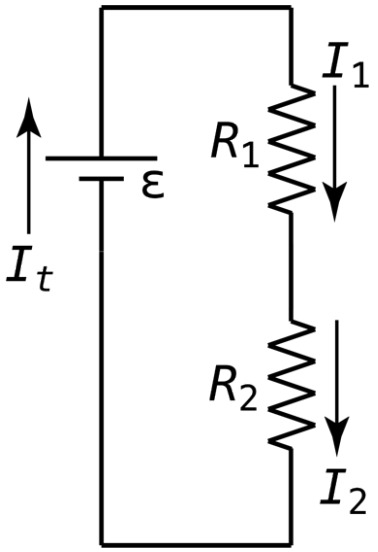
Whiteboard: 1/60, f4.5, iso 640, EV+1.3, Auto Focus, H4n **INPUT @ 95%** gain.
BBB 1/60, f6.7, iso 640, **WB Use Grey Card**, Manual Audio at level 11, focal length ½ way to ∞. H4n **INPUT @ 95%** gain.
BBB Check Horizontal Level & Billy's Lights!! Middle line at bottom 1/3 of desk & remember Billy and Bo chair locations!
Series and Parallel Circuits - Review for AP Physics C: Electricity and Magnetism **Switch audio to 96kHz!!**
Thoughts for this time: mr.p: keep overhead light on. Change height of lights to middle of video. Make BBB a bit brighter?

Mr.p: Good morning. Today we are going to review series and parallel circuits for AP Physics C: Electricity and Magnetism. [♪ Flipping Physics ♪] Bo, review for me please how we know these two resistors are in series.



- Bo: Well, … is this that thing with

the anthropomorphic charge?

- Billy: Absolutely! A charge which we have given human-like characteristics to, even though charges are clearly not human.
- Bobby: He loves his arcane words.
- Billy: Anthropomorphism is not arcane!
- Bobby: Sure.
- Bo: Right. … An anthropomorphic charge which moves through resistor 1 has no other choice but to also move through resistor 2. That means those two resistors are in series.
- Bobby: To clarify, every charge which goes

through resistor 1 has to also go through resistor 2 … and every charge that goes through resistor 2 has to also have gone through resistor 1. … In other words, if there is a wire between resistor 1 and 2, that wire provides an alternate path for the anthropomorphic charges to choose, and those two resistors are not in series.

- Bo: Right.
- Billy: And when those two resistors are in series, that means the current through resistor 1 is equal to the current through resistor 2. …

And, actually, because the charges also have to go through the battery, the current through the battery is also the same. $I_t = I_1 = I_2$

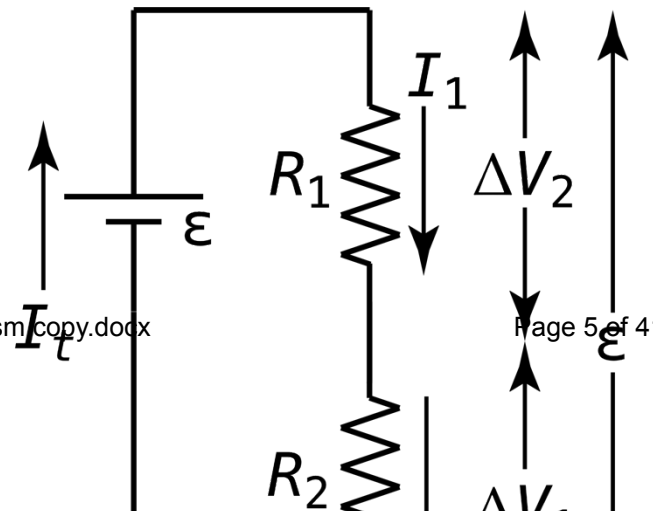
- Bo: … What's the epsilon symbol next to the battery mean?
- Bobby: That stands for the emf of the battery, the electromotive force, or the ideal electric potential difference across the battery.
- Bo: Right. It's an ideal battery with no internal resistance. Thanks.
- Bobby: … What does the "t" subscript on the current mean?

