Name ______________________________

Section 5: HOW DO WIRES DISTRIBUTE ELECTRIC PRESSURE IN A CIRCUIT?

INTRODUCTION

We learned in Section 4 that the uniform pressure in a wire is represented by a uniform color throughout the wire. We also learned how to assign pressure-colors to wires with one end touching a battery terminal. But what, we might ask, determines the pressure-color in a wire that does NOT touch a battery?

<u>NOTE</u>: In the next series of investigations, you will be using FOUR D-cells. It is VERY important that you NOT wire a SINGLE round bulb using all four batteries. You WILL burn out the bulb, and your teacher WILL take notice of your failure to follow directions and your irresponsible and wasteful stewardship of school resources. You have been warned.

<u>INVESTIGATION ONE: HOW DO PRESSURE CHANGES GET TO THE WIRES?</u>

5.1 Activity: Four identical bulbs in series

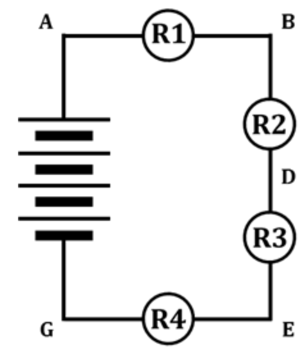

Fig. 5.1

Set up the circuit shown in Figure 5.1. Again, NOTE that we are using FOUR D-cells, not three.

The problem with using four D-cells – besides the danger of burning out round bulbs – is that the battery pack becomes full. The "nub" at the (–) end of the pack is still easy to alligator-clip onto, and Wire G in Fig. 5.1 will clip-and-stay at that location. But there is NO available spring to clip Wire A onto at the (+) end. The SOLUTION to this is that you will connect Wire A by simply TOUCHING-and-HOLDING Wire A to the metal circle on the EXTERIOR surface of the battery pack. Find this metal circle on the SAME SIDE of the pack as the "nub." Once again: Wire A will be UNABLE to be clipped on; you will have to HOLD it. This is done on purpose, to MINIMIZE the amount of time that four batteries can be continuously used in a circuit.

1. Describe what you observe about the bulbs after constructing the circuit in Fig. 5.1.

2. a. Draw TWO sets of starbursts on the bulbs in Fig. 5.1 to show that they all have the same brightness.

   b. Draw TWO arrowtails next to each bulb to indicate the flow rate of charge through each bulb.

   c. Correctly color-code the wires in Fig. 5.1 to indicate the electric pressures in each wire.

3. Explain WHY you colored the wires the way you did. In essence, you need to state HOW the pressure-colors of the wires explain why all four bulbs have identical brightnesses in Fig. 5.1.

5.2 Activity: What causes pressure change in the wires?

You should by this time understand and accept that ALL the wires in Figure 5.1 would have had a NORMAL electric pressure BEFORE they were connected in the circuit, and that therefore they would have been colored YELLOW. Upon connection, Wire A changed to RED (highest) pressure and Wire G changed to BLUE (lowest) pressure because they were connected to the (+) and (–) terminals, respectively, of the battery. But the colors of wires that DON'T touch the battery – Wires B, D, and E – can't be explained so easily. These colors show:

-- above-normal pressure in Wire B; namely, the color ______________

-- below-normal pressure in Wire E; namely, the color ______________

To make the pressure go ABOVE yellow in Wire B and BELOW yellow in Wire E, charge must have been COMPRESSED in Wire B and DEPLETED in Wire E. You might wonder: How did that compression and depletion happen? The process occurred too quickly to give us any observable clues.

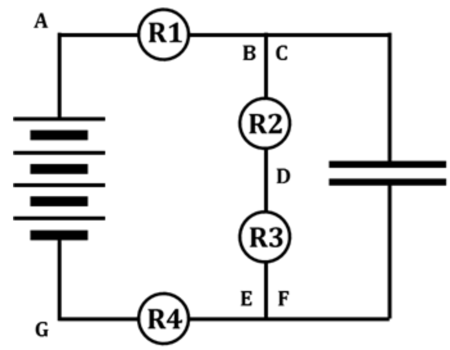

Fig. 5.2a

** Do NOT set up the next circuit yet. Just READ and LEARN.

We will slow the process down by adding a LOT more metal to Wires B and E, by using capacitor plates, as shown in Figure 5.2a. In order to do that, we need to add TWO MORE wires, Wires C and F, which will connect the original circuit (Fig. 5.1) to the capacitor. The simplest way to do this is shown in Fig. 5.2b. Note that Wires B and C should be connected to the SAME CLIP of Bulb 2, while Wires E and F should be connected to the SAME CLIP of Bulb 3. Wires B and C, as well as the top capacitor plate, now form a region of uniform electric pressure because there are no bulbs or batteries WITHIN that region. Therefore, from now on, this region will be called "BC" and ALL parts of this region, when pressure-colored, MUST ALWAYS have the SAME color.

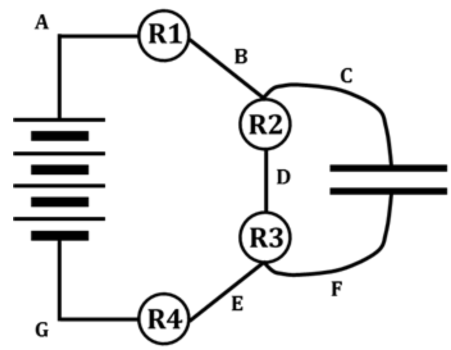

Fig. 5.2b

For the same reasons, the new region EF, when pressure-colored, MUST ALWAYS have the SAME color throughout it.

One last thing: When you DO set up Fig. 5.2a and/or 5.2b (after all, they DO represent the same circuit), be sure to set everything up, then you will (but NOT YET!) make the FINAL connection by touching Wire A to the (+) battery terminal.

Okay, NOW set up the circuit shown in Fig. 5.2a and 5.2b, except DON'T YET make the final connection of Wire A to the (+) terminal. You will need to obtain one of the LARGE, 0.10 F capacitors from the available materials. Push the four bulbs so they are as near to each other as possible, so that you will be able to see ALL of them at the same time once you make the final connection. (They WON'T all behave the same!) Your job will be to describe what you observed about each of the four bulbs, so make sure you and your partner are watching as you prepare to connect Wire A to the (+) terminal.

Ready? We're going to do this in several steps, so follow directions carefully.

Now, JUST TAP Wire A to the (+) terminal ONCE. You may repeat this several times, to make sure you are clear about what you are observing. Make each tap last for the shortest possible time: super-freaky fast!

1. Describe what happened to each bulb when you TAPPED.

    Bulb R1:

    Bulb R2:

    Bulb R3:

    Bulb R4:

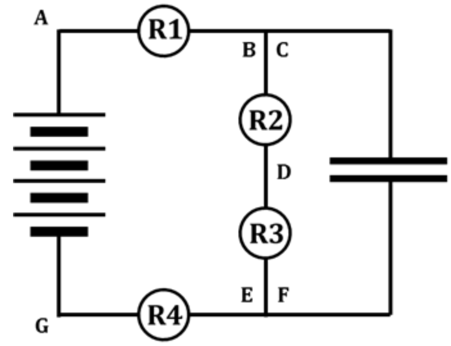

Fig. 5.2c
first instant of connection

2. Look back at Fig. 5.1 for a moment, noting the number of starbursts you put on the bulbs there. Now, draw DIFFERENT numbers of starbursts on the bulbs in Fig. 5.2c to show what you observed at the first instant of connection.

3. Hopefully, you found that TWO of the bulbs in Fig. 5.2c needed starbursts, and two didn't. Similarly, TWO of the bulbs in Fig. 5.2c should now get arrowtails, and those arrowtails should point in a particular (correct) direction. Just for consistency, for each bulb in Fig. 5.2c, put the SAME NUMBER of arrowtails as you have starbursts.

4. Charge is also flowing through the battery at the first instant of connection. However many arrowtails you drew on the bulbs in Q3… Draw that number next to the battery. Again, the direction matters.

