Contents

Chapter 1

Introduction

This chapter had no questions.

Part I

Basic Concepts

Chapter 2

Dealing with Units

1. **Question:** How many nanometers is 23 meters?

   Solution: $23,000,000,000$ meters

   Explanation: To convert from basic units to a prefixed unit, you divide by the conversion factor in Figure 2.2.

   $$23 \div 0.000000001 = 23,000,000,000$$

2. **Question:** How many seconds is 23.7 microseconds?

   Solution: 0.0000237 microseconds

   Explanation: To convert from prefixed units to a basic unit, you multiply by the conversion factor in Figure 2.2.

   $$23.7 * 0.000001 = 0.0000237$$

3. **Question:** How many grams is 89.43 megagrams?

   Solution: $89,430,000$ grams

   Explanation: To convert from prefixed units to a basic unit, you multiply by the conversion factor in Figure 2.2.

   $$89.43 * 1,000,000 = 89,430,000$$

4. **Question:** How many meters is 15 nanometers?

   Solution: 0.000000015 meters

   Explanation: To convert from prefixed units to a basic unit, you multiply by the conversion factor in Figure 2.2.

   $$15 * 0.000000001 = 0.000000015$$

5. **Question:** How many kilograms is 0.3 micrograms?

   Solution: 0.0000000003 kilograms

   Explanation: To convert from one prefixed unit to another prefixed unit, first convert to a basic unit, then convert to the other prefix. So, to convert from micrograms to grams, we multiply by the conversion factor in Figure 2.2.

   $$0.3 * 0.000001 = 0.0000003$$

   Then, to convert from the basic unit to a prefixed unit (kilograms in this case), we divide by the conversion factor in Figure 2.2.

   $$0.0000003 \div 1,000 = 0.0000000003$$

6. **Question:** How many milliseconds is 45 kiloseconds?

   Solution: $45,000,000$ milliseconds

   Explanation: To convert from one prefixed unit to another prefixed unit, first convert to a basic unit, then convert to the other prefix. So, to convert from milliseconds to seconds, we multiply by the conversion factor in Figure 2.2.

   $$45 * 1,000 = 45,000$$

   Then, to convert from the basic unit (seconds) to the prefixed unit (milliseconds), we divide by the conversion factor in Figure 2.2.

   $$45,000 \div 0.001 = 45,000,000$$

7. **Question:** What is the abbreviation for picoseconds?

   Solution: ps

   Explanation: Abbreviations are taken from combining the abbreviation for the prefix (Figure 2.2) with the abbreviation for the unit (Figure 2.1).

   Question: What is the abbreviation for microgram?

   Solution: µg or ug

8. **Question:** What is the abbreviation for a terameter?

   Solution: Tm

9. **Question:** How many significant figures does the number 476 have?

   Solution: 3

   Explanation: Significant figures are basically the number of digits in a number.

10. **Question:** How many significant figures does the number 5 have?

    Solution: 1

11. **Question:** How many significant figures does the number 000352 have?

    Solution: 3

    Explanation: Leading zeroes do not count in significant figures.

12. **Question:** How many significant figures does the number 0.00043 have?

    Solution: 2

    Explanation: Leading zeroes do not count in significant figures, even if they are to the right of the decimal.

13. **Question:** How many significant figures does the number 1.0004 have?

    Solution: 5

    Explanation: In this case, since there is a 1 at the front, none of the zeroes are leading zeroes.

14. **Question:** How many significant figures does the number 2.34000 have?

    Solution: 6

    Explanation: Trailing zeroes are considered to be significant because we assume that if they are reported with that many zeroes then they are measured that accurately.

Calculate the problems below taking into account significant figures.

15. **Question:** What is $23 * 5$?

    Solution: 100

    Explanation: $23 * 5 = 115$. However, the number 5 only has one significant figure. Therefore, using the multiplication rule, the solution should be rounded to one significant figure.

16. **Question:** What is $23 + 0.6$?

    Solution: 24

    Explanation: $23 + 0.6 = 23.6$. However, the addition rule states that we should only use the number of places equivalent to the value with the smallest precision. 23 is only accurate to the ones place, so the result should be rounded to the nearest ones place.

17. **Question:** What is $0.005 * 209$?

    Solution: 1

    Explanation: $0.005 * 209 = 1.045$. 0.005 only has one significant digit, so 1.045 gets rounded to 1.

18. **Question:** What is $0.0023 * 45$?

    Solution: 0.10

    Explanation: $0.0023 * 45 = 0.1035$. Both numbers have two significant digits, so the result will be rounded to two significant digits, 0.10.

19. **Question:** What is $0.5 + 0.5$?

    Solution: 1.0

    Explanation: Using addition rules, after the addition is performed the result is rounded to the least precise value in the list. Since both are precise to one digit after the decimal point, the result is rounded to one digit after the decimal point.

20. **Question:** Why are significant figures important?

    Solution: Significant figures make sure that you communicate the precision of your result in a way that matches the precision of your inputs.

Chapter 3

What is Electricity?

1. **Question:** If I have 56 milliamps of current flowing, how many amps of current do I have flowing?

   Solution: 0.056 A

   Explanation: A milliamp is 0.001 A, so, to convert, we multiply milliamps by 0.001.

   $$0.001 \frac{\mathrm{A}}{\mathrm{mA}} * 56\,\mathrm{mA} = 0.056\,\mathrm{A}$$

2. **Question:** If I have 1,450 milliamps of current flowing, how many amps of current do I have flowing?

   Solution: 1.45 A

   Explanation: A milliamp is 0.001 A, so, to convert, we multiply milliamps by 0.001.

   $$0.001 \frac{\mathrm{A}}{\mathrm{mA}} * 1450\,\mathrm{mA} = 1.45\,\mathrm{A}$$

3. **Question:** If I have 12 amps of current flowing, how many milliamps of current do I have flowing?

   Solution: $12,000\,\mathrm{mA}$

   Explanation: There are $1,000$ milliamps in each amp. So, to convert, we multiplay amps by $1,000$.

   $$1,000 \frac{\mathrm{mA}}{\mathrm{A}} * 12\,\mathrm{A} = 12,000\,\mathrm{mA}$$

4. **Question:** If I have 0.013 amps of current flowing, how many milliamps of current do I have flowing?

   Explanation: There are $1,000$ milliamps in each amp. So, to convert, we multiplay amps by $1,000$.

   $$1,000 \frac{\mathrm{mA}}{\mathrm{A}} * 0.013\,\mathrm{A} = 13\,\mathrm{mA}$$

5. **Question:** If I have 125 milliamps of current flowing for one hour, how many coulombs of charge have I used up?

   Solution: 450 coulombs

   Explanation: An amp is a flow of 1 coulomb per second. First we have to convert milliamps to amps:

   $$0.001 \frac{\mathrm{A}}{\mathrm{mA}} * 125\,\mathrm{mA} = 0.125\,\mathrm{A}$$

   Because an amp is 1 coulomb per second, this is equal to $0.125 \frac{\text{coulomb}}{\text{seconds}}$. Since it is flowing for an hour, we have to convert hours into seconds.

   $$1 \text{ hour} * \frac{60 \text{ min}}{\text{hour}} * \frac{60 \text{ seconds}}{\text{minute}} = 3,600 \text{ seconds}$$

   So, we have 0.125 coulombs per second for $3,600$ seconds. So the total number of coulombs is:

   $$3,600 \frac{\text{coulombs}}{\text{second}} * 0.125 \text{ seconds} = 450 \text{ coulombs}$$

6. **Question:** What is the difference between AC and DC current?