- Bo: Oh, that means terminal. As in the current through the terminals of the battery.
- Bobby: Okay. Thanks.

Mr.p: Thank you everybody. … Billy, tell me what we know about the electric potential differences across all the circuit elements.

$$\Delta V_{\text{bottom wire}\rightarrow\text{top wire}} = \varepsilon = \Delta V_1 + \Delta V_2$$

Billy: Certainly! … Because these are ideal wires with zero resistance, the electric potential difference from the bottom wire to the top wire is the same as the electric



potential difference across the battery and it is the same as the electric potential difference across both resistors which equals the summation of the electric potential differences across the two resistors.

$$\Delta V_{\text{loop}} = V_f - V_i = V_a - V_a = 0 = \varepsilon - \Delta V_1 - \Delta V_2 \Rightarrow \varepsilon = \Delta V_1 + \Delta V_2$$

Mr.p: Thank you Billy. … Realize we can get to the same equation by recognizing that if you go all the way around a loop in an electric circuit the electric potential difference equals zero. … For example, starting at point “a” which is in the lower left-hand corner of the

circuit and going clockwise through the circuit all the way back to point a. … Electric potential difference equals final electric potential minus initial electric potential, and, if we start and end at point a, both of those are the same electric potential at point a, and the differences of the two equals zero. … Going up from point a through the circuit we have the electric potential difference across the battery which equals the emf of the battery. … Next, we have the electric potential differences across the two resistors, however, we showed last

time that, when going in the direction of current in a resistor, the electric potential goes down, so we subtract both electric potential differences across the resistors. … Moving both of the electric potential differences across the resistors to the other side of the equation gives us the same equation Billy solved for.

- Bobby: … Uh, I like Billy's solution better.
- Bo: Billy's solution only took 57 words to explain. Yours took 194 words. 57 words is a lot fewer than 194. I'll take 57.
- Billy: I like mr.p's solution too.

- Bo: Yeah.

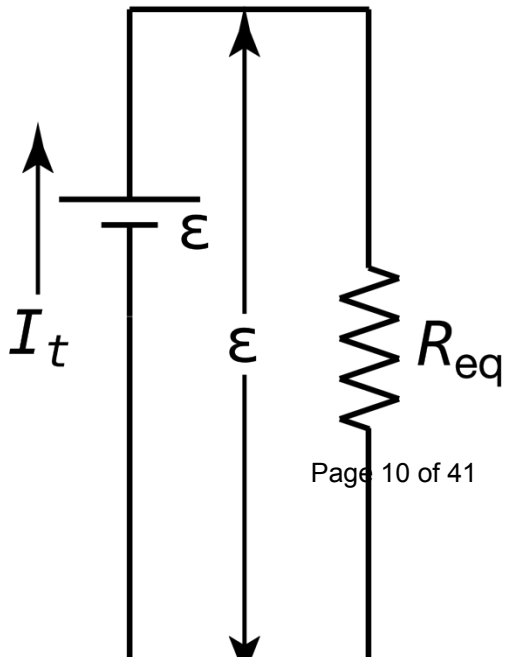
Mr.p: Either way. They are both correct, so it does not matter to me. … Bobby, use Ohm's law with this equation and let's see what happens.

$$\Delta V = IR \Rightarrow \varepsilon = I_t R_{\text{eq}} = I_1 R_1 + I_2 R_2 \Rightarrow R_{\text{eq}} = R_1 + R_2$$

- Bobby: Okay. … Ohm's law states that electric potential difference equals current times resistance. … So, we can substitute current times resistance in for each of the electric potential differences in that equation. … The subscripts for the two resistors are … 1

and 2 for the current through, and the resistance of, each resistor. … For the current through the battery, … let's use a subscript of t like you did before for the current through the terminals of the battery. … For the resistance of the battery, … uh … you said it is an ideal battery, so it has zero resistance, right? But that doesn't really make any sense.

