Physics 310
Lecture 1 – DC Circuits, the basics

Thurs. 1/12 Fri. 1/13	**Ch 1.1 - .8** Basic DC Circuits, & *skim* **Ch 7** **Ch 1.9-.10** Intermediate DC Circuits & **App. A** pg. **A-1-A-4**	
Mon. 1/16 Wed. 1/18 Thurs. 1/19 Fri. 1/20	**Ch 1.11-.13** & *lightly* **Ch 6.1, .3, .4, .8, .10, .11** **Quiz** Ch 1 & 6**, Lab 1:** DC Circuits More of the same **Ch 2.1-2.5:** Capacitors	**HW1**: Ch1 Pr 4, 25; Ch 6 Pr 9*, 12 **Lab 1 Notebook**

Equipment
- **One of every 220/221 Lab detector connected to a computer**
- **radioactive watch**
- **Prepare computers for 5Spice simulations**
- **Ppt visuals of circuits**
- **Ppt Group problems.**

Handout (in lecture on Thursday, except Excel handout):
- Solving sets of linear equations with Excel (a separate Excel file & posted on web page)
- Lab 1 w/ supplements
  - Resistor color code (lab 1 supplement)
  - Diagram of breadboard layout (lab 1 supplement)
  - Tips on constructing circuits (lab 1 supplement)
  - Multimeters (lab 1 supplement)

What we actually did: We went over Ohm's law, Kirchoff's laws, and then used them to a) reduce a circuit to its equivalent and b) set up and solve a system of equations (pr. 16)
Students then worked two examples and then tackled them in 5Spice.

Announcements
- The assigned homework is fairly brief. You should judge whether or not it would be useful to try your hand at some of the other problems. For example, if Pr. 25 is overwhelming, you might want to work your way up to it.
- On the website, I've made all of the "Quiz" entries into links to a list of topics that are fair game for the Quiz and the equations that will be provided on the quiz (so you don't need to be able to derive them, but you do need to know how to use them.)

Equation List: [units in square brackets]

$$V=IR\,[1\ \text{V}=1\ \text{A}\cdot\Omega] \qquad P=IV\,[1\ \text{W}=1\ \text{A}\cdot\text{V}]$$

$$R_S=R_1+R_2+\ldots \qquad \frac{1}{R_P}=\frac{1}{R_1}+\frac{1}{R_2}+\ldots$$

Questions from Lecture Preps
- Potential-difference, Waterfall analogy was unclear
- In the ground section, what do they mean by the "common" of the circuit?
- Transducer?
- Problem 16?
- Benefit/use of resistors?

- Are Kirchoff's equations *always* applicable?
- Conventional or electron current – which will be we be thinking about?

What Questions / topics are you particularly interested in our covering?

- **Study List for Quiz #1:**
  - Ohm's Law
  - Series and parallel combinations of resistors and equivalent resistances.
  - Power dissipation by a resistor.
  - Kirchhoff's voltage (loop) law and current junction (node) law.
  - Voltage divider (with a load).
  - Thévenin's equivalent circuit theorem. (Reducing real voltage source/resistor networks to their Thévenin equivalent circuits.

We live in an electronically-enabled age, and it's getting only more so. Why is that? Let's step way-the-heck back for a moment. We humans want a lot done, but we don't want to have to do it ourselves. So we're always looking for more powerful and convenient tools that can do things for us. Of course, for any device to perform any function it is going to expend potential energy. The industrial revolution was all about finding ways to fuel devices on chemical and gravitational potential energy. One of the greatest developments of industrialization is electricity; rather than needing a water wheel or heat engine mechanically connected to any device, we can have them *electrically* connected. With far less overhead (which may have historically referred to the system of shafts and gears that literally ran 'overhead' of a factory floor), we can transmit just as much oomph with a stream of nearly massless electrons as could with cumbersome shafts, gears, and levers: a single 15 Amp / 120 Volt socket has the potential to deliver 1,800 J of energy *per second*! And that's getting fueled by a power plant miles and miles away! Thus our society has been evolving to use more and more electrically powered devices.