   Solution: AC stands for "alternative current." In AC current moves back and forth, continually changing the direction that it is moving. DC stands for "direct current." In DC current moves in essentially one direction.

7. **Question:** In AC mains current, how often does the direction of current go back and forth?

   Solution: The direction of current goes back and forth $50--60$ times per second.

8. **Question:** Why is AC used instead of DC to deliver electricity within a city?

   Solution: There is much less loss over large distances using AC

9. **Question:** In working with electronic devices, do we normally work in amps or milliamps?

   Solution: With small electronic devices, we usually measure our currents in milliamps.

Chapter 4

Voltage and Resistance

1. **Question:** If I have a 4-volt battery, how many volts are between the positive and negative terminals of this battery?

   Solution: 4 V

   Explanation: The definition of a battery's voltage is the number of volts between the positive and negative terminals.

2. **Question:** If I choose the *negative* terminal of this battery as my ground, how many volts are at the *negative* terminal?

   Solution: 0 V

   Explanation: Because volts are relative units, a point must be chosen as the "zero-volt" level. This is known as the ground. Therefore, if the negative terminal is the ground, it is, by definition, zero volts.

3. **Question:** If I choose the *negative* terminal of this battery as my ground, how many volts are at the *positive* terminal?

   Solution: 4 V

   Explanation: On a 4 V battery, the positive terminal is by definition 4 volts above the negative terminal. If the negative terminal is the ground (i.e., the zero point), then 4 volts above that will be 4 V.

4. **Question:** If I choose the *positive* terminal of this battery as my ground, how many volts are at the *negative* terminal?

   Solution: −4 V

   Explanation: On a 4 V battery, the positive terminal is by definition 4 volts above the negative terminal. If the positive terminal is the ground (i.e., the zero point), then that is 4 volts above the negative terminal. That must mean that the negative terminal is 4 volts below zero, or −4 V.

5. **Question:** If I have a Point A on my circuit that is 7 volts above ground and I have a Point B on my circuit that is 2 volts above ground, what is the voltage difference between Point A and Point B?

   Solution: 5 V

   Explanation: Since we know the voltage differences of the two points above ground, then we can subtract them to find the voltage difference between them, yielding $7 - 2 = 5$.

6. **Question:** Given a constant voltage, what effect does increasing the resistance have on current?

   Solution: The current will decrease.

   Explanation: Because $V = I * R$, with constant voltage increasing the resistance will reduce the current.

7. **Question:** Given a constant current, what effect does increasing the resistance have on voltage?

   Solution: The voltage will increase.

   Explanation: Because $V = I * R$, if the current is kept constant, increasing the resistance will increase the voltage.

8. **Question:** If I have a 10 V battery, how much resistance would I need to have a current flow of 10 amps?

Solution: $1\,\Omega$

Explanation: Because we are looking for resistance, we can use Equation 4.3.

$$\begin{aligned} R &= V/I \\ &= 10/10 \\ &= 1 \end{aligned}$$

We would need $1\,\Omega$ of resistance.

9. **Question:** If I have a 3-volt battery, how much resistance would I need to have a current flow of 15 amps?

   Solution: $0.2\,\Omega$

   Explanation: We can use Equation 4.3 to find how much resistance we need:

$$\begin{aligned} R &= V/I \\ &= 3/15 \\ &= 0.2 \end{aligned}$$

   We would need a $0.2\,\Omega$ resistance.

10. **Question:** Given 4 amps of current flow across 200 ohms of resistance, how much voltage is there in my circuit?

    Solution: $800\,\mathrm{V}$

    Explanation: This can be solved using Equation 4.1:

$$\begin{aligned} V &= I * R \\ &= 4 * 200 \\ &= 800 \end{aligned}$$

    This circuit has 800 volts.

11. **Question:** If I am wanting to limit current flow to 2 amps, how much resistance would I need to add to a 40-volt source?

    Solution: $20\,\Omega$

    Explanation: This problem can be solved using Equation 4.3:

$$\begin{aligned} R &= V/I \\ &= 40/2 \\ &= 20 \end{aligned}$$

    You would need to add $20\,\Omega$ of resistance to that source to limit the current flow.

12. **Question:** If I am wanting to limit current flow to 2 milliamps, how much resistance would I need to add to a 9-volt source?

    Solution: $4,500\,\Omega$

    Explanation: Since Ohm's law only works for amps, we need to first convert milliamps to amps:

$$0.001 \frac{\mathrm{A}}{\mathrm{mA}} * 2\,\mathrm{mA} = 0.002\,\mathrm{A}$$

    Now we can use Equation 4.3 to find the resistance we need:

$$\begin{aligned} R &= V/I \\ &= 9/0.002 \\ &= 4500 \end{aligned}$$

    We would need to add 4500 ohms of resistance to this source to limit the current flow.

13. **Question:** If I am wanting to limit current flow to 20 milliamps, how much resistance would I need to add to a 5-volt source?

    Solution: $250\,\Omega$

    Explanation: Since Ohm's law only works for amps, we need to first convert milliamps to amps:

$$0.001 \frac{\mathrm{A}}{\mathrm{mA}} * 20\,\mathrm{mA} = 0.02\,\mathrm{A}$$

    Now we can use Equation 4.3 to find the resistance we need:

$$\begin{aligned} R &= V/I \\ &= 5/0.02 \\ &= 250 \end{aligned}$$

    We need to add 250 ohms of resistance to this voltage source to limit the current.

Chapter 5

Your First Circuit

Special Note - In the problems below, since we have not yet studied LED operation in-depth, we are ignoring the electrical characteristics of the LED and just focusing on the resistor. If you know how to calculate the circuit characteristics using the LED, please ignore it anyway for the purpose of these exercises.

1. **Question:** Calculate the amount of current running in the circuit you built in this chapter using Ohm's law. Since Ohm's law gives the results in amps, convert the value to milliamps.

   Solution: 18 mA

   Explanation: We can use Ohm's Law (Equation 4.2) to find the current running through this circuit:

   $$\begin{aligned} I &= V/R \\ &= 9/500 \\ &= 0.018 \end{aligned}$$

   Therefore, the circuit produces 0.018 A of current. Multiply by 1,000 to get milliamps and we get 18 mA of current.

2. **Question:** Let's say that the minimum amount of current needed for the LED to be visibly on is 1 milliamp. What value of resistor would produce this current?

   Solution: 9,000 Ω

   Explanation: To find this out, we just need to use Ohm's law to find the necessary resistance using Equation 4.3. However, Ohm's law is given in amps, so we need to convert 1 mA to amps. 1 mA = 0.001 A. Therefore, we can calculate the resistor value with the following:

   $$\begin{aligned} R &= V/I \\ &= 9/0.001 \\ &= 9,000 \end{aligned}$$

   We would need 9,000 Ω of resistance to reduce the current to 1 milliamp.