If your taps were super-freaky fast enough, you should have observed in Fig. 5.2c (and answered in Q1) that Bulbs R1 and R4 lit up – equally bright – at the first instant of connection, while Bulbs R2 and R3 remained unlit. If you did NOT observe that, ask your teacher for assistance right now and prepare to change your answers to Q1-4. Everything that follows from here depends on your having witnessed correct observations and answered Q1-4 above correctly. Once all is in order, continue on.

5. Color-code ONLY Wires A and G in Fig. 5.2c. This should be fairly easy for you to figure out.

6. Again, at the first instant of connection – i.e., the TAP – you should have observed that <u>Bulbs R1 and R4 were lit and EQUALLY bright, while Bulbs R2 and R3 were UNLIT</u>. See if you and your partner can reason through how Region BC, Wire D, and Region EF should be color-coded to satisfy the conditions of the underlined part of this question. Write your answers below.

    At the first instant of connection, the pressure-colors should be….

    Region BC: ______________ Wire D: ______________ Region EF: ______________

** CHECK YOUR ANSWERS TO Q6 WITH YOUR TEACHER, THEN COLOR THESE REGIONS IN Fig. 5.2c.

In your answer to Q3 above, you should have drawn arrowtails on Bulbs R1 and R4 and NO arrowtails on Bulbs R2 and R3. Keep this in mind as you reason through the next couple of questions.

7. The charge passing through Bulb R1 at the first instant of connection: Where MUST it go next?
    HINT: The answer is NOT "to Bulb R2" or "to the wire leading to Bulb R2." Look at Fig. 5.2c and identify the only other place that that charge can go, then write your answer here.

8. The charge passing through Bulb R4 at the instant of connection: Where must it have come FROM?
HINT: The answer is NOT "from Bulb R3" or "from the wire leading from Bulb R3." Look at Fig. 5.2c and identify the only other place that that charge could have come from.

9. In Fig. 5.2c, draw TWO MORE SETS of arrowtails: one that reflects your answer to Q7 and one that reflects your answer to Q8. The number of arrowtails you use should match the number you originally used in Q3.

Soon (NOT YET!), you will make the same final connection of Wire A at the (+) battery terminal, but this time you will TOUCH-and-HOLD Wire A to the (+) terminal for an extended period of time. This will allow you to observe how the bulbs behave beyond the first (TAP!) instant of connection. Again, push the four bulbs as near to each other as possible so you can see what ALL of them are doing.

Now, go ahead and TOUCH-and-HOLD Wire A to the (+) terminal while watching the bulbs.

10. Describe what happened to each bulb.

Bulb R1:

Bulb R2:

Bulb R3:

Bulb R4:

11. Describe the brightness of all four bulbs, once they have all "settled down" and stopped changing. For EACH bulb, be sure to mention how the final, "settled down brightness" compared to its original brightness, i.e., its brightness at the first instant of connection.

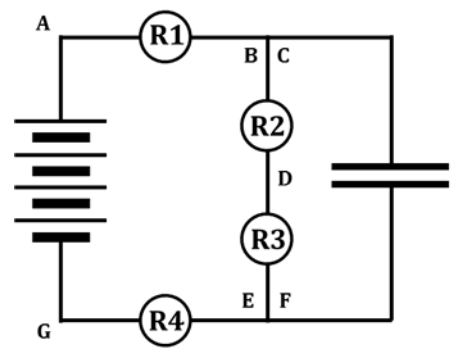

Fig. 5.2d
steady-state condition

The final, "settled down" condition mentioned in Q11 is properly called the <u>steady-state condition</u>. (The "state" of affairs is "steady", constant, unchanging…. "Steady-state." Get it? Anyway…) Between the first instant of connection and steady-state, you noticed that there is a period of time during which THINGS ARE CHANGING: bulb brightnesses, for example. Anything occurring during THAT time interval is called a <u>transient</u> process where, here, the word *transient* means "while things are still changing."

12. Look back now at the starbursts you drew in Fig. 5.2c, which represented the first instant of connection. You now need to draw DIFFERENT starbursts on the bulbs in Fig. 5.2d to show what you observe once steady-state is reached. The NUMBER of starbursts you draw MUST be consistent with (i.e., must be logically-related TO) what you already drew in Fig. 5.2c AS WELL AS your answers to Q10 and Q11 above. (It will also DEFINITELY HELP to look back at Fig. 5.1.)

13. Now, draw arrowtails next to the bulbs in Fig. 5.2d. Again, these arrowtails need to point in a specific (correct) direction, and they need to be consistent or somehow correlated with the arrowtails you

already drew in Fig. 5.2d AS WELL AS your answers to Q10 and Q11 above. (It will also definitely help to look back at Fig. 5.1.) Also, here, you should have NO arrowtails near the capacitor plates.

14. Charge is also flowing through the battery at steady-state. However many arrowtails you drew on the bulbs in Q13… Draw that number next to the battery. Again, the direction matters.

15. List here the pressure-colors for the following parts of the steady-state circuit in Fig. 5.2d.

A: ______________ BC: ______________ D: ______________ EF: ______________ G: ______________

16. How did you KNOW what colors to write in the blanks above? Your answer, most likely, will sound very much like your answer to Q3 in Sec. 5.1.

17. Look back at Fig. 5.2c and list here the pressure-colors that existed at that first instant of connection.

A: ______________ BC: ______________ D: ______________ EF: ______________ G: ______________

18. Based on your answers to Q15 and Q17, state what happens to the electric pressure in each part of the circuit, between the first instant of connection and the time when steady-state is achieved. Use the terms INCREASES, DECREASES, and/or STAYS THE SAME.

Pres. in region A: ______________ Pres. in region BC: ______________ Pres. in region D: ______________ Pres. in region EF: ______________ Pres. in region G: ______________

Feel free, at this time, to repeat (or not) the investigations you've done so far with the 0.10 F capacitor (TAP…..TAP, or TOUCH-and-HOLD). It is important that you are able to describe what happens to each bulb from the very first instant of connection to the final steady state. You should also be able to state IF and HOW the electric pressures change in each part of the circuit.

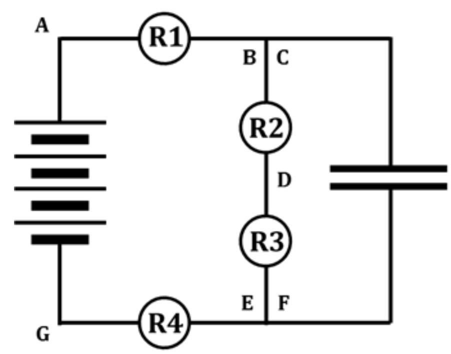

Fig. 5.3a
first instant of connection

5.3 Activity: What happens if the capacitor isn't there?

1. In Fig. 5.3a, re-copy exactly the starbursts and arrowtails you drew into Fig. 5.2c. Also, color-code the circuit, as you did in Fig. 5.2c.

2. Now, make Fig. 5.3b look EXACTLY like Fig. 5.2d.

3. Using the large, 0.10 F capacitor, set up the circuit shown in Fig. 5.3a. Make the FINAL connection between Wire A and the (+) battery terminal. TOUCH-and-HOLD Wire A to the (+) battery terminal and make a mental note of how long it takes for the circuit to reach steady-state.

4. Repeat Step 3, but this time use the 0.025 F capacitor from your CASTLE kit. How does the time required to reach steady-state compare to when you used the 0.10 F capacitor?

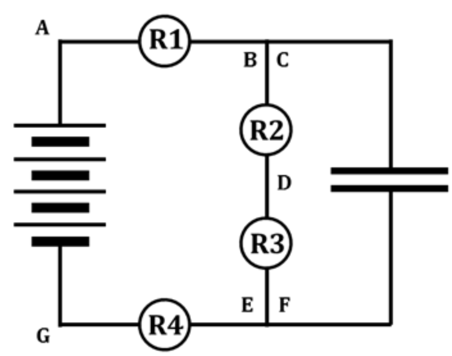

Fig. 5.3b
steady-state condition

5. Look at your work in Fig. 5.3a, specifically at the ARROWTAILS. With this in mind, come up with a reason WHY the system took SO much longer to reach steady-state with the 0.10 F capacitor, as compared to the 0.025 F capacitor.

