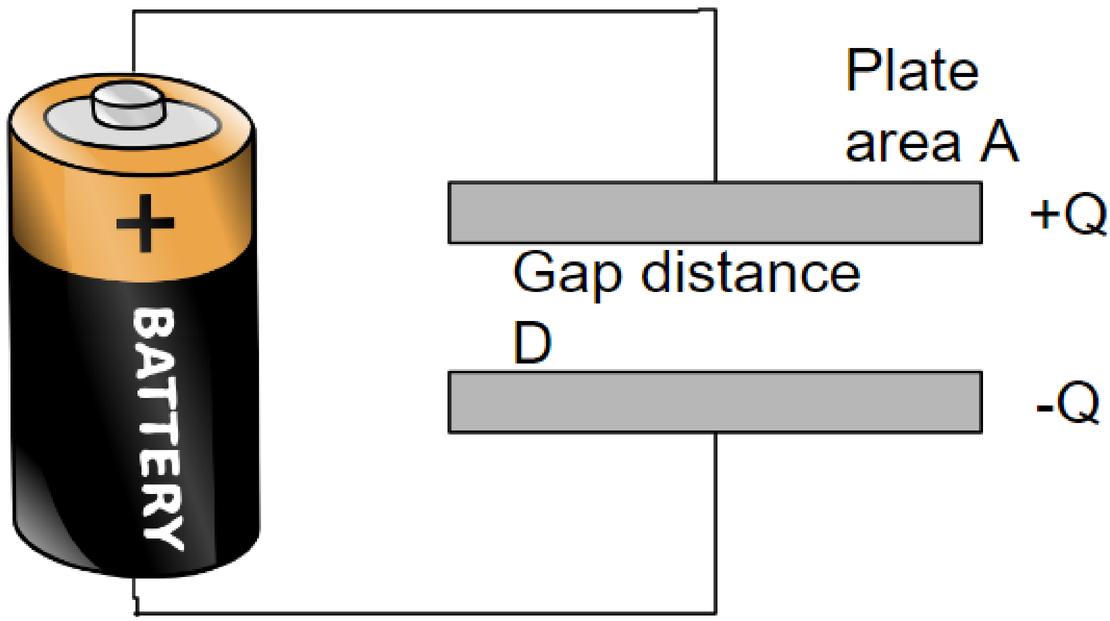
A parallel plate capacitor is created by positioning two conductive metal plates apart from each other, while hooked up to opposite terminals of a voltage source. Positive charge builds on one end of the plate, and negative charge builds on the other. The air gap acts as a natural insulator which separates the charge, permitting a charge separation to build. If we apply a standard voltage, V, across the plates, and we get charge Q to build on either plate (+Q on the positive plate and -Q on the negative plate), then we have a parallel plate capacitor with capacitance modeled by

$$C = \frac{Q}{V}$$

The SI unit for capacitance is the **Farad** (1 F = 1 Coulomb/volt), named after Michael Faraday. This is a very large value for most purposes; most capacitors are in the micro (10^{-6}), nano (10^{-9}), or picofarad (10^{-12}) range. <u>Do not confuse this with the Faraday constant from electrochemistry.</u>

Based on the geometry of the parallel plate capacitor, we can calculate the capacitance using

$$C = \varepsilon_0\left(\frac{A}{d}\right)$$



where ε_0 is the permittivity of free space (8.85×10^{-12} F/m --- no don't memorize this), A is the area that the plates overlap, and d is the distance between the plates. This produces a uniform electric field between the plates, modeled by

$$E = \frac{V}{d}$$

(This is the ONLY time the electric field equation looks this nice, by the way.) Do not worry yourself too much with understanding the numbers behind an E field, since exact calculations will not be tested. They involve rigorous calculus.

Capacitors, as charge storing units, can therefore store e n e r g y. Discharge of a capacitor releases a large burst of electrical energy at once. This potential energy can be modeled by the equation

$$U = \frac{1}{2}CV^2$$

where U is potential energy, C is the capacitance, and V is the voltage between the plates.