3. **Question:** Let's say that the maximum amount of current the LED can handle is 30 milliamps. What value of resistor would produce this current?

   Solution: 300 Ω

   Explanation: To solve this problem we need to use Ohm's law, but first we need to convert milliamps into amps to do this. 30 mA = 0.03 A. Now we can use Equation 4.3 to solve:

   $$\begin{aligned} R &= V/I \\ &= 9/0.03 \\ &= 300 \end{aligned}$$

   Therefore, a resistor of 300 Ω would produce this current.

4. **Question:** Draw a circuit diagram of a short circuit.

   Solution: This is an open-ended question, so a number of results are possible. For it to be successful, you must be able to trace a path from the positive terminal of the battery to the negative terminal of the battery without going through a resistor.

5. **Question:** Take the circuit drawing in this chapter, and modify it so that it is an open circuit.

   Solution: This is an open-ended question, so a number of results are possible. For it to be successful, you must not be able to trace *any* path from the positive terminal of the battery to the negative terminal of the battery.

6. **Question:** Draw a circuit with just a battery and a resistor. Make up values for both the battery and the resistor and calculate the amount of current flowing through.

   Solution: This is an open-ended question, but the circuit should be neither a short circuit nor an open circuit. Equation 4.2 should be used to calculate the amount of current flowing through the circuit.

Chapter 6

Constructing and Testing Circuits

Note that measured values on a circuit will vary quite a bit because of both the quality of the components and the quality of the multimeter. For measured results, your values should probably be within 20% of the values shown here.

All measured values should be measured using the ranging technique discussed in this chapter.

1. **Question:** Start with the circuit you built in Figure 6.8. Measure the voltage drop across the resistor, then measure the voltage drop across the LED. Now, measure the voltage drop across both of them (put the red multimeter lead on the left side of the resistor and the black multimeter lead on the right side of the LED). Write down your values.

   Solution: The voltage drop across the LED should be around 1.8 V. The voltage drop across the resistor should be around 7.2 V, but will vary with the battery's current voltage (i.e., how new or old it is). However, the voltage drop across both of them should be exactly the two of them added together (around 9 V).

2. **Question:** Using the same circuit, change the LED from red to blue. Measure the values again and write them down. Measure the current going through the circuit using any wire. Is it the same or different than before?

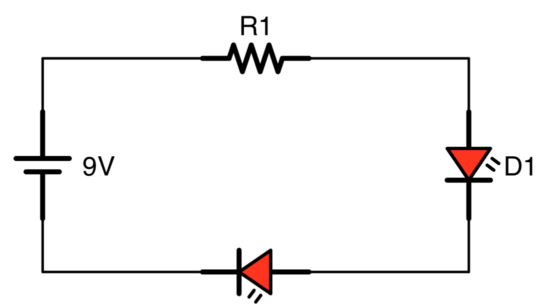
   Solution: With a blue LED, the voltage drop across the LED should be around 3.3 V. The voltage drop across the resistor should be around 5.7 V, and the voltage drop across both of them should be your two results added together. The current should be at 5.7 mA. This should be the case no matter where you test the current.

3. **Question:** Add another LED in series with the one you have already. Measure the voltage drops between each side of each component in the circuit. Measure the current going through any given wire. Write down each value.

   Solution: This will vary with the color of the LED. However, in general, it should drop the voltage another 1.8 – –3.3 volts. It will also reduce the current flowing through the circuit. However, all wires should have the same current going through them.

4. **Question:** Take the new circuit you built in the previous problem and draw the schematic for the circuit.

   Solution: This may vary a little, but should look something like this:



Chapter 7

Analyzing Series and Parallel Circuits

1. **Question:** There is a junction in a circuit that has one wire with current flowing in and two wires with current flowing out. There is 1.25 A of current coming in, and the first wire going out has 0.15 A of current going out. How much current is leaving through the second wire?

   Solution: 1.1 A

   Explanation: The total amount of current leaving must equal the total amount coming in. If we think of the unknown wire as x, we can say that $1.25 = x + 0.15$. Therefore $x = 1.1$ A.

2. **Question:** There is a junction in a circuit that has two wires with current flowing in and two wires with current flowing out. The first wire with current flowing in has 0.35 A of current, the first wire with current flowing out has 0.25 A of current, and the second wire with current flowing out has 0.42 A of current. How much current is flowing in on the second incoming wire?

   Solution: 0.32 A

   Explanation: The total amount of current coming in must equal the total amount leaving. We have two wires coming in and two wires going out. The total going out is $0.25 + 0.42 = 0.67$ A. The total coming in must equal that. We know that one wire has 0.35 A coming in. Since the totals coming in must equal the total going out, we can say that $0.35 + x = 0.67$. Therefore, our unknown wire must be 0.32 A.

3. **Question:** At a junction of four wires, wire 1 has 0.1 A of current flowing in, wire 2 has 0.2 A of current flowing in, and wire 3 has 0.4 A of current flowing out. Is the current in wire 4 going in or out? How much current is flowing on it?

   Solution: The current in wire 4 is going in with 0.1 A of current.

   Explanation: The total amount of current coming in must equal the total amount leaving. Wire 1 and 2 have current coming in. So, we can add them together and find that together they bring $0.1 + 0.2 = 0.3$ A of current coming in. Wire 4 has 0.4 A of current flowing out. Since that is greater than the amount of current coming in, that means the last wire must have current flowing in. The amount is $0.4 - 0.3 = 0.1$ A. Therefore, wire 4 has 0.1 A of current going in.

4. **Question:** If I have three 100 Ω resistors in series, what is the total resistance of the series?

   Solution: 300 Ω

   Explanation: Resistance in series just adds together. So we have $100 + 100 + 100 = 300\,\Omega$ resistance.

5. **Question:** If I have a 10 Ω resistor, a 30 Ω resistor, and a 65 Ω resistor in series, what is the total resistance of the series?

   Solution: 105 Ω

   Explanation: Resistance in series just adds together. So we have $10 + 30 + 65 = 105\,\Omega$ total resistance in this series.

6. **Question:** If I have a 5 Ω resistor and a 7 Ω resistor in series, what is the total resistance of the series?

   Solution: 12 Ω

   Explanation: Resistance in series just adds together. So we have $5 + 7 = 12\,\Omega$ resistance in this series.

7. **Question:** If I have two resistors in parallel, a 30 Ω resistor and a 40 Ω resistor, what is the total resistance

of this circuit?

Solution: 17.14 Ω

Explanation: Equation 7.2 tells us how to add together parallel resistance:

$$\begin{aligned} R_T &= \frac{1}{\frac{1}{30} + \frac{1}{40}} \\ &\approx \frac{1}{0.03333 + 0.025} \\ &\approx \frac{1}{0.05833} \\ &\approx 17.14\,\Omega \end{aligned}$$

8. **Question:** If I have three resistors in parallel—25 Ω, 40 Ω, and 75 Ω, what is the total resistance of this circuit?

Solution: 12.77 Ω

Explanation: Equation 7.2 tells us how to add together parallel resistance:

$$\begin{aligned} R_T &= \frac{1}{\frac{1}{25} + \frac{1}{40} + \frac{1}{75}} \\ &\approx \frac{1}{0.04 + 0.025 + 0.0133} \\ &\approx \frac{1}{0.0783} \qquad \approx 12.77\,\Omega \end{aligned}$$

9. **Question:** If I have four resistors in parallel—1,000 Ω, 800 Ω, 2,000 Ω, and 5,000 Ω, what is the total resistance of this circuit?