- **Mr.p: (Let's use a subscript of "eq" for the resistance there. That "eq" subscript means "equivalent". In other**



words, the current through the battery times the resistance of one hypothetical resistor which has a resistance equivalent to the resistance of the two series resistors, equals the emf across the battery. … Again, this is just Ohm's law, electric potential difference equals current times resistance. … It's just that the electric potential difference across the battery, the emf, has the same magnitude as the electric potential difference across a resistor equivalent to the two series

resistors.)

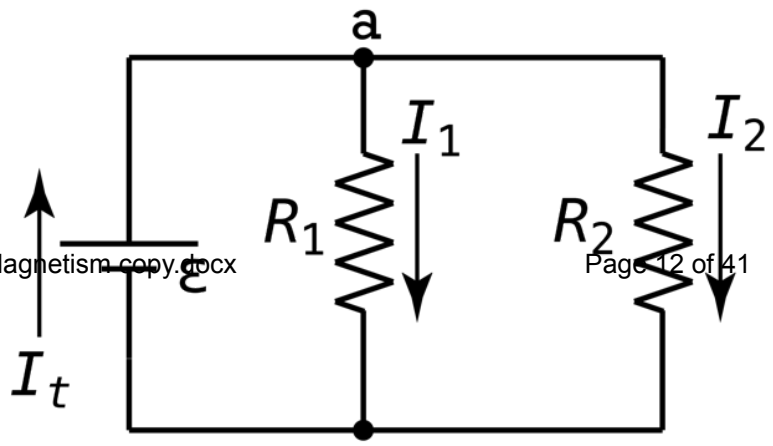
- Bobby: Got it. That makes sense. But …
- Bo: All the currents are equal. So …
- BBB: Everybody brought current to the party! {dancing}

Mr.p: {dancing}

Bobby: {finish dancing} That means a resistor with resistance equivalent to the two series resistors equals resistance 1 plus resistance 2.

$$R_{\text{eq series}} = \sum_n R_n = R_1 + R_2 + \ldots$$

Mr.p: Right! … And, a more



general equation for the equivalent resistance of “n”, a variable number of resistors, in series … equals the summation of the resistances of “n” number of resistors. … You just add up the resistances of all the series resistors. … Alright, let’s move on to two resistors in parallel. … Again, let’s use an anthropomorphic charge. … An anthropomorphic charge has the choice between paths that go through the two resistors, and then those two paths join back again without going through any other circuit

elements. That is why these two resistors are in parallel. … Notice then that the electric potential differences across all three of these circuit elements are equal. $\varepsilon = \Delta V_1 = \Delta V_2$ … This is actually always true of circuit elements which are in parallel; they always have equivalent electric potential differences. … Billy, use what you know about the two junctions in the circuit which I have labeled a and b to derive the equation for the equivalent resistance of two resistors in parallel, please.

$$I_{\text{in}} = I_{\text{out}} \Rightarrow I_t = I_1 + I_2$$

$$\Delta V = IR \Rightarrow I = \frac{\Delta V}{R} \Rightarrow \frac{\varepsilon}{R_{eq}} = \frac{\Delta V_1}{R_1} + \frac{\Delta V_2}{R_2} \Rightarrow \frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2}$$

- Billy: Absolutely! … Because conservation of charge states that every charge which goes into a junction will also come out of that junction, the current into a junction equals the current coming out of a junction. Therefore, for junction “a”, the current through the terminals of the battery equals the sum of the two currents going through the two resistors. … From Ohm’s law we know current equals electric potential difference divided by resistance, and we can substitute that in for

each current in our previous equation. … That means … emf over equivalent resistance equals … the sum of the electric potential differences across each resistor divided by the resistance of each resistor. …

- Bo: … All the electric potential differences are equal. So …
- BBB: Everybody brought electric potential difference to the party! {dancing}