But electricity isn't just a medium for transferring energy, it's also a medium for manipulating information. The most powerful and common example is the computer. Think of a computer game – all the information that is transmitted and processed electronically while you play the game. All of that information is encoded in voltage values. Similarly, electricity is the medium for your commands to flow through your cell phone or a remote control.

Studying electronics gives you a ground-floor understanding of technological organisms / electronic instruments, perhaps the same way that studying cell biology would for biological organisms. For an experimental physicist, there's a very practical reason for learning this – you may need to build, diagnose, modify, or repair an electronic device or instrument that helps you with your work. As physicists, what *we* do is explore the physical world – measure, analyze, and manipulate. Then that's what we use electronics to accomplish.

Physical Measurements: Think of everything you've ever measured in physics, while many of these *can* be measured manually (balance scales, yard stick,…) if you can get a device to make the measurements for you, it's often easier, more accurate, and more reproducible. For that matter, you can even get the device to do much of the analysis for you or take some appropriate actions like turn down a heater coil when a set temperature is exceeded, increase a current until a desired brightness is achieved... Such devices are invaluable lab tools.

Devices that translate between the action of measuring or manipulating and the logic of electronics are called Transducers; thus, they are literally our point of contact with electronics and perhaps logically our pedagogical point of entry.

Transducers (Ch 7) – Electronics in Experimental Physics

I asked you to skim the chapter on Transducers, Ch 7, because they are literally our typical point of entry (and exit) to electronic instruments – they're what take a measurement from the world outside and represent it with an electronic "signal", or take an electronic "signal" and produce a physical effect. These are then key points of entry for you as a physicist and as a member of our electronically-enabled society.

How many electronic instruments and devices have you used today? How many more have been used for you today?

Monitor, computer, cell phone, ipod, camera, television, radio, a range of sensors and controls in your car (monitoring speed, engine temperature, fuel level, oil level, and timing the sparks in the cylindars) thermostats,…

Transducer: A Transducer is a device that translates a physical input / measurement into an electrical output / signal, or vice versa. So it's through the transducer that Electronics enters the realm of Experimental Physicists.

Demos: Go over to Rm 131

Type	Input Transducers	Output Transducers
temperature	thermistor thermocouple	resistive heater thermoelectic cooler (TEC)
light	photodiode (in photogate) phototransistor	lightbulb light-emitting diode (LED)
force	Hall effect force probe piezoelectric disk	mechanical drive piezoelectric disk
position	ultrasonic motion detector	see force
pressure	pressure gauge	see force
sound	microphone	Speaker
humidity	hygristor	
magnetic field	Hall probe	any wire carrying current
particle	Geiger counter	

As you can see, there's a wide variety of Transducers. You can read about how some of them work in Chapter 7 of our text. It won't be covered in this class; for now, it is more important to know *what's available* than to know how each one work. You can look up more information as needed.

The main point is that it is easy to process (filter, logic, etc.) an electric signal! So, once you translate a physical measurement into an electrical signal, the sky's the limit on what you can do with it.

Okay, now let's begin our study of electronics in earnest. As always, we'll start simple.

Ch 1 : Direct Current Circuits

1-1 Intro

- Now that you've read the text, I imagine you know what I meant Wednesday when I said that the approach was more – how to use than understand why it works that way. The beginning of Chapter 1 is mostly a superficial coverage of what you'd treated more deeply in Phys 232.

1-2 Current

- **Def.** Rate at which charge crosses through a cross-section. $I = \frac{dQ}{dt}$
  - Usually treated as a pseudo-vector in that a sign often indicates which way it's flowing along a wire.
- **Unit.** Amps = Coulombs / second

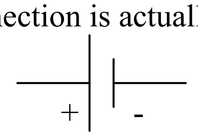
1-3 Potential Difference, a.k.a. Electric Potential Difference, a.k.a. Voltage Difference

- You may recall that the Electric Potential Difference between two points is related to the Electric Potential Energy Difference for a charge at the two points $\Delta V = \frac{\Delta U}{q}$.
- **Units**: Volt = Joule / Coulomb
- In practice, the Δ symbol is often dropped, and you have to judge by context exactly what two points Electric Potentials are being compared.