Solution: 338.98 Ω

Explanation: Equation 7.2 tells us how to add together parallel resistance:

$$\begin{aligned} R_t &= \frac{1}{\frac{1}{1{,}000} + \frac{1}{800} + \frac{1}{2{,}000} + \frac{1}{5{,}000}} \\ &= \frac{1}{0.001 + 0.00125 + 0.0005 + 0.0002} \\ &= \frac{1}{0.00295} \\ &\approx 338.98\,\Omega \end{aligned}$$

10. **Question:** If I have three resistors in parallel—100 Ω, 5,000 Ω, and 10,000 Ω—what is the total resistance of this circuit? Which of the resistors is the total resistance most similar to?

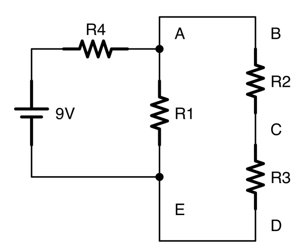
Solution: 97.09 Ω—this is very similar to the 100 Ω resistor.

Explanation: Equation 7.2 tells us how to add together parallel resistance:

$$\begin{aligned} R_T &= \frac{1}{\frac{1}{100} + \frac{1}{5{,}000} + \frac{1}{10{,}000}} \\ &= \frac{1}{0.01 + 0.0002 + 0.0001} \\ &= \frac{1}{0.0103} \\ &\approx 97.09\,\Omega \end{aligned}$$

This is very close to the 100 Ω resistance. Parallel resistance is always lower (even if slightly) than the lowest parallel resistance.

11. **Question:** Take a look at the following circuit diagram. If the voltage drop between B and C is 2 volts, and the voltage drop between C and D is 3 volts, what is the voltage drop between A and E? What is the voltage at E? What is the voltage at A?



Solution: Voltage drop between A and E is 5 V. Voltage at E is 0 V. Voltage at A is 5 V.

Explanation: The voltage starts at 9 V. Every path from the positive of the battery to the ground must take 9 V. Kirchoff's Voltage Law states that every path between every two points must be the same voltage drop. The path from A to E can take two different routes (either through R1 or through both R2 and R3) but they will *both* have the same voltage drop because of Kirchoff's Voltage Law. Therefore, since the drop across R2 is 2 V and the drop across R3 is 3 V, the total drop is $2 + 3 = 5$ V. This is the same no matter what path you travel, so the voltage drop across R1 must also be 5 V.

So the voltage drop from A to E is 5 V.

There is no resistor between E and the ground terminal.

That means that these voltages are the same. Therefore the voltage at E is 0 V.

Because the voltage at E is zero, the voltage at A is 5 V above that, which is 5 V.

12. **Question:** If the circuit above runs with 2 A total current, what is the value of the resistor R4?

    Solution: 2 Ω

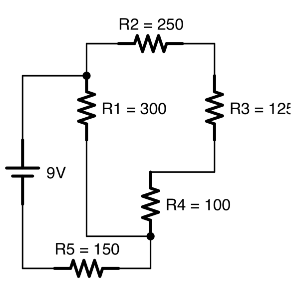
    Explanation: Since we are imagining 2 A coming out of the battery (just to note—it is unrealistic for a battery to supply even 1 A), the entire 2 A will go through resistor R4.

    Now, at the end of R4, we determined that the voltage is 5 V. Since we started with 9 V that means that R4 had to drop us 4 V. We can use Ohm's Law to figure out how much resistance was in that resistor:

$$\begin{aligned} R &= V/I \\ &= 4/2 \\ &= 2\,\Omega \end{aligned}$$

    So, R4 is 2 Ω.

13. **Question:** The circuit below is a combination of series and parallel resistances. Each resistor is labelled with its resistance value, given in ohms. Find out how much current is flowing through each resistor, and how much each resistor drops the voltage.



    Solution:

    R1 4.95 V and 0.0165 A

    R2 2.625 V and 0.0105 A

    R3 1.3125 V and 0.0105 A

    R4 1.05 V and 0.0105 A

    R5 4.05 V and 0.025 A

    Note that these do not exactly add up correctly (because of rounding issues), but that is perfectly normal. If you are within 1% of the right answer, you are most likely more accurate than your equipment supports.

    Explanation: Every circuit like this, no matter how complicated, can be solved by just breaking it down a piece at a time, and solving for each piece as you go. The most straightforward way to solve these is to first add up *all* of the resistances to get a total resistance, and then solve for total current. After that, you can go back through the circuit to find the individual currents and voltages.

    So, the easiest way to start adding up the resistors is to take all of the resistors that are in series, and replace them with a single resistance that is the total of them. Notice that R2, R3, and R4 are all in series with each other with no branches. Therefore, we can replace these resistors with a single resistor that just adds up the resistances. So, that segment has a total resistance of $250 + 125 + 100 = 475\,\Omega$.

    That segment is in parallel with R1. Therefore, we can use the parallel resistance rule to combine these resistances:

$$\begin{aligned} R_T &= \frac{1}{\frac{1}{300} + \frac{1}{475}} \\ &\approx \frac{1}{0.00333 + 0.00211} \\ &\approx \frac{1}{0.00544} \\ &\approx 183.82\,\Omega \end{aligned}$$

    Therefore, the whole top network—R1, R2, R3, and R4—can be replaced by a single resistance, 183.82 Ω. This network is in series with R5. Therefore, we can just add these resistances together: $183.82 + 150 = 333.82\,\Omega$.

    That's the whole resistance of the whole circuit. We know the total voltage drop of the whole circuit, because, by definition, a 9 V battery supplies 9 V to the circuit. Therefore, Ohm's Law will give us the total current:

$$\begin{aligned} I &= V/R \\ &= 9/333.82 \\ &= 0.0270\,\mathrm{A} \end{aligned}$$

    The battery will put out 0.027 A (i.e., 27 mA) of current to this circuit.

    Now we need to figure out currents and voltages to each individual component. R5 is the easiest one to start with because it is directly connected in series with the battery terminal. That means that all of the current will go through this resistor. So this resistor is getting 0.027 A. We can find the voltage drop with Ohm's Law:

$$V = I * R = 0.027 * 150 = 4.05\,\mathrm{V}$$

    So the current through R5 is 0.027 A and the voltage drop is 4.05 V. That means that the voltage drop through the rest of the network is 4.95 V. We can use that to find the currents flowing through here.

The voltage drop across R1 is 4.95 V and the resistance is 300 Ω. Therefore, the current is:

$$I = V/R = 4.95/300 = 0.0165\,\mathrm{A}$$

Therefore, R1 has 0.0165 A flowing through it. Since we started with 0.027 A, that means the rest of the current must be flowing through the other junction. So, the right-hand-side of the network has $0.027 - 0.0165 = 0.0105$ A of current flowing through it. Since R2, R3, and R4 are all in series, that means they all have this same current flowing through them. To find voltages, we just use Ohm's Law:

$$V_{R2} = I * R = 0.0105 * 250 = 2.625\,\mathrm{V}$$
$$V_{R3} = I * R = 0.0105 * 125 = 1.3125\,\mathrm{V}$$
$$V_{R4} = I * R = 0.0105 * 100 = 1.05\,\mathrm{V}$$

Note that this total voltage is actually slightly higher than what we were looking for (these add up to 4.9875 V instead of 4.95 V like we were expecting), but being off on the decimal point is normal when we do as much rounding as we have been.