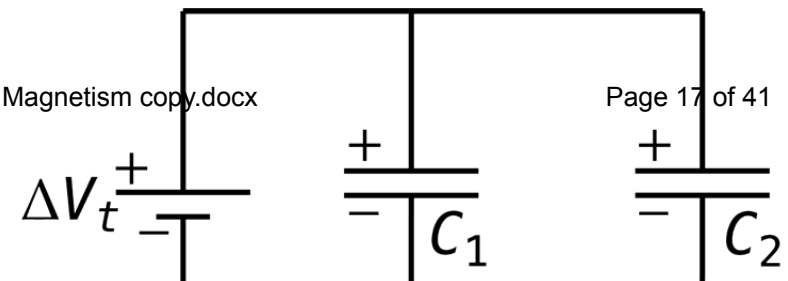
Mr.p: {dancing}

$$\Rightarrow R_{\text{eq}} = \left(\frac{1}{R_1} + \frac{1}{R_2} \right)^{-1}$$

Billy: {finish dancing} That means one resistor with the equivalent resistance of two resistors in parallel equals the inverse of the sum of the inverses of the resistances of the two parallel resistors!

$$\Rightarrow R_{\text{eq parallel}} = \left(\sum_n \frac{1}{R_n} \right)^{-1} = \left(\frac{1}{R_1} + \frac{1}{R_2} + \ldots \right)^{-1}$$

Mr.p: Exactly! … And, a more general equation for the equivalent resistance of “n”, a variable number of resistors, in parallel … equals the inverse of the sum of the inverses of the resistance of “n” number



of resistors. … You just add up the inverses of the resistance of all the parallel resistors and take the inverse of that. … … … Now, looking at the general concept of resistors in series and in parallel, from the equations you can see that when we add resistors in series, … the equivalent resistance goes up …. and when we add resistors in parallel … the equivalent resistance goes down. … Now let's switch over to capacitors. Bo, see what you can do with two capacitors in parallel.

- Bo: Well. … Those two capacitors are in

parallel. … Then we know all the electric potential differences are equal in magnitude. … $\Delta V_t = \Delta V_1 = \Delta V_2$ … Hold up, what happened to the emf of the battery? Now we have an electric potential difference with a “t” subscript instead. What is that?

- Billy: That is the terminal voltage.
- Bobby: Which is the electric potential difference measured across the terminals of the battery.
- Billy: And, whenever the battery is supplying current to a circuit, the terminal voltage is less

than the electromotive force or emf of the battery.

- Bobby: Because all real batteries have internal resistance which decreases the voltage measured across the terminals of the battery.
- Billy: Yep. Terminal voltage equals emf minus current through the battery times the internal resistance of the battery, lowercase r. $\Delta V_t = \varepsilon - Ir$ … Which means, as the current through the battery increases, the terminal voltage across the battery decreases.

- Bo: Okay. Yeah. I remember that now. But, why would he switch it from emf to terminal voltage in the middle of a lecture like this.
- Bobby: To review.
- Billy: Mr.p never misses an opportunity to do a quick review.
- **Mr.p: (Psha. That doesn't sound like me at all!)**
- Bo: Right. … Anyway. … Two capacitors in parallel with a battery. All the electric potential differences are the same. …
- **Mr.p: (Think about the charges moved by**

the battery to the plates of the capacitors.)

- Bo: Sure. … Because the charges moved by the battery to the top plates of the capacitors need to go to either capacitor 1 or capacitor 2, the charge moved by the battery to the plates of the capacitors equals the sum of the charges on the capacitors. … $Q_t = Q_1 + Q_2$ And now we can use the definition of capacitance. Capacitance equals the magnitude of the charge stored on one of the plates of the capacitor over the electric potential difference across the plates of the capacitor. …

$C = \frac{Q}{\Delta V} \Rightarrow Q = C\Delta V$ That means charge equals capacitance times electric potential difference. … Which we can substitute into the charge equation to get equivalent capacitance times terminal voltage equals the sum of the capacitance of each capacitor times the electric potential difference across each capacitor. … And, because the electric potential differences are all equal …