1-3.1 Ground

- **The Voltage Reference Point.** In a complex circuit, often a specific point (and all points at electrical equilibrium with it) is the default reference point for voltages. For consistency sake (when interfacing one complex circuit with another to form a device) and for safety sake (when you accidentally touch a live circuit) that point is quite often connected to the Earth. Whether that connection is actually made or not, the convention is to call this point "Ground."

1-3.2 Batteries



- You're familiar with batteries. They generally hold constant Potential Differences between their terminals (due to the energies associated with the chemical processes by which charge is transported through them).
- Pedagogically, they're nice voltage supplies because they're self-contained – you plug one into our circuit and nothing else (no wall socket necessary). Practically, they have other characteristics (slight internal resistance, limited lifetime, clean voltage, unreferenced voltage difference), but we won't worry too much about them at this point.

1-4 Resistance 

- Given an Electric Potential Difference between two points and a population of eager charges, you're going to get a current flowing between the two points. But how much? That depends on how hard it is for the charges to get between the two points, i.e., the path's resistance. Without worrying too much about the details (see the Phys 232 text about Drude model and resistance), there *is* resistance and generally, it scales with how *long* the path is and inversely with how *fat* it is. This is somewhat analogous to a pot-hole ridden road, the longer the stretch of crappy road, the more it impedes traffic, but the more lanes there are, the more traffic it can carry.
    - $R = \rho L / A$
    - Where ρ = "resistivity" and depends on the material
    - Units of Resistance are Ohms.

1-5 Ohm's Law

- Exactly how the current and Electric Potential Difference are related is
    - $\Delta V = (-)IR$
    - The sign in brackets reflects that positive charge flows from high to low Electric Potential / 'down hill.'

- **Derivation of Ohm's Law.** Should you be interested in seeing a quick derivation of Ohm's law reminiscent of Phys 232, see the posted notes.
    - $I = \frac{dQ}{dt}$
        - $Q = nqAL$
            - n is the volume density of charge carriers, q is the charge carried by one, A is the cross-sectional area of a wire, and L is the length of a segment, then Q is the amount of mobile charge in that length. For that to be the same as the amount of charges that cross the 'finish line' in time dt, we need $dL = vdt$, so
    - $I = \frac{d(nqAL)}{dt} = nqA\frac{dL}{dt} = nqAv$
        - Where v is the average drift velocity of the charge carriers.
        - $v = \mu E$

- Where μ is the charge carrier's mobility. According to the Drude model, the charge carriers continually get accelerated by an electric field, and decelerated by crashing into obstacles in the wire, so that the average drift velocity ends up being proportional to the electric filed.
- $E = -\frac{\Delta V}{L}$

- $v = -\mu \frac{\Delta V}{L}$

  - $I = -nqA\mu \frac{\Delta V}{L}$
  - Flipping that around, we have $\Delta V = -I\left(\frac{L}{nq\mu A}\right)$
    - We can identify $R = \left(\frac{L}{nq\mu A}\right)$ and $\rho = \left(\frac{1}{nq\mu}\right)$

- **Limitation**: this only handles one of a few different ways that an Electric Potential can be maintained. An ideal battery is a counter example – there, the electric potential difference has nothing to do with how much current is flowing through the battery.

(Example 1.1)

→ **1-6 Power**

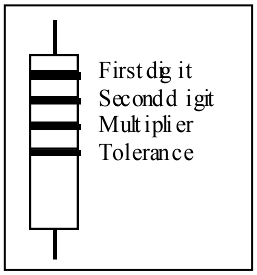
- Recalling from Phys 232 that $\Delta V = \frac{\Delta U}{q}$ and $I = \frac{dQ}{dt}$, then if the q in the first relation (the amount of charge imagined to move through the space corresponding to the change in potential), and the *dQ* the second relation (the amount of charge flowing across a cross-section of wire per unit time) are the same, then the product of the two relations is the rate at which traveling charges gain or loose electrical potential energy, and a rate of energy change is power: $P = I\Delta V$
  - **Units:** Watts
- In the case of a resistor, we can combine *this* relation with Ohm's Law and have
  - $P = I\Delta V = I^2 R = \frac{(\Delta V)^2}{R}$

1-7 **Types of Resistors** (see inside back cover of text / page of lab handout)

- The book points out that there are lots of different types of resistor, they vary in two main ways: how resistive they are and how much current they can handle / power they can dissipate before breaking.