14. **Question:** Build the circuit in Figure 7.11 on your own breadboard. Measure the voltage drops across every component, and measure the amount of current flowing into the first series resistor.

    Solution: The actual voltage drops will depend on the specific resistor values and colors of your LED. However, in general you should have between 5 and 40 mA flowing through any part of your circuit. Additionally, every complete path from positive to ground should be 9 V (or whatever size battery you are using).

Chapter 8

Diodes and How to Use Them

1. **Question:** If you have a 9 V voltage source, a blue LED, and a 500 Ω resistor all in series, how much current is running through the LED?

   Solution: The current running through the LED is 0.0114 A, or 11.4 mA.

   Explanation: Blue LEDs have a 3.3 V voltage drop. Diode voltage drops are relatively fixed. Therefore, in this circuit, there are $9 - 3.3 = 5.7$ V left to account for. Using Ohm's Law, we can figure out the current based on our resistor:

   $$\begin{aligned} I &= V/R \\ &= 5.7/500 \\ &= 0.0114\,\mathrm{A} \end{aligned}$$

   The current in the circuit is 0.0114 A, or 11.4 mA. Since this is a series circuit, the amount of current going into each junction is the same as the amount going out, so the current is the same throughout the whole circuit. Therefore, this is also the amount of current going through the LED.

2. **Question:** If you have a 3 V voltage source and a red LED, what size resistor do you need to put in series with the LED to have it use 3 mA of current?

   Solution: 400 Ω

   Explanation: A red LED will yield a 1.8 V drop. Therefore, the amount of voltage left to account for is $3 - 1.8 = 1.2$ V. If we want 3 mA of current, we have to first convert that to amps to use Ohm's Law. 3 mA is the same as 0.003 A. Therefore, using Ohm's Law we can see that:

   $$\begin{aligned} R &= V/I \\ &= 1.2/0.003 \\ &= 400\,\Omega \end{aligned}$$

   We would need a 400 Ω resistor to limit the current to 3 mA.

3. **Question:** If you have a 10 V voltage source, a blue LED, a red LED, and a 200 Ω resistor all in series, how much current is running through the LEDs?

   Solution: 24.5 mA

   Explanation: The red LED will yield a 1.8 V drop, the blue LEDD will yield a 3.3 V drop. With a 10 V source, that leaves $10 - 1.8 - 3.3 = 4.9$ V remaining to account for. After that, we can use Ohm's Law to determine how much current the resistor will limit the circuit to:

   $$\begin{aligned} I &= V/R \\ &= 4.9/200 \\ &= 0.0245\,\mathrm{A} \end{aligned}$$

   Therefore, the circuit will have a 0.0245 A current going through it, or 24.5 mA. Since it is a series circuit, that is the same current running through all the components, so the LEDs will have the same amount of current as well.

4. **Question:** If I have a 12 V voltage source, a blue LED, and a red LED, and the LEDs have a maximum current of 30 mA before it breaks and a minimum current of 1 mA before it turns on, what range of resistors can I put in series with the LEDs to get them to light up without breaking?

   Solution: This circuit requires a resistor between 230 Ω and 6, 900 Ω.

   Explanation: This is solved just like the other problems, but we will have to solve the problem twice. We need to know both the resistor value for 1 mA as well as the resistor value for 30 mA. This is very similar to problems encountered in real life, as you will often have a variety of components, and you just need to know the range of which components will work and which ones will break things.

So, first we need to calculate the amount of voltage which will be dropped by the resistors. Since the LEDs have a fixed voltage drop, we can just subtract them from the battery voltage—1.8 V for the red and 3.3 V for the blue. That leaves us with $12 - 1.8 - 3.3 = 6.9$ V remaining.

The LEDs require a minimum of 1 mA (0.001 A) to light up. So let's solve for resistance using that value:

$$\begin{aligned} R &= V/I \\ &= 6.9/0.001 \\ &= 6,900\,\Omega \end{aligned}$$

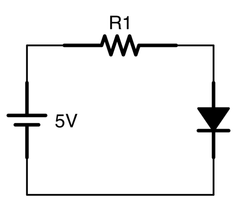
Therefore, the largest resistor we can put in this circuit and have it light up is $6,900\,\Omega$.

On the other end, the maximum current that can flow without harming the LEDs is 30 mA (0.03 A). Therefore, we need to solve for resistance using that value for the current:

$$\begin{aligned} R &= V/I \\ &= 6.9/0.03 \\ &= 230\,\Omega \end{aligned}$$

Therefore, the smallest resistor we can get away with is $230\,\Omega$. That means that we must use a resistor between $230\,\Omega$ and $6,900\,\Omega$.

5. **Question:** In the circuit below, calculate the how much current flowing through each component and each component's voltage drop if R1 is $500\,\Omega$ (note that the diode is just a regular diode, not an LED).



Solution:

R1 4.4 V drop with 8.8 mA current

Diode 0.6 V drop with 8.8 mA current

Explanation: The total voltage drop for the circuit is 5 V because that is the size of the battery. The voltage drop across the diode is fixed at 0.6 V. That means that the remaining voltage is dropped across the resistor, which will be $5 - 0.6 = 4.4$ V. We can use Ohm's Law to find the current flowing across the resistor:

$$\begin{aligned} I &= V/R \\ &= 4.4/500 \\ &= 0.0088\,\mathrm{A} \end{aligned}$$

The current flowing through the resistor is 0.0088 A, which is 8.8 mA. Since the circuit is a series circuit, this is the same current flowing through every component.

6. **Question:** Let's say instead of an ordinary diode, the diode is a blue LED. Recalculate the current going through each component and the voltage drops for each component.

Solution:

R1 1.7 V drop with 3.4 mA current

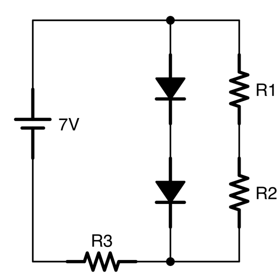
Diode 3.3 V drop with 3.4 mA current

Explanation: With a blue LED, the voltage drop changes from 0.6 V to 3.3 V. This means that there is only $5 - 3.3 = 1.7$ V left to account for in the circuit (thus, dropped by the resistor). Using Ohm's Law, we can calculate the current flowing through the resistor:

$$\begin{aligned} I &= V/R \\ &= 1.7/500 \\ &= 0.0034\,\mathrm{A} \end{aligned}$$

Therefore, the current is 0.0034 A (3.4 mA) through the circuit.

7. **Question:** In the circuit below, calculate how much current is flowing through each component and each component's voltage drop if R1 is $300\,\Omega$, R2 is $400\,\Omega$, and R3 is $500\,\Omega$.