- $\Rightarrow C_{\text{eq}}\Delta V_t = C_1\Delta V_1 + C_2\Delta V_2 \Rightarrow C_{\text{eq}} = C_1 + C_2$
- BBB: Everybody brought electric potential

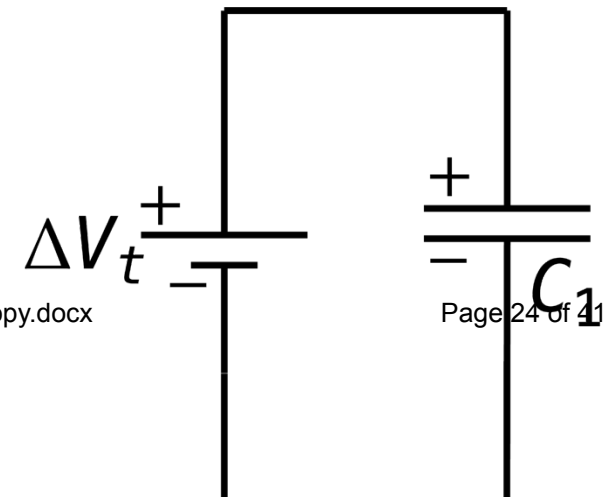
difference to the party! {dancing}

Mr.p: {dancing}

Bo: {finish dancing} And we get that the equivalent capacitance of two capacitors in parallel equals the sum of the capacitances of the two parallel capacitors.

$$\Rightarrow C_{\text{eq parallel}} = \sum_n C_n = C_1 + C_2 + \ldots$$

Mr.p: Correct Bo. … And, a more general equation for the equivalent capacitance of "n", a variable number of capacitors, in parallel … equals the summation of the



capacitances of “n” number of capacitors. … You just add up the capacitances of all the parallel capacitors. … Alright let’s move on to two capacitors in series. … Bobby, it’s your turn again.

- Bobby: Okay. … We know the electric potential difference equation is the same as for two resistors in series. $\Delta V_t = \Delta V_1 + \Delta V_2$ Terminal voltage equals voltage across capacitor 1 plus voltage across capacitor 2. … And, looking at the charges moved by the battery to the plates of the capacitors. … Well,

we know the magnitude of the charge moved by the battery to the top plate of capacitor 1 and the magnitude of the charge moved to the bottom plate of capacitor 2, are equal in magnitude. … But, what happens then? I mean, how would any charge get on the bottom plate of capacitor 1 and the top plate of capacitor 2? Those two plates are connected by a wire, and that whole system is not physically connected to any part of the circuit. …

- Bo: … There are already electric charges

located there on the wire and the two plates of the capacitor, right?

- Bobby: Oh, yeah! So, negative charges are pulled to the bottom plate of capacitor 1 by the positive charges on the top plate of capacitor 1. … And positive charges are pulled to the top plate of capacitor 2 by the negative charges on the bottom plate of capacitor 2. That's cool.
- Billy: Yeah, that area gets polarized by the top plate of capacitor 1 and the bottom plate of capacitor 2. That is cool!

- Bobby: Yeah! And that means that the charges on all the plates of those capacitors are equal in magnitude. In other words, the total charge moved by the battery equals the charge on capacitor 1 which equals the charge on capacitor 2. $Q_t = Q_1 = Q_2$… That's basically just conservation of charge. Right mr.p?
- **Mr.p: (Exactly Billy!)**
- Bobby: … Yeah. Okay. Uh, …

$$Q = C\Delta V \Rightarrow \Delta V = \frac{Q}{C}$$ Using the equation for capacitance, we can show the electric

potential difference across a capacitor equals the magnitude of the charge on one of the plates of a capacitor over the capacitance of the capacitor. … We can substitute that into our electric potential difference equation. … All the charges are the same. So, …

- BBB: Everybody brought charge to the party!
- Bo: {while dancing} We are partying a lot today!
- Bobby: {while dancing} Yeah!
- Billy {while dancing} I like it!