- **Resistance**

Resistor Color Code: (The colors from red to violet are those of the rainbow, excluding indigo.)



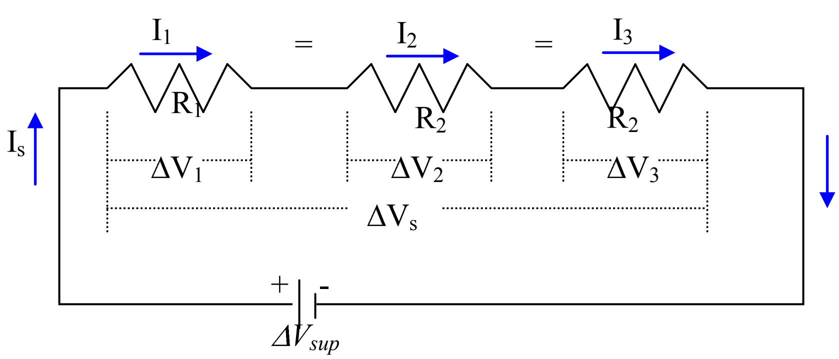
Color	Digit	Multiplier	Tolerance
Silver		$10^{-2} = 0.01$	±10%
Gold		$10^{-1} = 0.1$	±5%
Black	0	$10^{0} = 1$	
Brown	1	$10^{1} = 10$	
Red	2	$10^{2} = 100$	
Orange	3	$10^{3} = 1$ k	
Yellow	4	$10^{4} = 10$ k	
Green	5	$10^{5} = 100$ k	
Blue	6	$10^{6} = 1$ M	
Violet	7	$10^{7} = 10$ M	
Gray	8		
White	9		

1-8 Kirchoff's Equations

- These are two very common sense, but very useful, rules.
- **Loop Rule:** $\Sigma V = 0$ around a closed path. This has its roots in the path independence of potential energy. In many ways Electric Potential is analogous to Elevation (or, more accurately, Gravitational Potential). So, an analogous statement is that, independent of what road trip you take, if you start at Redlands and end up back at Redlands, you haven't changed your elevation.
- **Node Rule:** In steady-state, $\Sigma I = 0$ no net charge flow into a point – unless charge is accumulating or depleting, what flows in must flow out.

1-8.1 Resistors in Series

- To qualify as "in series" two resistors must have the *same current* flowing through them.