Let's look back at insulating materials. In the context of capacitors, they are known as **dielectrics**, due to their useful properties in capacitor construction. Air is a well known insulator/dielectric, and its ability to prevent or hinder charge movement is what allows for charge buildup in the first place. Greater insulating properties allow for even greater capacitances.

Why are they known as dielectrics as well as insulators? It's a great question.

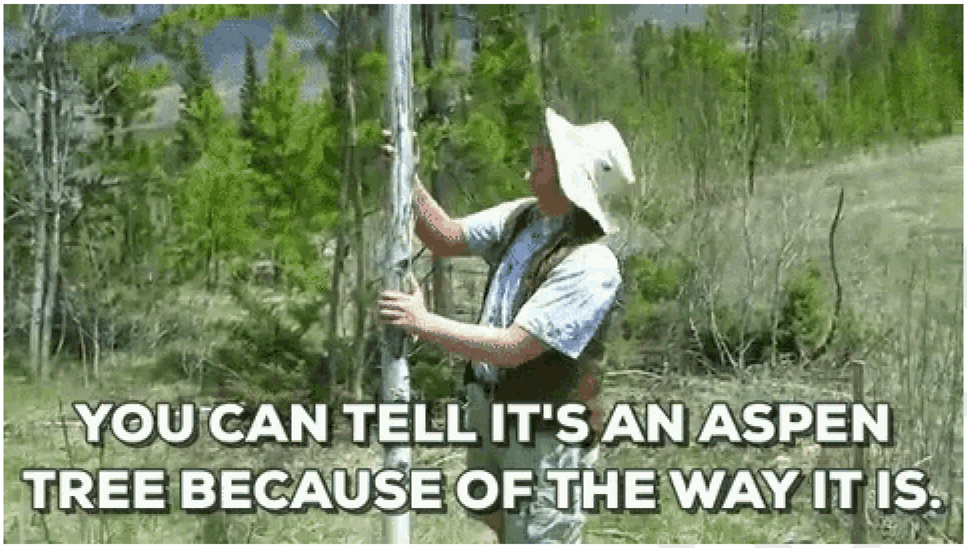


Fig. 6. How I imagine my forebears decided naming conventions..

Every dielectric has an intrinsic ability to affect the capacitance of a parallel plate capacitor by opposing electron flow, via a constant known as the **dielectric constant (κ)**. Air, as a reference material, has a dielectric constant of 1. Other materials have other values - glass is 4.7, rubber is 7, etc. Do not memorize these numbers, they will be given.

Because air by definition has a κ of 1, it is simple to calculate the new capacitance from inserting a dielectric and replacing the air in a parallel plate capacitor.

$$C' = \kappa C$$

where C' is the new capacitance, C is the old capacitance, and κ is the dielectric constant of the dielectric we now inserted.

Let's talk about the conditions in which we hypothetically insert a dielectric. Now, smart people do not insert dielectrics into active, charging capacitors, but the MCAT examiners are not smart people. They may ask questions on what happens if you insert plastic into circuit components designed to start a heart, and that's ok! Just understand the principles of what changes.

Case 1: an isolated capacitor

An isolated capacitor is one that is not connected to a completed circuit. Remember, **charge can only flow if the circuit is completed**. This is analogous to the state of a defibrillator capacitor before the switch is pressed and a shock is given - the capacitor is basically "free floating", but has a charge built up into it. Inserting a dielectric at this point will INCREASE the capacitance, as per our previous equation. However, since this component is completely disconnected from a circuit, NO CHANGE in the charge may occur. Therefore, the voltage of the capacitor drops. This behavior is also explained by the fact that the dielectric shields the charges of the plates, thus lowering the voltage. We say that the increase in capacitance is a function of the decrease in voltage, because $C = \frac{Q}{V}$.