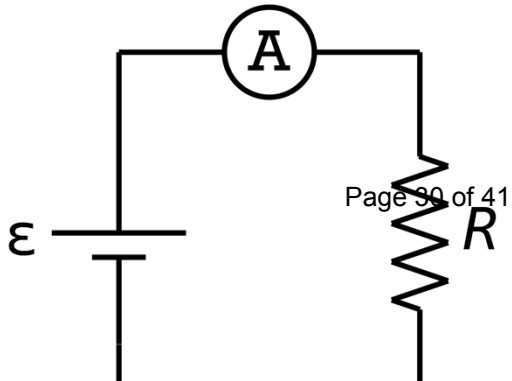
$$\Rightarrow \frac{Q_t}{C_{eq}} = \frac{Q_1}{C_2} + \frac{Q_2}{C_2} \Rightarrow \frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2} \Rightarrow C_{eq} = \left(\frac{1}{C_1} + \frac{1}{C_2}\right)^{-1}$$

Mr.p: {dancing}

Bobby: {finish dancing} That means one capacitor with the equivalent capacitance of two capacitors in series equals the inverse of the sum of the inverses of the capacitance of the two series capacitors!

$$\Rightarrow C_{eq\ series} = \left(\sum_n \frac{1}{C_n}\right)^{-1} = \left(\frac{1}{C_1} + \frac{1}{C_2} + \ldots\right)^{-1}$$

Mr.p: Perfect Bobby, thanks! …

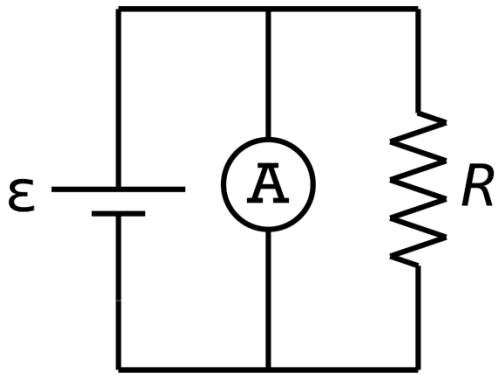


And, a more general equation for the equivalent capacitance of “n”, a variable number of capacitors, in series … equals the inverse of the sum of the inverses of the capacitances of “n” number of capacitors. … You just add up the inverses of the capacitances of all the parallel capacitors and take the inverse of that. … … … Now, looking at the general concept of capacitors in series and in parallel, from the equations you can see that, when we add capacitors in series, … the equivalent capacitance goes down …. and

when we add capacitors in parallel, … the equivalent capacitance goes up. … Please notice the series and parallel equations for resistors and capacitors are reversed. … Now, let's discuss how to use the tools which measure current and electric potential difference. Starting with the ammeter which measures current or number of amperes. … We need to decide if an ammeter needs to be put in series or parallel with the circuit element it is meant to measure the current through. … So, let's look at what happens when we

attempt to measure the current through a resistor using an ammeter in series and in parallel with a resistor. … Billy, tell me what you see.

Billy: Yep. I can do that! … Well, it looks like, when you put an ammeter in parallel with a resistor, the charges which go through the ammeter will be different from the charges which go through the resistor. So, putting an ammeter in parallel with a resistor will not actually



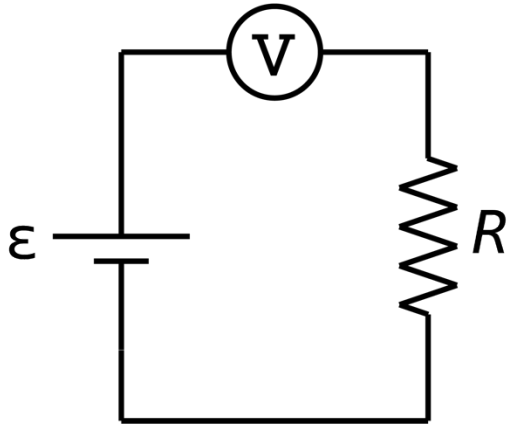
measure the current through the resistor. So, an ammeter needs to be placed in series with the circuit element you are trying to measure the current through.