6. Suppose now you had a capacitor with REALLY tiny plates in Fig. 5.3a, SO tiny that even Wires C and F leading to the plates had more surface area than the plates. How long would it take THAT system's components to go through the pressure changes that result in a steady-state condition?

7. Is what is described in Q6 ANY different from the circuit you started Section 5 with, which is shown for you again here as Fig. 5.3c?

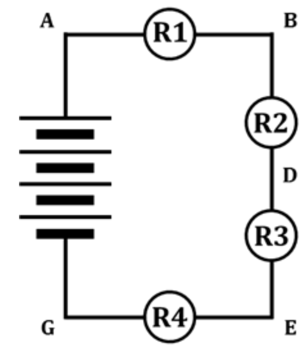

Fig. 5.3c

8. In short, Wires B and E in Fig. 5.3c go through the SAME pressure changes that happen to, respectively, Regions BC and EF in Figs. 5.3a and 5.3b, but the time required in Fig. 5.3c is…

And finally!

9. Way back in Section 1 of this program, we stated something to the effect that "all bulbs light at the same time" because…WHY?

10. NOW, based on our work in this Section, we can modify that statement slightly. As you hinted at in your answers to Q1 and Q10 in Activity 5.2, in any set of light bulbs in series, the bulbs that (in theory) light up first are WHICH ones?

5.4 Exercise: The transient process and steady-state in a series circuit

Long ago, when we had a series circuit such as what is shown in Figure 5.4a, we used a compass beneath each wire as evidence that the flow rate of charge was the same in BOTH DIRECTION and MAGNITUDE at each point in the circuit.

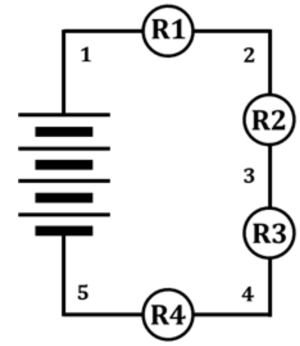

Fig. 5.4a

But back in Section 4, when we were first learning to color-code circuits, it was stated that, although wires touching the battery terminals IMMEDIATELY acquired the electric pressures of those terminals, bulb filaments RESISTED the flow of charge such that the OTHER wires' pressures DIDN'T change at the instant of connection. In other words, at the instant of connection, the pressure-colors of the wires of Fig. 5.4a are those shown in Fig. 5.4b.

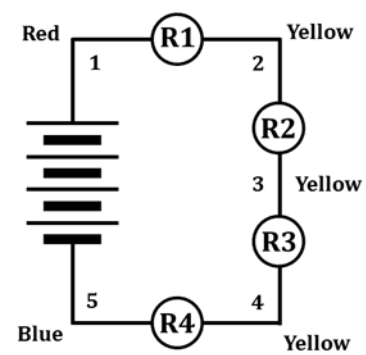

Fig. 5.4b
first instant of connection

1. Using markers, color-code Fig. 5.4b.

2. According to your coloring, which bulbs light up first?

3. Draw arrowtails near the appropriate bulbs in Fig. 5.4b.

Let's now look at Wire 2. (Circle your answers.)

4. In Fig. 5.4b, is there a NET charge flow INTO or OUT OF Wire 2?

5. Therefore, Wire 2's electric pressure must: INCREASE DECREASE

6. Based on your answer to Q5, the pressure difference across Bulb R1 will… INCREASE DECREASE

7. …which will cause the flow rate through Bulb R1 to… INCREASE DECREASE

8. Based on your answer to Q5, the pressure difference across Bulb R2 will… INCREASE DECREASE

9. …which will cause the flow rate through Bulb R2 to… INCREASE DECREASE

Now, look at Wire 4.

10. In Fig. 5.4b, is there a NET charge flow INTO or OUT OF Wire 4?

11. Therefore, Wire 4's electric pressure must: INCREASE DECREASE

12. Based on your answer to Q11, the pressure difference across Bulb R4 will… INCREASE DECREASE

13. …which will cause the flow rate through Bulb R4 to… INCREASE DECREASE

14. Based on your answer to Q11, the pressure difference across Bulb R3 will… INCREASE DECREASE

15. …which will cause the flow rate through Bulb R3 to… INCREASE DECREASE

Go ahead: Guess on these next ones. (Most likely, you'll be right...)

16. Wire 2's pressure will STOP CHANGING when it reaches WHICH color?

17. Wire 4's pressure will STOP CHANGING when it reaches WHICH color?

18. Now color-code Fig. 5.4c, which shows the steady-state condition.

19. List the Fig. 5.4c wire colors in the blanks below:

1 = __________ 2 = __________ 3 = __________ 4 = __________ 5 = __________

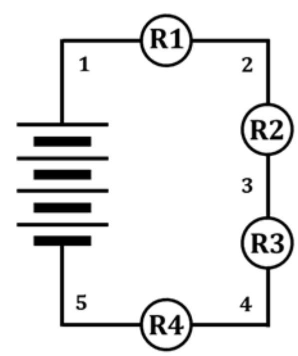

Fig. 5.4c
steady state

20. In Fig. 5.4c, how do the PRESSURE DIFFERENCES across Bulbs 1-4 compare?

Your answer to Q20? THAT, coupled with all of the bulbs having the SAME resistance, is WHY the flow rate is the SAME in ALL parts of Fig. 5.4c.

Here are some bogus pressure-colors, for the wires in this circuit:
1 = red, 2 = red, 3 = yellow, 4 = blue, 5 = blue

21. In Fig. 5.4d, color-code the bogus pressure-colors mentioned above.

22. Explain why the color-coding of Fig. 5.4d CANNOT POSSIBLY be correct.
What, specifically, would (or wouldn't) happen that violates reality?

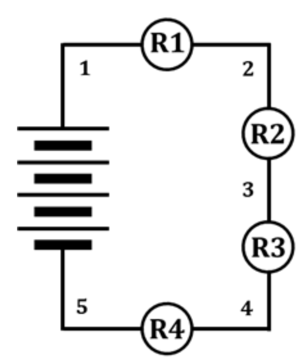

Fig. 5.4d
bogus circuit

5.5 Exercise: Non-standard (i.e., "tweener") pressure-colors

One of the main purposes of the previous section was to cement in your mind that, AT STEADY-STATE, the flow rate of charge is the SAME in ALL parts of a series circuit. This is likely NOT to be true at the first instant of connection and during the transient stage while electric pressures are changing (see Fig. 5.4b), but it is DEFINITELY true at steady-state. To say it again: When there is ONLY ONE flow path, the current (i.e., the ARROWTAILS) MUST be the same throughout.

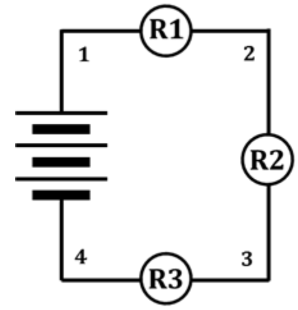

Fig. 5.5a
actual steady-state colors

We now begin to consider non-standard pressure-colors, which are colors other than "pure red," "pure orange," and so on. Because these pressure-colors are BETWEEN pure colors, we sometimes refer to them as "tweener" colors.

1. Color-code ONLY Wires 1 and 4 in the four figures on this page. DO NOT color Wires 2 and 3, at this time.
2. Put starbursts on the bulbs in Fig. 5.5a. Build the circuit, if you don't know how the bulb brightnesses will compare to each other.
3. Draw arrowtails by the bulbs in Fig. 5.5a. The arrowtails should tell the same story as the starbursts.
4. Now, color-code Wires 2 and 3 in Figs. 5.5b, 5.5c, and 5.5d with the BOGUS colors shown in the figures.
5. Draw starbursts on the bulbs in Figs. 5.5b, 5.5c, and 5.5d, BASED ON THE BOGUS COLORS shown.