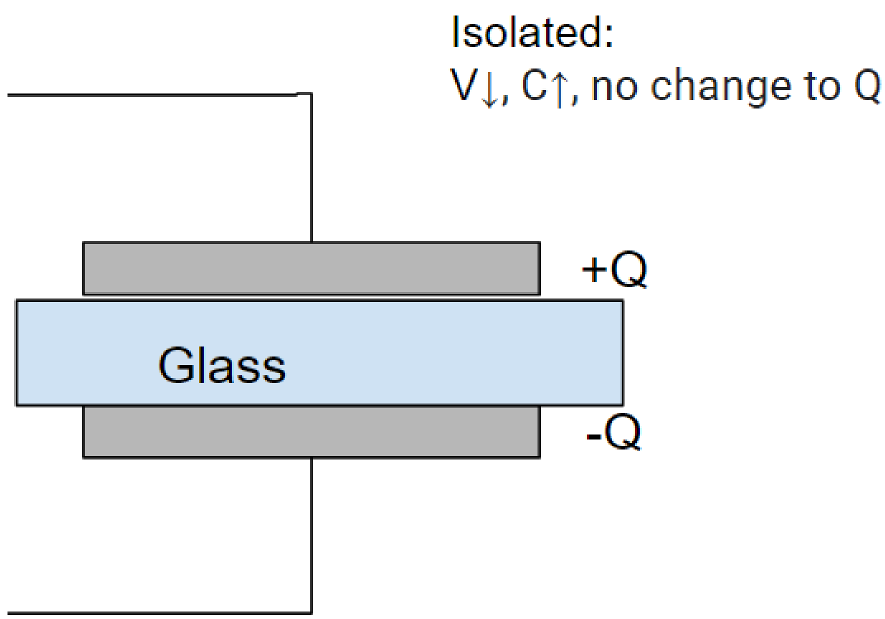


Fig. 7. Representation of the above

Case 2: capacitor in circuit

A capacitor in circuit (or connected to a voltage source) is a slightly different story. Since a voltage source is still connected, and Kirchoff's laws still apply, we know that the voltage CANNOT decrease across the capacitor simply because a dielectric is present. More charge will accumulate across the plates to accommodate the new dielectric, thus raising the capacitance in concert with a constant voltage. We say that in this case, the capacitance increases due to a rise in charge, following $C = \frac{Q}{V}$.

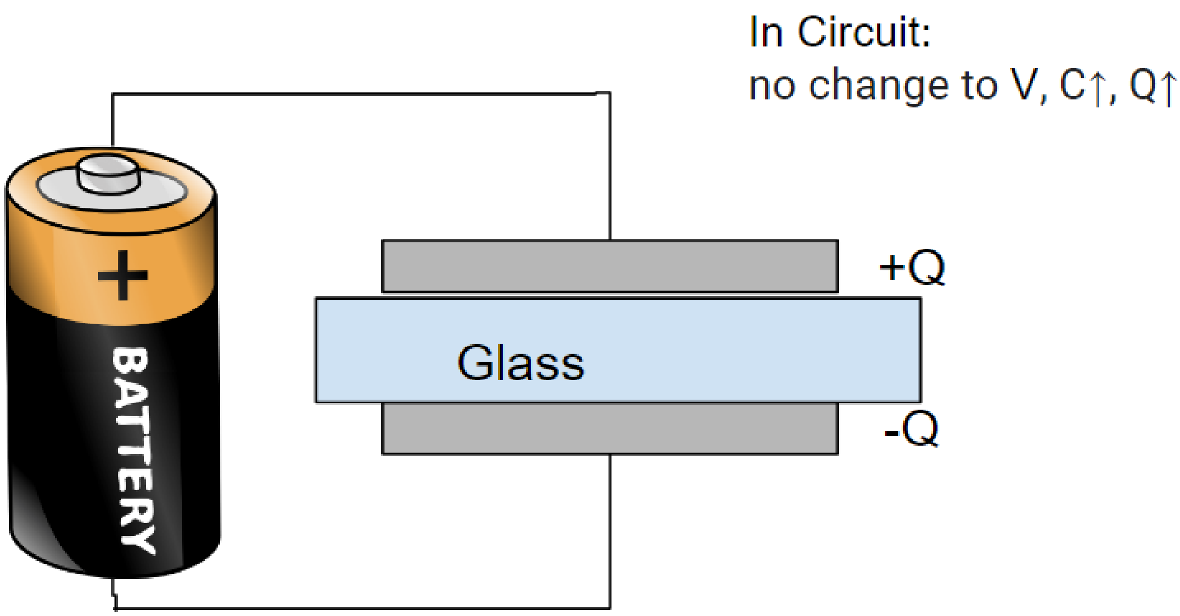
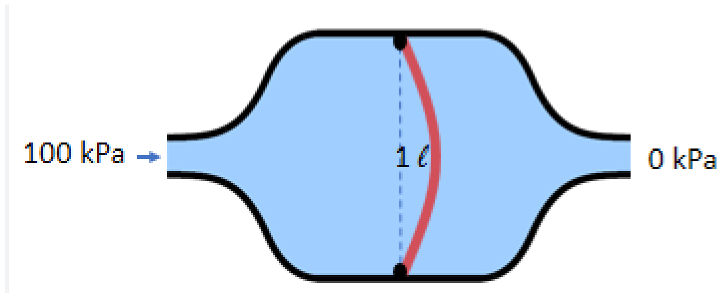