Solution:

Diodes Both diodes each have 0.6 V drop with 9.89 mA current

R1 0.513 V drop with 1.71 mA

R2 0.684 V drop with 1.71 mA

R3 5.8 V drop with 11.6 mA

Explanation: Here the voltage source is 7 V. That means that the total voltage drop along any path from the positive to the negative is 7 V. Additionally, the voltage drop down the center (the two diodes) is fixed at $0.6 + 0.6 = 1.2$ V. That means that both the center and the right side (R1 and R2) both have a 1.2 V drop (because Kirchoff's Voltage law states that all paths must have the same voltage drop, and these paths both begin and end in the same place). So, the remaining part of the circuit is R3, and there are $7 - 1.2 = 5.8$ V left to account for in the circuit. This means the voltage drop across R3 must be 5.8 V.

To calculate the current running through R3 we use Ohm's Law:

$$\begin{aligned} I &= V/R \\ &= 5.8/500 \\ &= 0.0116\,\mathrm{A} \end{aligned}$$

Because all current has to flow through R3 to get back to the negative terminal, this is the total current in the circuit.

Now, to find the current on the right side of the circuit, we can use Ohm's Law again. Since R1 and R2 are in series, their total resistance is $300 + 400 = 700\,\Omega$. So, to find the current:

$$\begin{aligned} I &= 1.2/700 \\ &= 0.00171\,\mathrm{A} \end{aligned}$$

Therefore, the rest of the current has to be flowing through the diodes across the middle:

$$0.0116 - 0.00171 = 0.00989\,\mathrm{A}$$

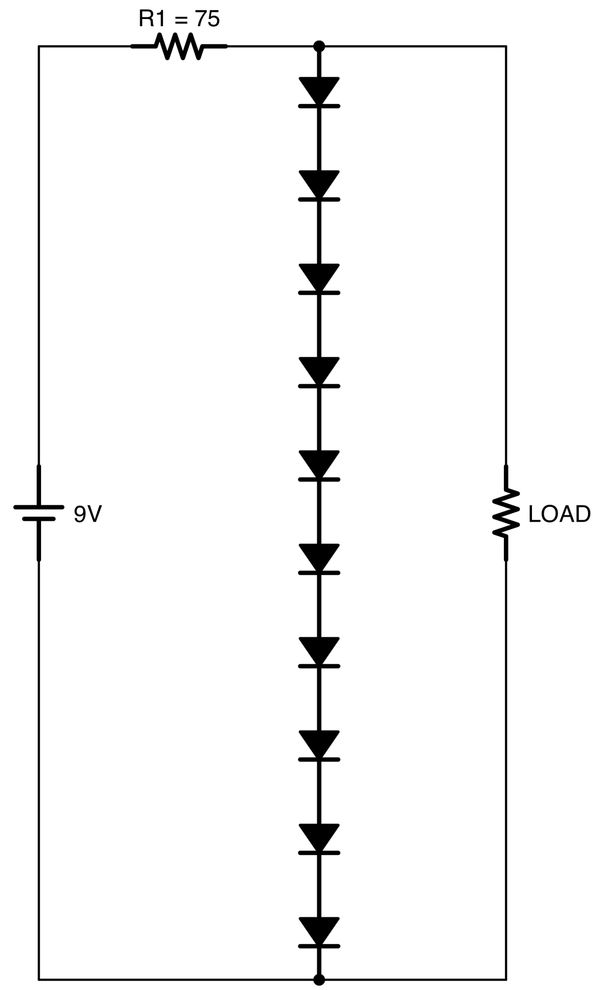
The voltage drop for each resistor can be done with Ohm's Law:

$$\begin{aligned} V_{R1} &= I * R \\ &= 0.00171 * 300 \\ &= 0.513\,\mathrm{V} \\ V_{R2} &= I * R \\ &= 0.00171 * 400 \\ &= 0.684 \end{aligned}$$

This doesn't exactly add up to 1.2 V because of rounding issues.

8. **Question:** Draw a circuit that provides a 6-volt regulated power supply to circuit load from a 9-volt battery using regular diodes. Choose a resistor that works efficiently for a circuit load of 500 Ω and operates with a battery voltage from 7 V to 9.6 V. What is the current at the lowest and highest ranges of the battery? How much is used by the circuit load and how much is wasted through the diodes in each configuration?

Solution: The circuit below utilizes 13.3 mA at the lowest battery level, and 48 mA at the highest. The circuit load will always utilize 12 mA, and the rest of the current will be wasted through the diodes.



Explanation: If the circuit load is 500 Ω with 6 V, then the current supplied can be calculated with Ohm's Law:

$$\begin{aligned} I &= V/R \\ &= 6/500 \\ &= 0.012\,\mathrm{A} \end{aligned}$$

We need this voltage drop to be fixed (that's what the problem states), so we will run diodes in parallel. This will fix the voltage drop across the load. Since each diode drops 0.6 V, we just need to supply 10 diodes in parallel with our load to ensure a 6 V drop.

Now, the battery itself will supply more than 6 V, so we need an additional resistor either before or after the diode drop to mop up the extra voltage. If the resistor is too small, a lot of current will be wasted (and, as we will see in later chapters, could cause the resistor to burn up). If the resistor is too large, then the current will be too low to provide the power needed. There will always bee some wasted current (this current will flow through the diode bridge), but the goal is to keep it to a minimum.

If we decided to allow a 1 mA current go through the bridge at the lowest battery voltage (this is somewhat arbitrary, but 1 mA is a workable amount of waste current), then we can calculate the resistor we need using Ohm's law. We said that the lowest battery setting we would consider is 7 V, which leaves 1 V left over.

Since the current that needs to flow through the circuit is 0.012 A, and we want a 1 mA (0.001 A) headroom, that means that the current going through the resistor will be 0.013 A. So the resistor will be:

$$\begin{aligned} R &= V/I \\ &= 1/0.013 \\ &= 76.92 \end{aligned}$$

$$myohm$$

You might round this down to whatever value of resistor you have (you want to round down because rounding up could limit the current too much). I have a 75 Ω resistor in my collection, so we will work with that.

So, with a 75 Ω resistor, we can calculate the current flowing at each configuration—the battery at 7 V and at 9.6 V. Since the circuit load is fixed at 6 V, that means that the current flowing through the resistor will be $7-6 = 1$ V and $9.6 - 6 = 3.6$ V, respectively.

So, the current at 6 V is:

$$\begin{aligned} I &= V/R \\ &= 1/75 \\ &= 0.0133\,\text{A} = 13.3\,\text{mA} \end{aligned}$$

Since the circuit is using 12 mA this circuit wastes 1.3 mA.

At 9.6 V the current will be:

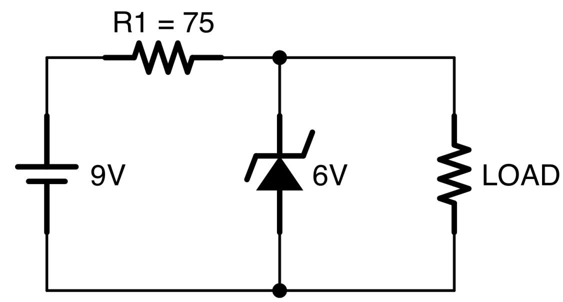
$$\begin{aligned} I &= V/R \\ &= 3.6/75 \\ &= 0.048\,\text{A} = 48\,\text{mA} \end{aligned}$$

Since the circuit uses 12 mA, this circuit wastes 36 mA.