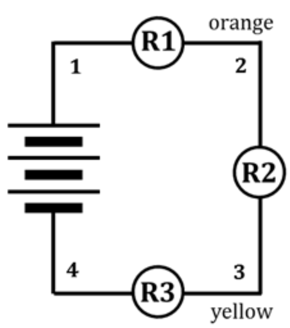

Fig. 5.5b
bogus steady-state colors #1

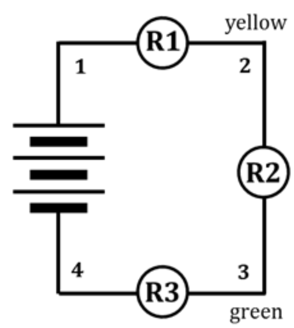

Fig. 5.5c
bogus steady-state colors #2

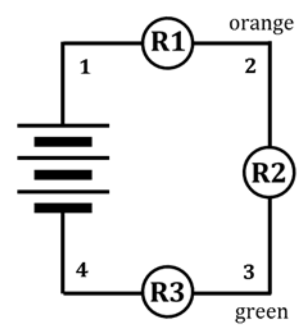

Fig. 5.5d
bogus steady-state colors #3

6. Draw arrowtails by the bulbs in Figs. 5.5b, 5.5c, and 5.5d, based on your bogus starbursts from Q5.
7. Compare your three bogus figures to the actual steady-state circuit shown in Fig. 5.5a. Hopefully, you can see that the pressures in Wires 2 and 3 in the ACTUAL circuit are BEST approximated by "tweener" colors. Fill in the blanks below. "In the actual circuit (Fig. 5.5a)…"

…Wire 2's pressure-color is HIGHER than the color ____________, but LOWER than the color ____________.

…Wire 3's pressure-color is HIGHER than the color ____________, but LOWER than the color ____________.

8. In the blanks below, hyphenate your two color answers from Q7 above:

"Wire 2's steady-state pressure-color is some kind of ______________–______________."

"Wire 3's steady-state pressure-color is some kind of ______________–______________."

9. Summarize what we've just learned here by completing the statement:
   In order for identical bulbs to have identical brightnesses, they must also have, across them…

INVESTIGATION TWO: CAN SERIES PRESSURE DIFFERENCES BE UNEQUAL?

5.6 Activity: Non-identical bulbs in series

1. DON'T make the final connection yet, but set up the circuit shown in Fig. 5.6a. Note that the circuit contains FOUR D-cells, TWO round bulbs, and TWO long bulbs. BE SURE to place the bulbs in the correct order: ROUND, LONG, LONG, ROUND.

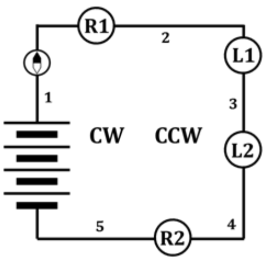

Fig. 5.6a

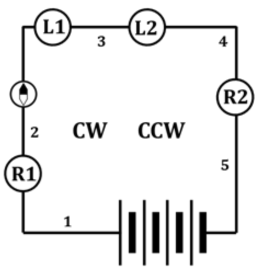

Fig. 5.6b

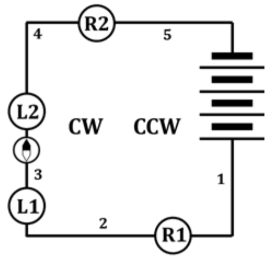

Fig. 5.6c

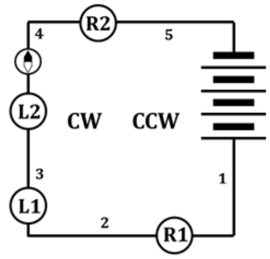

Fig. 5.6d

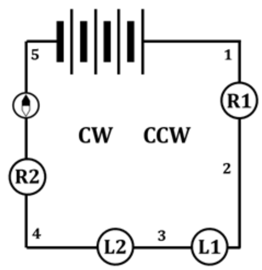

Fig. 5.6e

2. TAPE the compass from your kit to the table; the needle will point in whatever direction it prefers.

3. In Fig. 5.6a, locate the compass; it is under Wire 1. WITHOUT moving the compass, MOVE and/or ROTATE the ENTIRE rest of the circuit such that Wire 1 lies parallel to the compass needle.

4. Hold Wire 1 over – and PARALLEL to – the needle. Now, make the final connection while observing the compass. If the compass deflects clockwise when the connection is made, circle "CW" in Fig. 5.6a. If it deflects counterclockwise, circle "CCW" in Fig. 5.6a. ALSO, make a mental note of the AMOUNT of compass deflection.

5. You now will need to disconnect and re-connect the circuit FOUR MORE TIMES to test the compass under Wires, 2, 3, 4, and 5. Before each new trial, you MUST ROTATE the entire circuit counter-clockwise, WITHOUT moving the compass. You will note in Figs. 5.6a-e that the SAME HALF of the compass is INSIDE the loop, every time (and the SAME HALF of the compass is OUTSIDE the loop, every time). For each trial, make sure the wire you are testing is PARALLEL to the needle BEFORE you make the final connection. Observe the compass deflection and circle either "CW" or "CCW" in each of Figs. 5.6b-e. Again, make a mental note of the amount of deflection.

6. How did the DIRECTIONS of the compass deflections in Figs. 5.6a-e compare to each other?

7. What does your answer to Q6 tell you about the DIRECTION of the flow of charge at the varous points in this circuit?

8. How did the AMOUNTS of the compass deflections in Figs. 5.6a-e compare?

9. What does your answer to Q8 tell you about the MAGNITUDE of the flow rate at the various points in this circuit?

10. Fig. 5.6f is simply a larger version of Fig. 5.6a. Draw arrowtails next to the bulbs AND the battery in Fig. 5.6f; these arrowtails should support your answers to BOTH Q7 and Q9. Do NOT draw (or think about) starbursts yet.

11. In Fig. 5.6f, color-code ONLY Wires 1 and 5. Also, because there is symmetry in this circuit, you should be able to guess the pressure-color of Wire 3. That color is _________________. and you should color-code Wire 3 as well.

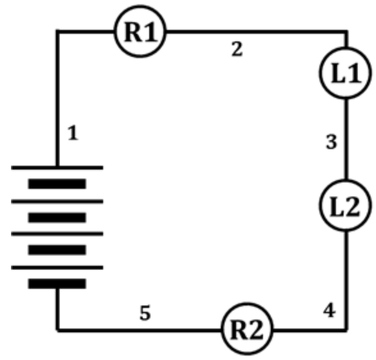

Fig. 5.6f

WARNING: DO NOT color Wires 2 and 4. PERIOD.

We're going to do a couple of guess-and-check thought experiments now.

Thought Experiment #1

Let's GUESS that Wire 2's pressure-color is orange, and Wire 4's is green. If you want to, VERY LIGHTLY – IN PENCIL – you may write an "O" above Wire 2 and a "G" next to Wire 4. (You'll erase them soon.)

12. IF Wires 1/2/3/4/5 had the respective colors R/O/Y/G/B (in reality, THEY DON'T!), how would the pressure DIFFERENCE across each bulb in Fig. 5.6f compare?

13. This IS reality…How do the flow rates in the various bulbs compare? HINT: See your answer to Q9 above.

Based on your answers to Q12 and Q13, you might think that everything seems in order…but it ISN'T.

14. Back in Section 2, you learned about the resistances of round bulbs and long bulbs. Just so we're all on the same page, how DOES the resistance of a round bulb compare to that of a long bulb?

"ROUND bulbs have a _________________ resistance; LONG bulbs have a _________________ resistance."

In Q12, hopefully you said that the pressure differences would all be equal IF (and it's NOT TRUE!) the pressures of Wires 1/2/3/4/5 were R/O/Y/G/B. If you didn't say that, change your answer to Q12 now.

NOW…IF the pressure differences across a round bulb and across a long were equal, that would mean that there is an equal "push" on the charges going through both of those bulbs. BUT, you stated in your answer to Q14 (hopefully) that a ROUND bulb has LESS resistance and a LONG bulb has MORE.

15. If you give an EQUAL PUSH to two things that have DIFFERENT RESISTANCES, will you get the same results? (Think about lifting weights, and giving an equal push to a very light weight, and then giving THAT SAME push to a very heavy weight.) Now answer the question.