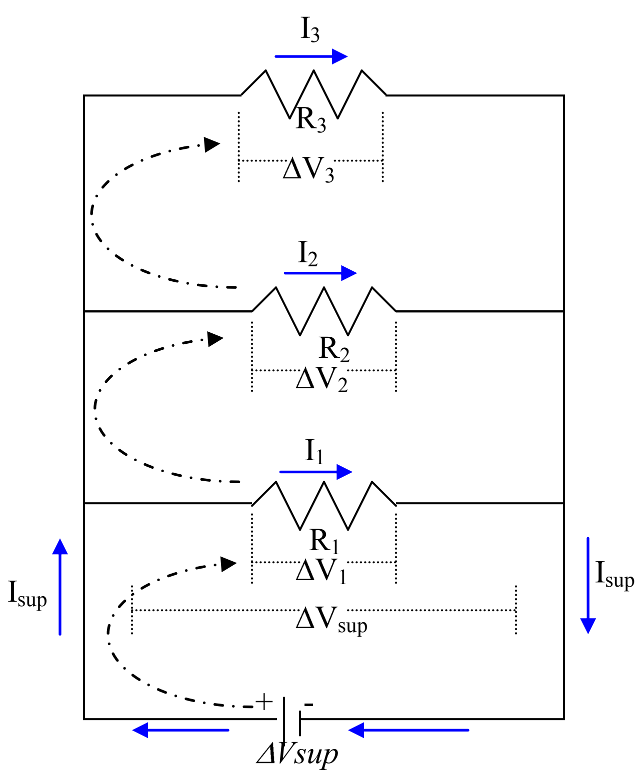


- Apply the loop rule
    - $\Delta V_{\sup ply} + \Delta V_1 + \Delta V_2 + \Delta V_3 = 0$
- Apply Ohm's Law
    - $\Delta V_{\sup ply} - I_1 R_1 - I_2 R_2 - I_3 R_3 = 0$
- Apply Node rule
    - $I_{\sup} = I_1 = I_2 = I_3$
    - $\Delta V_{\sup ply} - I_{\sup} R_1 - I_{\sup} R_2 - I_{\sup} R_3 = 0$

      $\Delta V_{\sup ply} - I_{\sup} (R_1 + R_2 + R_3) = 0$
- There'd be the same voltage difference, end to end, and the same current flowing through the circuit if there were just one resistor of value
    - $R_{series} = R_1 + R_2 + R_3$
- **Generally,** $R_{series} = \sum R_i$

1-8.2 Resistors in Parallel

- To qualify as "Parallel," resistors must have the *same voltage difference* across them.



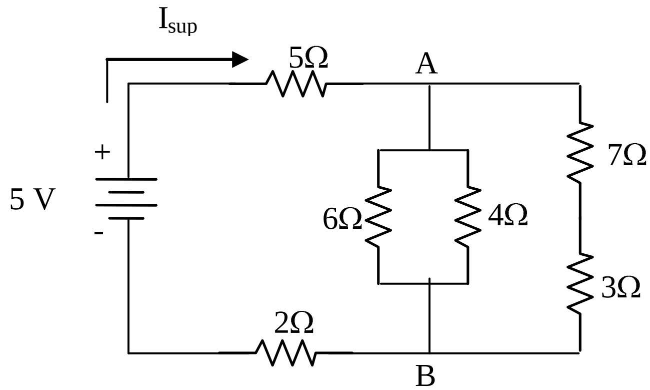
- Apply node rule at left or right fork
- $I_{sup} - I_1 - I_2 - I_3 = 0$ (note that signs are assigned according to whether the current flows in or out of the point)
- Apply Ohm's Law
- $$I_{sup} - \left(-\frac{\Delta V_1}{R_1}\right) - \left(-\frac{\Delta V_2}{R_2}\right) - \left(-\frac{\Delta V_3}{R_3}\right) = 0$$
  $$I_{sup} + \frac{\Delta V_1}{R_1} + \frac{\Delta V_2}{R_2} + \frac{\Delta V_3}{R_3} = 0$$
- Apply loop rule around each loop
- $$\left.\begin{array}{l} \Delta V_{sup} + \Delta V_1 = 0 \\ -\Delta V_1 + \Delta V_2 = 0 \\ -\Delta V_2 + \Delta V_3 = 0 \end{array}\right\} \Rightarrow \Delta V_1 = \Delta V_2 = \Delta V_3 = -\Delta V_{sup}$$
- $$I_{sup} - \frac{\Delta V_{sup}}{R_1} - \frac{\Delta V_{sup}}{R_2} - \frac{\Delta V_{sup}}{R_3} = 0$$
  $$I_{sup} - \Delta V_{sup}\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right) = 0$$
- The circuit would have the exact same current passing into it for the exact same voltage difference if the three resistors were replaced by one whose value satisfied
  $$\frac{1}{R_{parallel}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

1-8.3 Like Example 1.2: Equivalent Resistance

A. Calculate the current, I_{sup}, from the battery in the circuit shown in the figure.

B. Then calculate the voltage drop across each resistor in the circuit.

From the power supply's perspective, this circuit is equivalent to one single resistor. If we can figure out that single resistor, then we can easily apply Ohm's law to determine the current flowing out of the supply.