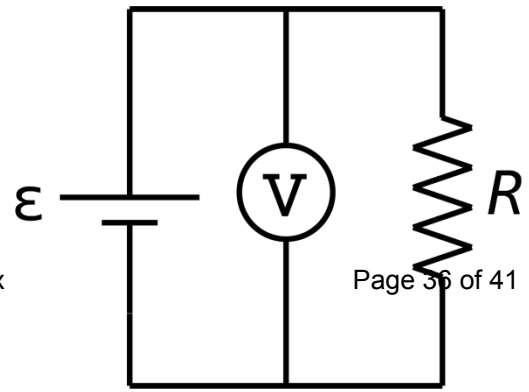
Mr.p: Correct Billy. … Also notice that the resistance of an ammeter needs to be very, very small. … In this example circuit, if the resistance of the ammeter is not very, very small, … the ammeter will increase the equivalent resistance of the circuit … and decrease the current through the resistor you are trying to measure the current through. …

So, unless otherwise indicated, ammeters in this class are considered to have zero resistance. … And, I'll just mention that, because ammeters have such a low resistance, if you accidentally place an ammeter in parallel with the electrical load of a circuit, … you are significantly decreasing the resistance in the electric circuit which can significantly increase the current in the electric circuit. … This can really damage equipment. So, please, never put an ammeter in parallel. … Now let’s switch to a voltmeter which

measures electric potential differences or voltage. … Let's attempt to measure the electric potential difference across a resistor using a voltmeter either in series or in parallel with a resistor. … Bo, tell me what you see.

Bo: Sure. … Uh, … placing a voltmeter in series with a resistor actually does not measure the voltage across the resistor. I mean, the voltmeter and the resistor would have different electric potential





differences. … So, I guess you have to place a voltmeter in parallel with the circuit element across which you are trying to measure the electric potential difference.

Mr.p: Correct Bo. … Also notice that the resistance of a voltmeter needs to be very, very large. … In this example circuit, if the resistance of the voltmeter is not very, very large, … the voltmeter will provide a parallel path and decrease the equivalent resistance of the circuit … and that will increase the current delivered by the battery, which

changes the way this electric circuit behaves. … The tools you use to take measurements should not change the circuit you are attempting to measure. … So, unless otherwise indicated, voltmeters in this class are considered to have infinite resistance. … To review: Ammeters measure current, are placed in series with the circuit element you are measuring, and have nearly zero resistance. … Voltmeters measure electric potential difference, are placed in parallel with the circuit element you are measuring, and

have nearly infinite resistance.

- Bo: Man, why didn't you just start with that? That table only took you 41 words to say. It took us 463 words to describe all the reasoning behind the table. All we really have to do is memorize the table. Geez.
- Billy: Because we have to understand why ammeters are placed in series and why voltmeters are placed in parallel.
- Bobby: And we have to understand why ammeters have nearly zero resistance and why voltmeters have nearly infinite resistance.

- Billy: It is the understanding that really matters.
- Bobby: Yeah, it is easy to make mistakes when trying to recall memorized facts.
- Billy: You are much less likely to make mistakes when you understand something.
- Bo: {grumpy} Okay.

Mr.p: I could not agree more. … That concludes my review of series and parallel circuits for AP Physics C: Electricity and Magnetism. … I was going to review Kirchhoff's Rules next time, however, I realized I already have a video

which details everything I would have said about Kirchhoff's Rules for AP Physics C: Electricity and Magnetism. I've already linked that video in appropriate locations. Please enjoy that video about Kirchhoff's Rules. And I'll start working on my video which will come after that one. That video will be about RC circuits! … Thank you very much for learning with me today, I enjoy learning with you.