So hopefully you are convinced that R/O/Y/G/B CANNOT be correct for Wires 1/2/3/4/5 in Fig. 5.6f: Equal pressure differences (i.e., equal pushes) on bulbs of different resistances will NOT produce the identical flow rates you (correctly) drew next to the battery and bulbs of Fig. 5.6f.

16. RIGHT NOW, on Fig. 5.6f, write "NOT ORANGE" above Wire 2 and "NOT GREEN" next to Wire 4.

Look back at Fig. 5.1, on the first page of this packet. R/O/Y/G/B WAS correct for those Wires 1/2/3/4/5 because they were ALL the same type of bulb; namely, round bulbs. EQUAL pushes on bulbs of IDENTICAL resistance yields the SAME flow rate through each bulb; NOT SO when we have bulbs of varying resistance, as in Figs. 5.6f and 5.6g.

So, you might ask, what IS needed in order to achieve the IDENTICAL flow rate through each bulb that we observe in ANY series circuit that has reached steady-state? First of all, we KNOW that the flow rate at steady-state is the same throughout the circuit; the arrowtails you drew in Fig. 5.6f and your answer to Q8 above should have told you that. Let's try another thought experiment, one you might already have thought of, based on the brightnesses of the various bulbs in the circuit.

17. In Fig. 5.6g, color-code Wires 1, 3, and 5 like you did in Fig. 5.6f. Also, draw arrowtails next to the battery and bulbs, as before.

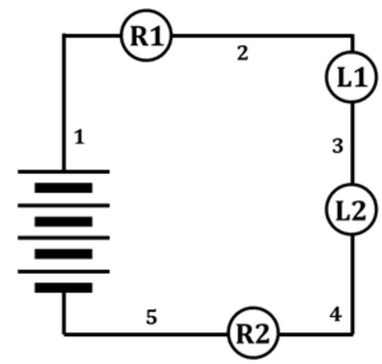

Fig. 5.6g

WARNING: DO NOT color Wires 2 and 4.

Thought Experiment #2

Now let's GUESS that Wire 2's pressure-color is red, and Wire 4's is blue. If you want to, VERY LIGHTLY – IN PENCIL – you may write an "R" above Wire 2 and a "B" next to Wire 4.

18. Based on what you observe when you construct this circuit, complete the following statements.

In reality, Wire 2 CAN'T have a "pure red" pressure because, if it did…

In reality, Wire 4 CAN'T have a "pure blue" pressure because, if it did…

19. RIGHT NOW, on Fig. 5.6g, write "NOT PURE RED" above Wire 2 and "NOT PURE BLUE" next to Wire 4.

So we've established that Wire 2 can be NEITHER orange (Thought Exp. #1) NOR red (TE #2), and Wire 4 can be NEITHER green (TE #1) NOR blue (TE #2). It's time for our third (and final!) thought experiment.

Thought Experiment #3

Now, we're going to make some compromise-guesses from our earlier thought experiments. Let's guess that Wire 2's pressure-color is BETWEEN red and orange, say, "red-orange" or – if you'd prefer – "red-red-orange." Similarly, let's guess Wire 4's pressure to be BETWEEN blue and green, say, "blue-green" or "blue-blue-green." On Fig. 5.6h ON THE NEXT PAGE:

20. Correctly color-code Wires 1, 3, and 5 AND draw in identical-flow-rate arrowtails, as before.

21. Write "RO" or "RRO" (your choice) above Wire 2 to indicate a red-orange or a red-red-orange color.

22. Write "BG" or "BBG" (your choice) next to Wire 4 to indicate a blue-green or a blue-blue-green color.

Now we're going to investigate, for a series circuit, if there's any correlation between the pressure difference across a given bulb and the resistance of that bulb. Remember, in a steady-state series circuit, the flow rates (i.e., the arrowtails) are all EQUAL; your earlier work at the very beginning of Activity 5.6 should have convinced you of that.

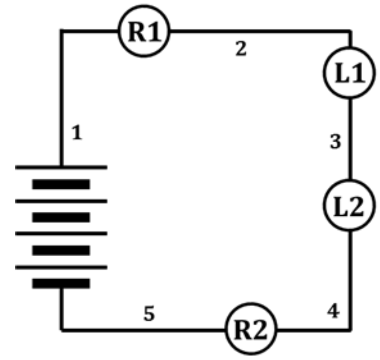

Fig. 5.6h

For the purposes of this exercise, we're going to say that 1.00 JUMPS on the pressure-color scale (e.g., red-to-orange or orange-to-yellow) is a MEDIUM pressure difference. Anything greater than that is a LARGE pressure difference; anything less is a SMALL pressure difference.

23. With reference to Fig. 5.6h, circle your answers below.

Pressure difference across R1 (i.e., between Wires 1 and 2):	*SMALL*	*MEDIUM*	*LARGE*
Resistance of R1:	*LOW*		*HIGH*
Pressure difference across L1 (i.e., between Wires 2 and 3):	*SMALL*	*MEDIUM*	*LARGE*
Resistance of L1:	*LOW*		*HIGH*
Pressure difference across L2 (i.e., between Wires 3 and 4):	*SMALL*	*MEDIUM*	*LARGE*
Resistance of L2:	*LOW*		*HIGH*
Pressure difference across R2 (i.e., between Wires 4 and 5):	*SMALL*	*MEDIUM*	*LARGE*
Resistance of R2:	*LOW*		*HIGH*

24. Was there a pattern to your answers in Q23? If there was, state what the pattern was.

25. Let's summarize what we've learned in this activity:

"In a SERIES circuit at steady-state, the flow rate of charge (i.e., the <u>current</u>, indicated by arrowtails) is the SAME through ALL resistors (e.g., bulbs). To achieve this uniform flow rate throughout the circuit, there must be a ____________ electric pressure difference (i.e., "color difference" or "push") across resistors with MORE resistance and a ____________ electric pressure difference across resistors with LESS resistance."

26. Can you see the next step on the path? See if you can figure out what goes in each of the blanks below.

"In a PARALLEL circuit, where the charge has a CHOICE as to which route it takes, there WILL be points where the electric pressure difference (i.e., the "color difference") across the various routes is the SAME, but the resistance of the different routes will be DIFFERENT. In such cases, I predict that the route having the HIGHER resistance will have a ____________ current, while the route having the LOWER resistance will have a ____________ current."

5.7 Activity: Electric pressure differences and flow rates

Color-code the circuit of Fig. 5.7a, with the middle wire being YELLOW. You will NOTE that this figure is labeled "first instant of connection."

1. AT THIS FIRST INSTANT OF CONNECTION, how does the pressure difference across the long bulb compare to that across the round bulb?

2. Because of your answer to Q1 and the KNOWN resistances of round versus long bulbs, how MUST the flow rates (i.e., currents) between the two bulbs compare, AT THIS FIRST INSTANT OF CONNECTION? HINT: They are NOT the same.

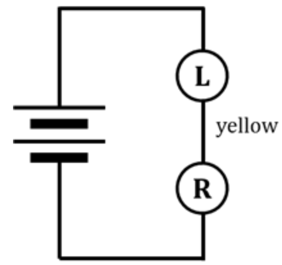

Fig. 5.7a
first instant of connection

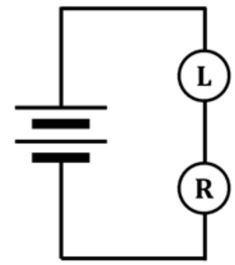

Fig. 5.7b
steady state

3. Draw arrowtails next to the bulbs in Fig. 5.7a that support your answer to Q2.

4. Therefore, AT THIS FIRST INSTANT OF CONNECTION, must there be a NET flow of charge INTO or OUT OF the middle wire? Circle your answer. INTO OUT OF

5. And therefore, the electric pressure of the middle wire MUST… INCREASE DECREASE

6. Now, based on your answer to Q5, color-code Fig. 5.7b, which is labeled "steady state," and draw arrowtails next to the bulbs and battery to correctly describe the steady-state condition.