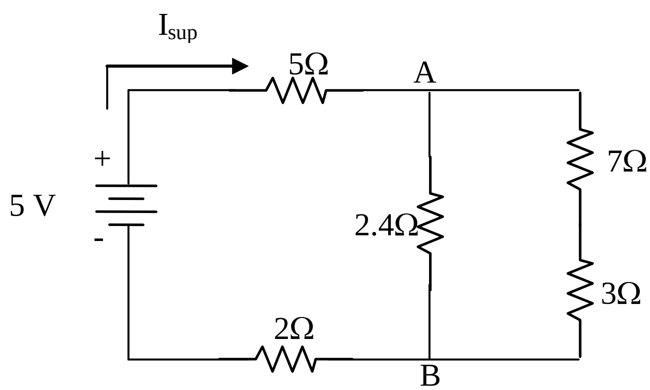


Real Circuit

It's easiest to proceed by replacing small segments with their equivalents. Eventually, we'll get down to just one equivalent resistor.

The 6 and 4 are "parallel" to each other since they connect to each other at both ends and thus have the same voltage drop across each other. Their equivalent is found by

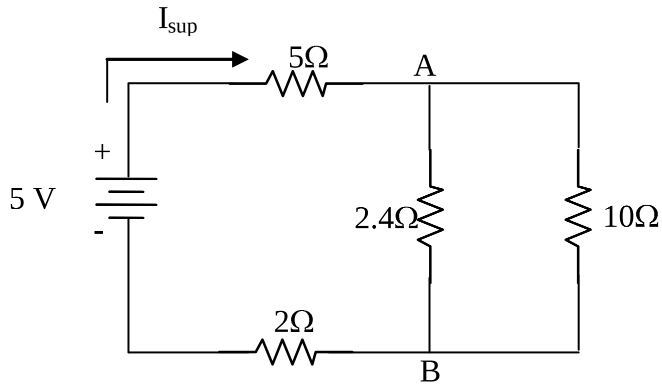
$$\frac{1}{R_{parallel}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots \Rightarrow \frac{1}{6\Omega} + \frac{1}{4\Omega} = 0.4166\ /\Omega = \frac{1}{2.4\Omega}$$



Equivalent 1

Similarly, the 7 and 3 are simply in "series" since whatever current passes through the 7 has no choice but to go on through the 3. Their equivalent resistor is found by

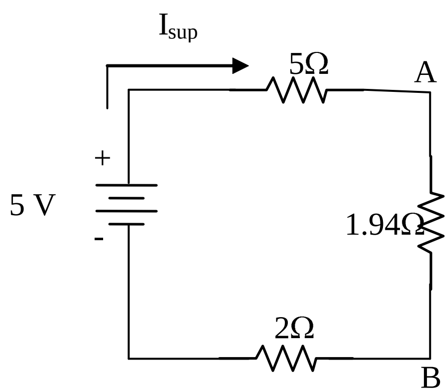
$$R_{series} = R_1 + R_2 + R_3 + \ldots \Rightarrow 7\Omega + 3\Omega = 10\Omega$$



Equivalent 2

Now, these two equivalent resistors, the 2.4 and the 10 are parallel to each other since they are joined to each other at both ends and must have the same voltage drop across each other. So

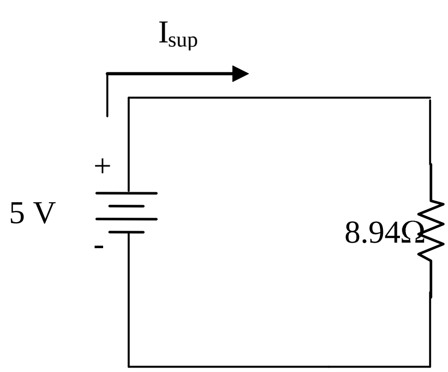
$$\frac{1}{R_{parallel}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots \Rightarrow \frac{1}{2.4\Omega} + \frac{1}{10\Omega} = 0.5166\ /\Omega = \frac{1}{1.94\Omega}$$



Equivalent 3

Now, all three of these are in series with each other, so

$$R_{series} = R_1 + R_2 + R_3 + \ldots \Rightarrow 5\Omega + 2\Omega + 1.94\Omega = 8.94\Omega$$