Your circuit design may be slightly different based on how much current you were willing to waste, but the important part is to calculate that the load will need 12 mA, to figure out a "reasonable" resistor value, and to calculate how much current is wasted in each battery level.

9. **Question:** Draw an equivalent circuit to the previous question using a Zener diode instead of normal diodes.

   Solution:



   Explanation: This is the same circuit, but with the individual diodes replaced with a single Zener diode of the proper voltage. Because we use the breakdown voltage of the Zener rather than the forward voltage drop, it is wired "backwards" in the circuit.

Chapter 9

Basic Resistor Circuit Patterns

1. **Question:** In Figure 9.3, calculate the amount of current used by the whole circuit for each configuration of the switches S2 and S3 when S1 is closed. You can assume that the LEDs are red LEDs.

   Solution:

   S2 closed 9 mA

   S3 closed 4.5 mA

   Both closed 13.5 mA

   Explanation: Because these circuit branches are in parallel, the total current is the sum of the individual currents. Because both branches connect to both positive and negative without going through resistance, then they each start at 9 V and connect to ground, so they each use a full 9 V. Therefore, we can use Ohm's Law to calculate the amount of current going through each branch:

$$\begin{aligned} I_{S2} &= V/R \\ &= 9/1000 \\ &= 0.009\,\mathrm{A} = 9\,\mathrm{mA} \\ I_{S3} &= V/R \\ &= 9/2000 \\ &= 0.0045\,\mathrm{A} = 4.5\,\mathrm{mA} \end{aligned}$$

   Therefore, when S2 is closed, that branch uses 9 mA of current, and when S3 is closed that branch uses 4.5 mA of current. Since they are in parallel and both connected on both sides to the battery, when they are closed they both use $9 + 4.5 = 13.5$ mA of current.

2. **Question:** Build the circuit given in Figure 9.3 (you may swap out resistors with different but similar values—anything from 300 Ω to about 5 kΩ should work).

   Solution: Since this is a building exercise, the question is whether or not it works correctly.

3. **Question:** Given a 15 V voltage supply, what size of a resistor would be needed to make sure that a circuit never went over 18 mA.

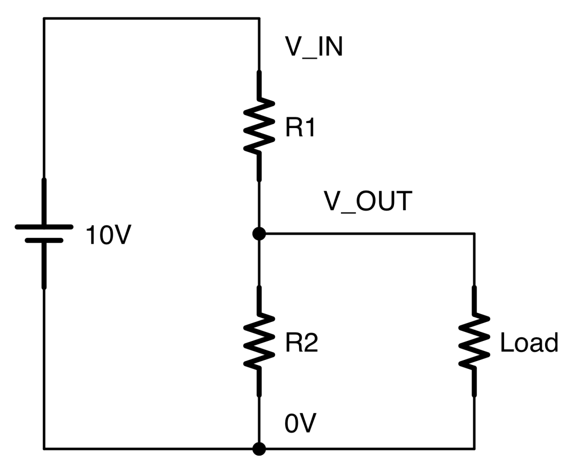
   Solution: 833.33 Ω

   Explanation: This can be figured out using Ohm's Law. We simply figure out the resistance needed for 18 mA (0.018 A).

$$\begin{aligned} R &= V/I \\ &= 15/0.018 \\ &= 833.33\,\Omega \end{aligned}$$

4. **Question:** Given a 9 V battery source, design a voltage divider that will output 7 V to a load that has a resistance of 10 kΩ.

   Solution: The general voltage divider circuit can be seen here:



To achieve the required design, we need R_1 to be $428.57\,\Omega$ and R_2 to be $1,000\,\Omega$.

Explanation: To create a voltage divider, we have to divide voltages between two resistors, with the output going out from between them. Equation 9.1 shows us what the calculation looks like:

$$V_{OUT} = V_{IN} * \frac{R_2}{R_1 + R_2}$$

Now, this equation only tells us about the ratio of the resistors, not what their specific value is. For an equation for specific values for the resistors, we need to look at Equations 9.2 and 9.3. Equation 9.2 says:

$$\begin{aligned} R_2 &= R_L/10 \\ &= 10,000/10 \\ &= 1,000\,\Omega \end{aligned}$$

Equation 9.3 says:

$$\begin{aligned} R_1 &= \frac{R_2 * (V_{IN} - V_{OUT})}{V_{OUT}} \\ &= \frac{1,000 * (10 - 7)}{10} \\ &= \frac{3,000}{7} \\ &= 428.57\,\Omega \end{aligned}$$

Therefore, R_1 needs to be about $428.57\,\Omega$ and R_2 needs to be about $1,000\,\Omega$. In reality, we would probably find a resistor that is close to $429\,\Omega$ even if it isn't exact. Even a $400\,\Omega$ resistor would give a voltage within a few percent of the desired value.

5. **Question:** Given a 3 V battery source, design a voltage divider that will output 1.5 V to a load that has a resistance of $1\,\mathrm{k}\Omega$.

   Solution: For this voltage divider, both R_1 and R_2 will be $100\,\Omega$.

   Explanation: Using the same equations as before, we can easily design a voltage divider. R_2 is determined by:

$$\begin{aligned} R_2 &= R_L/10 \\ &= 1,000/10 \\ &= 100\,\Omega \end{aligned}$$

   R_1 is determined by:

$$\begin{aligned} R_1 &= \frac{R_2 * (V_{IN} - V_{OUT})}{V_{OUT}} \\ &= \frac{100 * (3 - 1.5)}{1.5} \\ &= \frac{150}{1.5} \\ &= 100\,\Omega \end{aligned}$$

   Therefore, both R_1 and R_2 will be $100\,\Omega$.

6. **Question:** In Figure 9.6, how much current is going through the circuit when the switch is open? How much when it is closed? You can assume that the LED is a red LED.

   Solution: The circuit uses 7.2 mA of current when the switch is open and 9 mA when the switch is closed.

   Explanation: When the switch is open, the current passes through *both* the resistor and the LED. Therefore, we have to account for the voltage drop of the LED itself as well as the resistance. The starting voltage is 9 V and a red LED will give a voltage drop of 1.8 V. Therefore, the remaining voltage through the resistor will be $9 - 1.8 = 7.2$ V. Using Ohm's Law, we can find out the current flow:

$$\begin{aligned} I &= V/R \\ &= 7.2/1,000 \\ &= 0.0072\,\mathrm{A} = 7.2\,\mathrm{mA} \end{aligned}$$

   Therefore, when the switch is open, the circuit consumes 7.2 mA. When it is closed, the current does *not* flow through the LED. The reason is that since there is a direct connection between the resistor and the ground, then the resistor *must* be at a zero-volt state at the end of it. Therefore, there is no voltage remaining to push through the LED.