7. Now, build the circuit of Fig. 5.7b, make observations, and then draw starbursts on Fig. 5.7b.
   HINT: If there are any bulbs that you KNOW have charge flowing through them but yet the bulb DOESN'T light, put starbursts around that bulb that look like this:

We're going to repeat the process above, with the round and long bulbs having changed places.

8. Color-code Fig. 5.7c, then draw arrowtails by the bulbs.

9. Build the circuit and make observations.

10. Based on everything you've learned up to this point (and observed in Q9), color-code Fig. 5.7d. ALSO, draw arrowtails and starbursts that describe the steady-state condition in Fig. 5.7d.

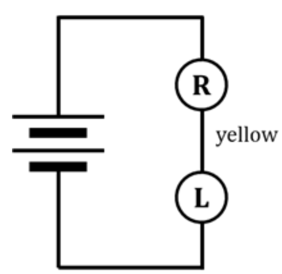

Fig. 5.7c
first instant of connection

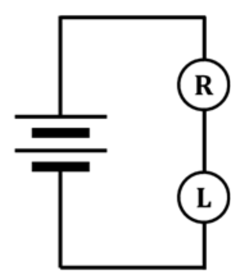

Fig. 5.7d
steady state

<u>NOTE</u>: It is best to understand EVERY SINGLE THING that has occurred so far in Activity 5.7 BUT, at the very least, you MUST understand what's happening at steady-state, i.e., in Figs. 5.7b and 5.7d.

Now, we're going to wire the bulbs in parallel. Figure 5.7e is the simplest schematic diagram, but Fig. 5.7f shows you how to actually construct the circuit. You can see you'll need four wires: A, B, C, and D.

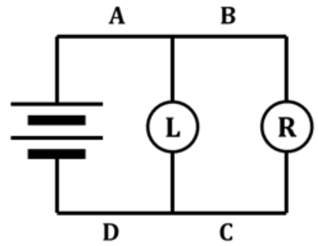

Fig. 5.7e

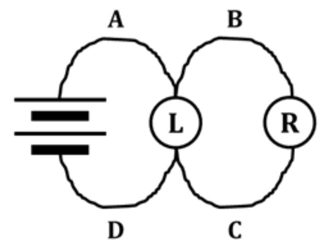

Fig. 5.7f

11. Build the circuit of Fig. 5.7e, then color-code both circuits at right. ALSO, draw STARBURSTS (NOT arrowtails) around the bulbs to indicate the brightness of each bulb.

12. How do the pressure differences (i.e., the color differences, the "pushes") across the two bulbs compare to each other?

13. Based on your answer to Q12 and the KNOWN resistances of round versus long bulbs, how MUST the flow rates/currents through the bulbs compare?

14. Do the starbursts you drew in Q11 support your answer to Q13? If they don't, ask your teacher for help now.

15. In Fig. 5.7e, draw arrowtails showing the currents passing through the bulbs. I don't care much about the ABSOLUTE number of arrowtails (e.g., 1, or 2, or 3) that you draw: What I definitely DO care about is that the RELATIVE number of arrowtails between the two bulbs MUST be correct; namely, one should have MORE, the other LESS…… Do it.

16. Look again at Fig. 5.7e. Let's pretend you were going to draw arrowtails in Wire B. How many would you draw, and why?

    What about in Wire C?

    Go ahead and draw in those arrowtails on Wires B and C in Fig. 5.7e.

17. Now look at Wire D in Fig. 5.7e. Count up the TOTAL number of arrowtails that are flowing INTO Wire D from Wire C PLUS the ones flowing into Wire D after passing through the LONG bulb. How many IS it?

18. In Wire D in Fig. 5.7e, draw in the correct number of arrowtails, that you determined in Q17.

19. Follow the arrowtails from Wire D into the battery. How many should flow into the battery?
    Also, DRAW THEM into Fig. 5.7e, next to the battery.

20. Now follow the arrowtails from the battery and into Wire A. DRAW the correct number by Wire A.

21. In the figure at right, the order of bulbs has been reversed. Use what you've learned above to draw arrowtails next to ALL parts of Fig. 5.7g.

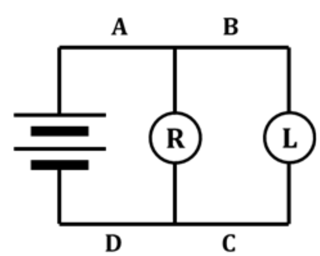

Fig. 5.7g

5.8 Activity: Changes in resistance and pressure difference when adding bulbs: series vs. parallel

Let's see if you remember something you should have learned back in Section 2. Circle your answers.

1. Whenever we add another resistor IN SERIES to an existing circuit…

…the total resistance of the circuit	INCREASES	DECREASES
…and the current through the battery	INCREASES	DECREASES

2. Whenever we add another resistor IN PARALLEL to an existing circuit…

…the total resistance of the circuit	INCREASES	DECREASES
…and the current through the battery	INCREASES	DECREASES

In this activity, we are going to gather experimental evidence to support the above statements. In addition, we will investigate how the PRESSURES (i.e., the colors) in a circuit MUST CHANGE upon the addition of resistors in series, and also in parallel.

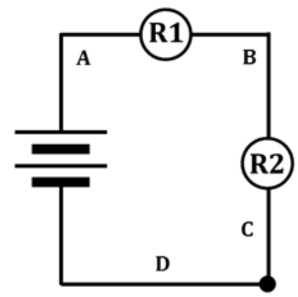

Fig. 5.8a

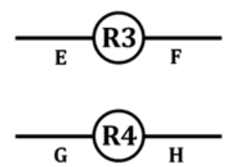

Fig. 5.8b

3. Construct the circuit shown in Fig. 5.8a. NOTE that you'll need ONLY TWO D-cells, as well as FOUR wires. You see that Wires C and D initially start out alligator-clipped together.

4. ALSO, at this time, put together the TWO "circuit-segments" shown in Fig. 5.8b: Wires E and F, on either side of a bulb, and Wires G and H, on either side of another bulb. You will use these Segments in a little bit.

5. Color-code all wires of Fig. 5.8a to indicate electric pressures. Also, draw arrowtails to indicate current through the bulbs and battery, and draw starbursts on the bulbs to indicate brightness.

6. Now, OPEN the circuit where Wires C and D are joined and INSERT Segments EF AND GH there, BOTH IN SERIES with the existing circuit. Wires C and E should connect, as should wires F and G, and as should H and D. In the space below Fig. 5.8b, draw a schematic of the circuit you've just constructed. Label the bulbs and wires, color-code the circuit, and draw arrowtails and starbursts. LABEL your newly-drawn schematic as Fig. 5.8c.

In many of the upcoming questions, you will be asked to FOCUS on the behavior of SPECIFIC bulbs, in order to analyze what is happening. For example, in ALL of the figures in this activity, the current through Bulb 1 IS EXACTLY EQUAL to the current through the battery. Thus, by examining Bulb 1, we will be able to gather information about what's happening with the battery and how the pressures are changing. Other bulbs will be used for other purposes.

7. When you added Bulbs 3 and 4 in series (Fig. 5.8c), the current through Bulb 1 ________________, compared to what it was in Fig. 5.8a. You know this because the brightness of Bulb 1 ________________. Since Bulb 1 and the battery have the same current, the current through the battery has also ______________. THIS means that the total resistance of the circuit (the resistance PERCEIVED by the battery) must have ______________when we added Bulbs 3 and 4 in series.

8. Assuming (mostly correctly) that Bulb 1's resistance DOESN'T change between Figs. 5.8a and 5.8c:

   State how the pressure difference across Bulb 1 CHANGES between those two figures…

   …and HOW the CHANGE in pressure difference explains the change in Bulb 1's brightness.

Now we will analyze a parallel circuit.