So, now we simply apply Ohm's Law:

$$I_{\text{sup}} = \frac{V}{R} = \frac{5V}{8.94\Omega} = 0.56A$$

B. Now for the voltage drop across each resistor:

Looking back at Equivalent Circuit 3, we can determine the voltage drop across the 5 and the 2 as well as that across the equivalent, 1.94.

$$V_R = IR$$
$$V_{5\Omega} = (0.56A)(5\Omega) = 2.8V$$
$$V_{2\Omega} = (0.56A)(2\Omega) = 1.12V$$
$$V_{1.94\Omega} = (0.56A)(1.94\Omega) = 1.08V$$

Looking back at the Real Circuit, this latter, the voltage drop from point A to point B, is the voltage drop across the 6 and 4.

$$V_{1.94\Omega} = V_{6\Omega} = V_{4\Omega} = 1.08V$$

Looking at the Equivalent Circuit 2, this is also the voltage drop across the equivalent 10 resistor; thus the current flowing down that branch is

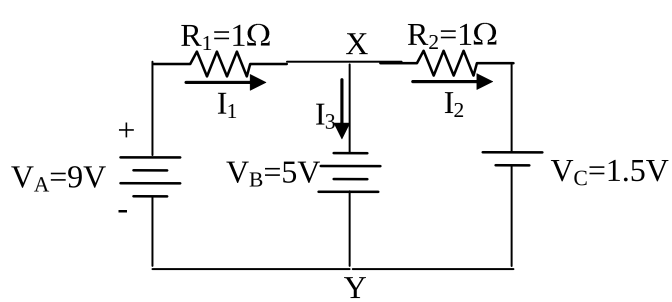
$$I = \frac{V}{R} = \frac{1.08V}{10\Omega} = 0.108A$$

Then that's the current flowing through the 7 and through the 3. Thus

$$V_R = IR$$
$$V_{7\Omega} = (0.108A)(7\Omega) = 0.756V$$
$$V_{3\Omega} = (0.56A)(3\Omega) = 0.324V$$

1-8.4 Example 1.3: Loop & Node Rules

Calculate the currents I_1, I_2, and I_3 in the circuit shown. What with its multiple batteries, this may appear more difficult than it really is. We'll walk through the book's approach: applying the loop and node rules to build algebraic equations. Once we've got 3 equations and 3 unknowns – it just becomes an exercise in applied algebra.



Note that the current directions chosen for the sake of analysis needn't be correct; if one isn't we'll just get a negative value in the end.

We only need three equations, whereas we have three possible loops and two distinct nodes, generating all 5 equations would cause some redundancies and could even tempt us to accidentally doe something like prove 1=1. So we pick just three that have the target variables in them.

Left Loop: $V_A + \Delta V_1 + V_B = 0$
$V_A + (-I_1 R_1) + V_B = 0$

Right Loop: $\Delta V_2 - V_c - V_B = 0$
$(-I_2 R_2) - V_c - V_B = 0$

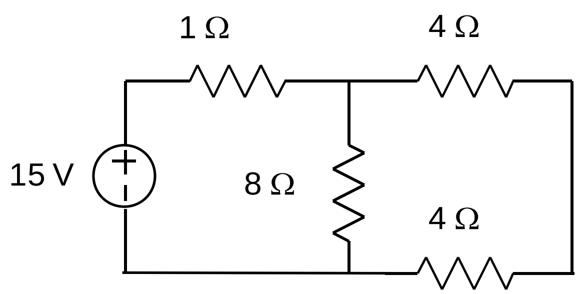
Node X: $I_1 - I_2 - I_3 = 0$

From the Left Loop equation, apparently $I_1 = (V_A + V_B)/R_1 = (9V + 5V)/1k\Omega = 14.0mA$