Fig. 8. Ditto.

The water analogy is a little esoteric when it comes to capacitors, but is still helpful. The equivalent to a capacitor in the water system is a waterproof, nonpermeable membrane that stretches across the pipe, which flexes under the pressure of water flow. It does not allow water to pass through, much like how the capacitor does not allow electron flow across the dielectric. However, a pressure difference (voltage, charge separation) does build on either side of the membrane. Switching a valve and completing a pipeline would allow this built up pressure to be **discharged**, just like an electrical capacitor.

For the dielectric to replace air, we can imagine that the stiffness of the membrane increases, such that it can handle more pressure before distending (in other words, it can RESIST the flow of water more strongly). It would be very physically difficult to replace a water membrane while the pipes are full of liquid, but it's a thought experiment, so we can assume the membrane *magically* changes. In the absence of a water pump, we can imagine the membrane becoming stiffer and bending less; since there is no pump driving more pressure onto the membrane, it will relax slightly. This corresponds to the fact that no additional charge is given, the voltage potential drops, but the capacitance increases in an isolated circuit.

In the presence of a water pump, the membrane will have additional pressure applied such that the membrane maintains its previous distension. This way, the pressure difference (voltage) is constant, but the stiffness and energy stored (charge and capacitance) increase, just like a capacitor in a circuit.



Subfig. 3. Listen, I know we're stretching it here, but it makes sense.

Let's now talk about capacitors in series and in parallel. Like resistance, capacitance can combine additively in a circuit.

Capacitors arranged *in series* see a total capacitance equivalence similar to resistors in parallel, because the voltage drop must be shared among the group of capacitors, reducing the charge that can be stored. This would be equivalent to a capacitor with a greater distance between its plates.