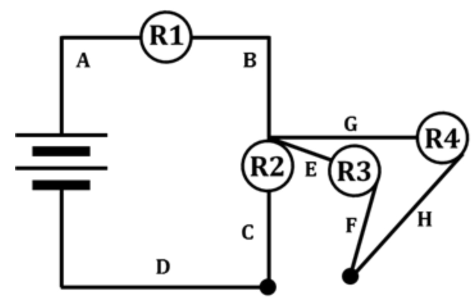

Fig. 5.8d

9. Remove Segments EF and GH from Fig. 5.8c and re-construct the circuit of Figure 5.8a.

10. Now, using Segments EF and GH, assemble the circuit of Fig. 5.8d. NOTE that Wires E and G are attached to the same clip of Bulb 2 as is Wire B, and that Wires F and H are clipped together to form a junction. In a minute, we will ask you to TOUCH the FH junction to the CD junction, but NOT YET.

11. Because of the way the circuit of Fig. 5.8d is constructed, Bulbs 3 and 4 are essentially NOT part of any circuit (yet). Convince yourself that what is shown in Fig. 5.8d is EXACTLY EQUIVALENT to Fig. 5.8a. Do this by – after building the circuit and observing – color-coding ALL the wires (A-H) and by drawing arrowtails and starbursts in Fig. 5.8d.

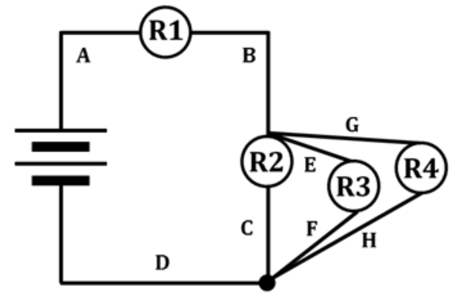

Fig. 5.8e

12. Now, TOUCH-and-RELEASE the FH junction to the CD junction. Do this as many times as necessary in order to grasp the changes in brightness that occur with BULBS 1 AND 2. State those changes here:

    "In going from Fig. 5.8d to Fig. 5.8e, Bulb 1 got ________________" and Bulb 2 got ________________."

13. Now, color-code Fig. 5.8e in a way that justifies your answers to Q12. You will note that NO resistors OR batteries lie within the Region BEG; thus, that entire Region MUST be given a uniform color.

14. Examine your coloring of Figs. 5.8d and 5.8e to answer this one…. State what happens to the PRESSURE DIFFERENCE across the part of any circuit TO WHICH a parallel branch is added.

"Whenever we add a resistor in parallel, the pressure difference in that part of the circuit _________________."

15. Based on what happened to the brightness of Bulb 1 in going from Fig. 5.8d to 5.8e, you must conclude that the current flowing through the battery _________________. Thus, the total resistance of the circuit (i.e., the resistance PERCEIVED by the battery) must have _________________ which, we know, is ALWAYS WHAT HAPPENS whenever we add resistors to a circuit in ________________.

5.9 Activity: The separation of current into parallel branches

Back in Section 5.4, you studied how, once steady state has been reached, the CURRENT is the SAME everywhere throughout a SERIES circuit. Here, we will investigate how the current DIVIDES when there are PARALLEL branches in a circuit.

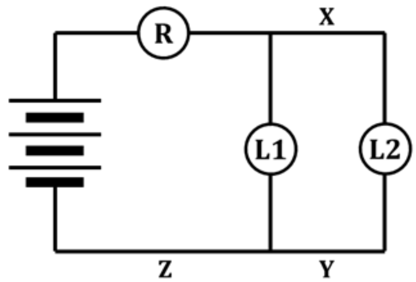

Fig. 5.9a

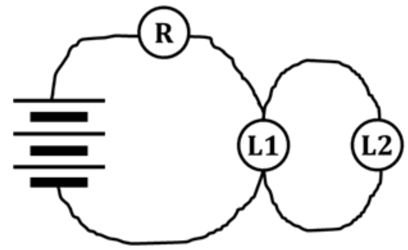

Fig. 5.9b

1. Construct the circuit shown in Fig. 5.9a. Fig. 5.9b shows a little more clearly how to construct this circuit. You can see you'll need five wires.
2. After observing the bulb brightnesses, draw STARBURSTS on the bulbs in Fig. 5.9a.
3. For arguments' sake, let's say there are FOUR arrowtails of current passing through the round bulb. Draw those four arrowtails by the round bulb in Fig. 5.9a.
4. How much current MUST be going through the battery? How much curent MUST be going through the wire at the point labeled Z? Draw arrowtails in Fig. 5.9a to indicate these currents.
5. Look again at the four arrowtails passing through the round bulb in Fig. 5.9a. Note that, shortly AFTER passing through the round bulb, these arrowtails MUST CHOOSE to go through EITHER Bulb L1 or L2. Observe the brightnesses of those long bulbs RELATIVE TO EACH OTHER. Given that FOUR arrowtails have to choose, it looks as though HOW MANY choose L1? And HOW MANY choose L2? Draw arrowtails next to Bulbs L1 and L2 in Fig. 5.9a to indicate your answers.
6. As you follow and keep track of your current arrowtails around the circuit, draw into Fig. 5.9a the number of arrowtails you think pass through the wire at Point X. Do the same for Point Y.

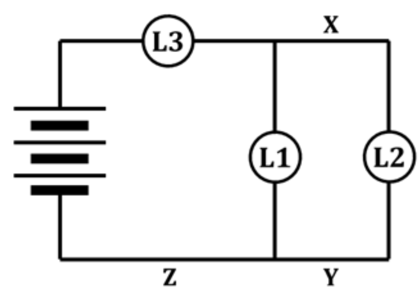

Fig. 5.9c

7. Now change out the round bulb for yet another long bulb, as shown in Fig. 5.9c.
8. Does this circuit have MORE or LESS resistance than that in Fig. 5.9a, given that the ONLY difference between the two is that a round bulb has been replaced with L3?
9. Draw STARBURSTS in Fig. 5.9c to indicate bulb brightness. Make your starbursts correlate to the ones you drew in Fig. 5.9a, i.e., if bulbs are brighter, then show MORE starbursts, etc.
10. Now, let's say there are TWO arrowtails of current passing through L3. Based on this and the brightness of L1 and L2, draw arrowtails THROUGHOUT the circuit of Fig. 5.9c, as you did before.

Here is another way to rationalize the arrowtails you drew next to L1 and L2 in Fig. 5.9c.

11. How does the PRESSURE DIFFERENCE across L1 compare to that across L2? (HINT: You don't have to color-code, but it helps to think, "But if I DID color-code…")
12. How does the RESISTANCE of L1 compare to that of L2?
13. Explain how your answers to Q11 and Q12 further support your L1- and L2-arrowtails in Fig. 5.9c.

14. In short, our work here suggests that, if the parallel branches have EQUAL resistances, the current entering the branch will divide HOW?

Now we are going to make observations with regard to current dividing if the parallel branches have UNEQUAL resistances.

12. Modify the circuit you've been working with so that it looks like Fig. 5.9d.

13. Based on the bulb brightnesses you observe, draw starbursts around the bulbs in Fig. 5.9d.

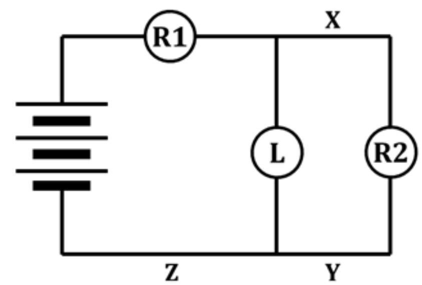

Fig. 5.9d

14. Let's assume that there are FIVE arrowtails of current passing through Bulb R1. Draw those FIVE arrowtails by Bulb R1 in Fig. 5.9d.

15. How much current MUST be going through the battery? How much curent MUST be going through the wire at the point labeled Z? Draw arrowtails in Fig. 5.9d to indicate these currents.

16. Consider the relative brightnesses of Bulbs L and R2 AS WELL AS the TOTAL number of arrowtails in Fig. 5.9d. Decide how many arrowtails should be drawn next to Bulbs L and R2. Then, draw those into Fig. 5.9d. ALSO, draw in arrowtails next to Points X and Y.

17. Discuss with your partner which would be the best "pure" pressure-color for Region X in Fig. 5.9d. What color would that be, and how did you come to that conclusion?