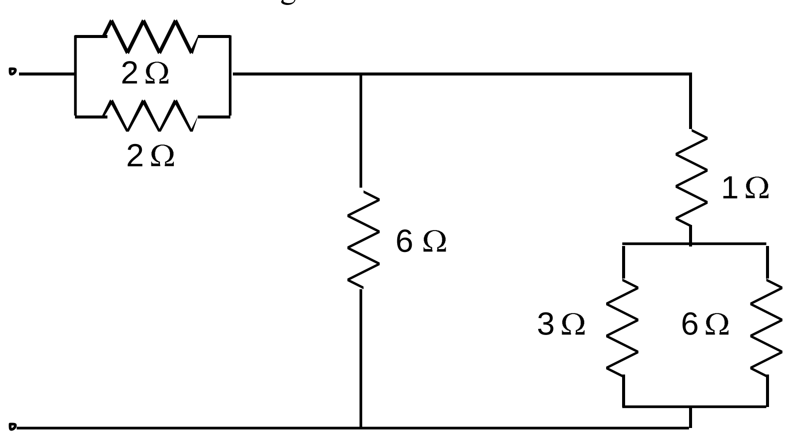
From the Right Loop equation, apparently, $I_2 = -(V_c + V_B)/R_2 = -(.5V + 5V)/5k\Omega = -1.3mA$ (note that the sign indicates that we'd guessed incorrectly about the direction I_2 was flowing.

From Node X: $I_3 = I_1 - I_2 = 14.0mA - -1.3mA = 15.3mA$ (see errata)

Group Problems.



- Calculate the total equivalent resistance.
- Find the current through the 8-Ω resistor.

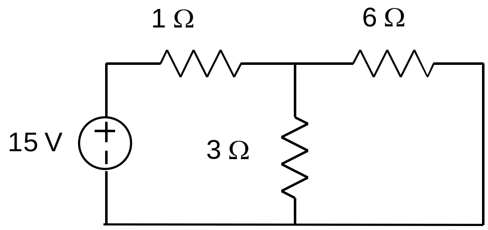


(a) Reduce the combination of resistors shown in the circuit above to a single equivalent resistor.

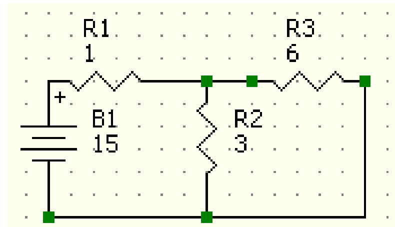
(b) Calculate the current through the 3-Ω resistor and the voltage across the 1-Ω resistor when a 120-V source is attached across the terminals.

5Spice Simulations

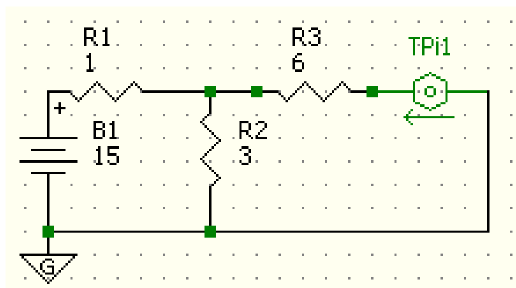
A circuit that is schematically represented as



Looks like



in 5Spice. Creating this in 5Spice doesn't just draw a nice picture; it creates a simulation of the circuit. To be able to 'run' the simulation and answer the same questions that you had addressed theoretically (what's the power dissipation in the 6-Ω resistor), you'll want to make two modifications: specify where where on the circuit you're calling "ground", and add a current probe. So you should draw



Build this circuit and Most of the steps you'll take to do this are obvious, and others will become so. Rather than giving detailed, and possibly distracting, directions here, I invite you to experiment and ask questions. Here are a couple of pointers:

- Once you've picked up an item, say a resistor, from the side menu, each place you left-click on the page you'll deposit a copy of it until you *right click* the mouse to return it to being just a cursor.
- To change anything about an object you've deposited, say, to rotate a resistor you've deposited or to change its resistance, right click on it and you'll get options to change things.

(a) Determine the power dissipated by the 6-Ω resistor (should be the same as you found when you analyzed this same circuit theoretically.)

Create and analyze the corresponding 5Spice simulations for the other circuits you've analyzed theoretically.