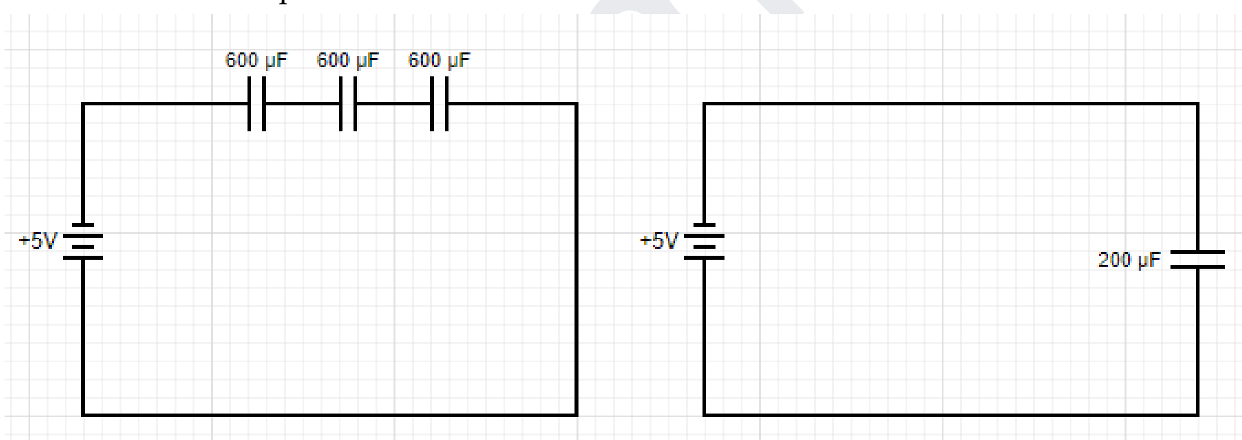


Fig. 9. $\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$...

Capacitors *in parallel* create an equivalent capacitance equal to the sum of the individual capacitances. We can consider that multiple parallel plate capacitors is equivalent to simply having a very large capacitor with a larger overlap area; thus multiple parallel capacitors grant an increase in charge capacity.

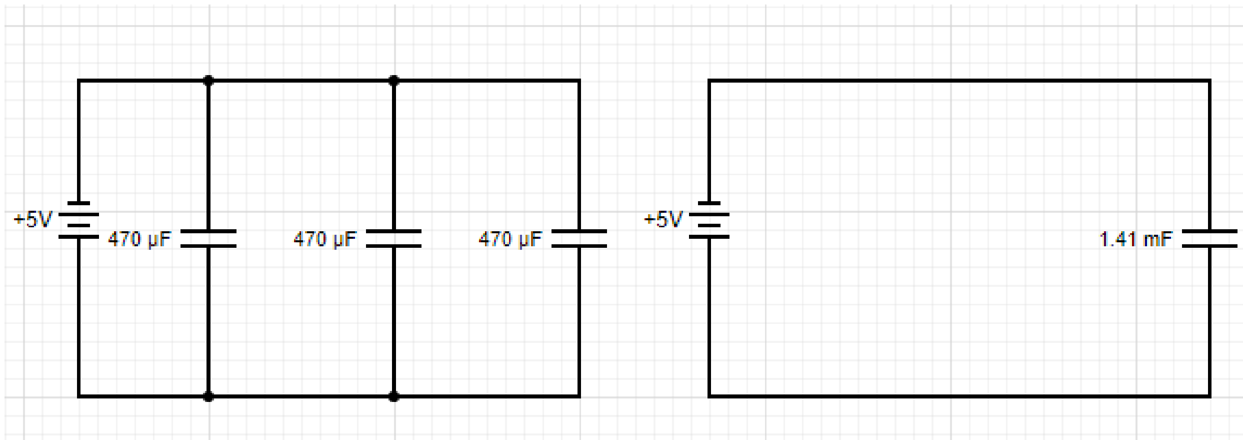


Fig. 10. $C_T = C_1 + C_2 + C_3$...

Meters

I have no idea why the AAMC believes this is useful information, but here it is.

Anmeters measure amperage across two points. To do so, current must flow through the ammeter - they ideally have ZERO resistance and complete a circuit when they are used to probe two points on a circuit. The circuit must be active to measure the current.

Voltmeters measure volts across two points. These are wired in parallel with the circuit, and ideally have infinite resistance and should NOT complete the circuit. The circuit must be active to measure the voltage.

Ohmmeters measure resistance across two points. Uniquely, these do not require the current to be active to measure the resistance, as they often provide their own charge. An active circuit can even distort the readings on an Ohmmeter, because it is based on comparative readings to internal circuitry.

That should be a wrap! Reach out to me with any concerns or questions.

--the bumblebee fellow