18. Check with your teacher about your answer to Q17, then color-code all of Fig. 5.9d.

19. Now, REMOVE ONE of the batteries and reverse the locations of Bulbs L and R2, so that you have the circuit of Fig. 5.9e.

20. Assuming there are THREE current arrowtails passing through Bulb R1, draw arrowtails throughout the circuit of Fig. 5.9e.

21. Color-code Fig. 5.9e. Again, choose a "pure" color for Region X.

22. Is the "pure" color you chose for Region X the same as what you chose above, in Q17? What caused you to change (or keep) the pressure-color of that region?

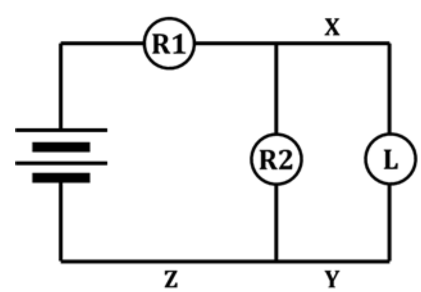

Fig. 5.9e

23. Refer often to Fig. 5.9e to answer these questions. Circle your answers.

Which has the larger pressure difference across it?	R1 R2-and-L	R1 R2-and-L-combo	*Which has the higher resistance?*
Which has the smaller pressure difference across it?	R1 R2-and-L	R1 R2-and-L-combo	*Which has the lower resistance?*

24. To sum up your answers to Q23…

A circuit's TOTAL AVAILABLE PRESSURE DIFFERENCE (red-to-blue, in everything we've done in CASTLE) will be divvied up according to the different resistances of the various parts of a circuit. Portions of a circuit with a HIGH resistance will require a comparatively ______________ pressure difference in order to push charge through them. Portions of a circuit with a LOW resistance will require a comparatively ______________ pressure difference in order to push charge through them.

25. And to sum up the rest of Activity 5.9…

The total current (i.e., total arrowtails) flowing through a circuit will divide when it reaches a parallel branch. The current will be divided ______________ if the parallel branches have the same resistance. If not, then MORE current will choose the path having the ______________ resistance, and LESS current will choose the path having the ______________ resistance.

SUMMARY EXERCISE

1. Take note of the labels beneath Figs. 1a and 1b, then:

a. Color-code the circuits.
HINT: You will need non-standard, 'tweener' colors in Fig. 1b.

b. Draw starbursts on the bulbs.

c. Draw arrowtails next to the bulbs and battery.

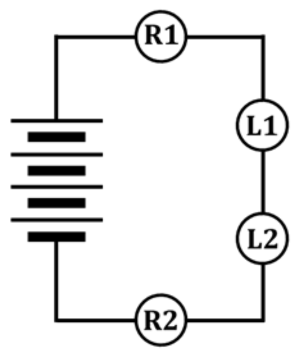

Fig. 1a
first moment of connection

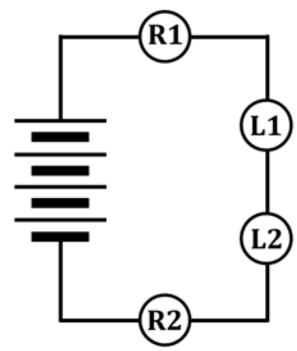

Fig. 1b
steady state

2. Take note of the labels beneath Figs. 2a and 2b, then:

a. Color-code the circuits.
HINT: You will need non-standard, 'tweener' colors in Fig. 2b.

b. Draw starbursts on the bulbs.

c. Draw arrowtails next to the bulbs and battery.

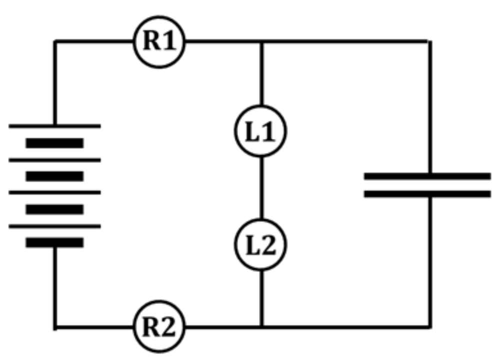

Fig. 2a
first moment of connection

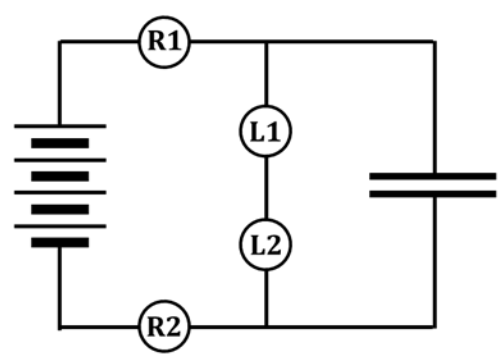

Fig. 2b
steady state

3. Explain why the circuit of Fig. 2 takes so much more time to reach steady state than that of Fig. 1.

4a. How does the <u>net resistance</u> (or <u>total resistance</u>, or <u>equivalent resistance</u>) of a SERIES COMBINATION compare to the resistance of any single resistor in that combination?

4b. How does the <u>net resistance</u> (or <u>total resistance</u>, or <u>equivalent resistance</u>) of a PARALLEL COMBINATION compare to the resistance of any single resistor in that combination?

5. How does the current in a parallel circuit divide:

   a. ...if all branches of the circuit have the same resistance?

   b. ...if different branches of the circuit have different resistances?

6. On Figures 6a and 6b, color-code the circuits.

   ALSO, draw starbursts around the bulbs AND arrowtails throughout the circuits.

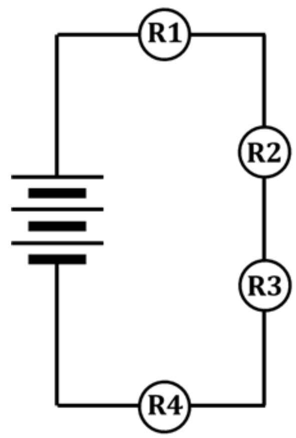

Fig. 6a
first moment
of connection

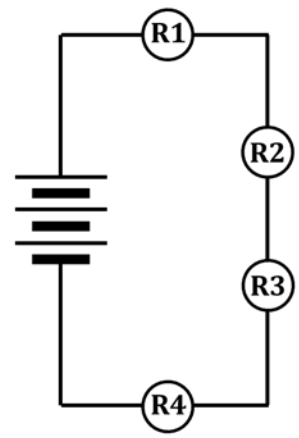

Fig. 6b
steady state

7. On Figures 7a and 7b, color-code the circuits.

   ALSO, draw starbursts around the bulbs AND arrowtails throughout the circuits.

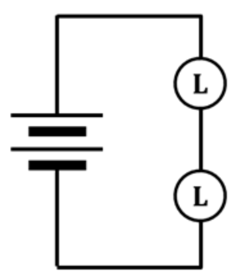

Fig. 7a

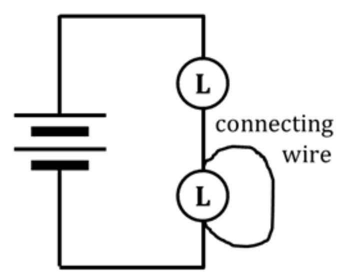

Fig. 7b

8. On Figures 8a and 8b, color-code the circuits.
   Use pure colors.
   ALSO, draw starbursts around the bulbs AND arrowtails throughout the circuits.

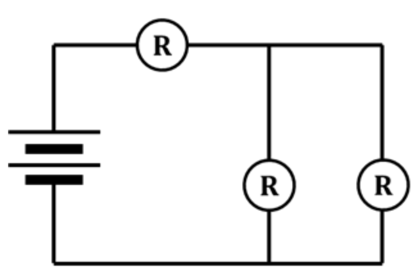

Fig. 8a

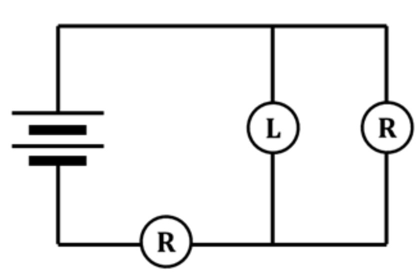

Fig. 8b