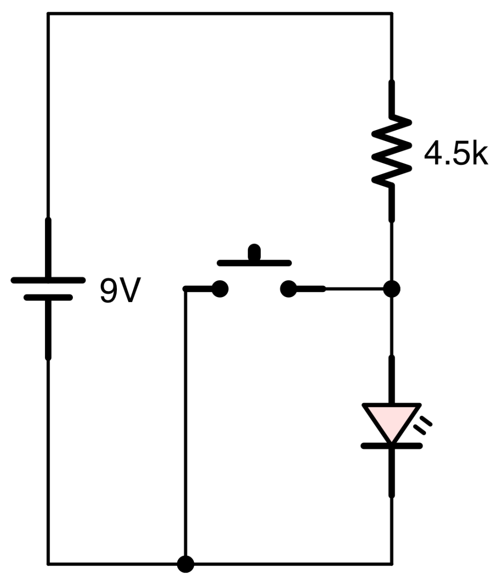
   Therefore, the entire 9 V is flowing across the resistor. This means that the calculation for Ohm's Law is as follows:

$$\begin{aligned} I &= V/R \\ &= 9/1,000 \\ &= 0.009\,\mathrm{A} = 9\,\mathrm{mA} \end{aligned}$$

   Therefore, when the switch is closed, the circuit uses 9 mA of current.

7. **Question:** How would you modify the circuit in Figure 9.6 to keep the maximum current in the circuit under 2 mA? Draw the full circuit out yourself.

   Solution: The full circuit should look like the below drawing:



Explanation: As we saw in the previous question, the circuit actually uses *more* current when the switch is closed than when it is open. Therefore, if we want to max sure the current never goes over 2 mA (0.002 mA), then we should design for that when the circuit is closed. Therefore, using Ohm's Law, we can solve for the needed resistance like this:

$$\begin{aligned} R &= V/I \\ &= 9/0.002 \\ &= 4,500\,\Omega \end{aligned}$$

The drawn circuit should be identical to Figure 9.6 but with a $4,500\,\Omega$ resistor.

8. **Question:** Build the circuit you designed in the previous question. If you do not have the right resistor values, use the closest ones you have.

   Solution: This is a project-building exercise. The solution is correct if pushing the button turns off the light. The one potential problem is if pushing the button creates a short circuit. If this happens the project will get hot quickly.

Chapter 10

Understanding Power

1. **Question:** If I have 50 joules of energy, what is the maximum amount of work I could possibly do with that amount of energy?

   Solution: 50 joules of work

   Explanation: You cannot do more work than you have energy, therefore, with 50 joules of energy you cannot do more than 50 joules of work. Likely you can do much less.

2. **Question:** If I am using up 10 joules of energy each second, how many watts am I using up?

   Solution: 10 W

   Explanation: Since a watt *means* a joule of energy each second, 10 joules per second is the same as 10 watts.

3. **Question:** If I convert 30 watts of mechanical power into electrical power with 50% efficiency, how many watts of electrical power are delivered?

   Solution: 15 W

   Explanation: The units of power are the same for both (watts), and, since there is only a 50% efficiency, that means that we only retain half (50%) of the power. Half of 30 is 15.

4. **Question:** If I have a circuit powered by a 9 V battery that uses 0.125 A, how many watts does that circuit use?

   Solution: 1.125 W

   Explanation: Power is voltage multiplied by current. Therefore:

$$\begin{aligned} P &= V * I \\ &= 9 * 0.125 \\ &= 1.125\,\mathrm{W} \end{aligned}$$

5. **Question:** If a resistor has a 2 V drop with a 0.03 A current, how much power is the resistor dissipating?

   Solution: 0.06 W or 60 mW

   Explanation: The amount of power consumed (and therefore dissipated) by the resistor is given by:

$$\begin{aligned} P &= V * I \\ &= 2 * 0.03 \\ &= 0.06\,\mathrm{W} = 60\,\mathrm{mW} \end{aligned}$$

6. **Question:** If a resistor has a 3 V drop with a 12 mA current, how much power is the resistor dissipating?

   Solution: 0.036 W or 36 mW

   Explanation: To solve, first we have to convert 12 mA to 0.012 A. Then we just use the power equation:

$$\begin{aligned} P &= V * I \\ &= 3 * 0.012 \\ &= 0.036\,\mathrm{W} = 36\,\mathrm{mW} \end{aligned}$$

7. **Question:** If a 700 Ω resistor has a 5 V drop, how much power is the resistor dissipating?

Solution: 0.0357 W or 35.7 mW

Explanation: Since we are given the voltage and the resistance, we can use Equation 10.5 to solve:

$$\begin{aligned} P &= V^2/R \\ &= 5^2/700 \\ &= 25/700 \\ &= 0.0357\,\mathrm{W} = 35.7\,\mathrm{mW} \end{aligned}$$

Therefore, this resistor is dissipating 35.7 mW.

8. **Question:** If a 500 Ω resistor has 20 mA flowing through it, how much power is the resistor dissipating? If the resistor was rated for 1/8 of a watt, are we within the rated usage for the resistor?

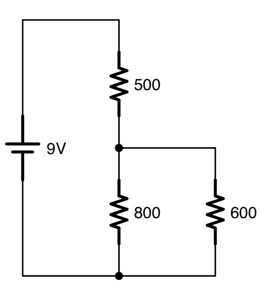
   Solution: The resistor is dissipating 0.2 W. 1/8 of a watt is 0.125 W. Therefore, this resistor is being used beyond its rated usage, which is hazardous.

   Explanation: Since we are given resistance and current, we can use Equation 10.4:

$$\begin{aligned} P &= I^2 * R \\ &= 0.02^2 * 500 \\ &= 0.0004 * 500 \\ &= 0.2\,\mathrm{W} \end{aligned}$$

   Now, is this above or below 1/8 of a watt? 1/8 = 0.125. Also, 0.2 > 0.125. Therefore, we have exceeded the power rating for this resistor, which is a hazardous situation, and can actually cause the resistor to catch fire if left in that state for too long.

9. **Question:** In the circuit below, calculate the voltage drop, current, and power dissipation of every component (except the battery). If the resistors are all rated for 1/8 of a watt, are any of the resistors out of spec?



   Solution:

   500 Ω resistor 5.35 V voltage drop, 0.0107 A current, 0.0572 W power dissipation

   800 Ω resistor 3.65 V voltage drop, 0.00456 A current, 0.0155 W power dissipation

   600 Ω resistor 3.65 V voltage drop, 0.00608 A current, 0.0222 W power disspiation

   All power dissipations were less than 1/8 of a watt (0.125 W), so all of the resistors are within specification.

   Explanation: To solve this, first we need to solve for all of the voltage drops and currents along each segment of the circuit. We can start by adding up the parallel resistances at the bottom of the circuit:

$$\begin{aligned} R_T &= \frac{1}{\frac{1}{800} + \frac{1}{600}} \\ &\approx \frac{1}{0.002917} \\ &\approx 342.82\,\Omega \end{aligned}$$

   Now, those parallel resistances together are in series with the 500 Ω resistor at the top of the circuit. Therefore they can be added together to get 342.82+500 = 842.82 Ω total resistance.

   To calculate the total current, we just use Ohm's Law:

$$\begin{aligned} I &= V/R \\ &= 9/842.82 \\ &= 0.0107\,\mathrm{A} \end{aligned}$$

   We can use this value to calculate the voltage drop of the first resistor:

$$\begin{aligned} V &= I * R \\ &= 0.0107 * 500 \\ &= 5.35\,\mathrm{V} \end{aligned}$$

   Therefore, the parallel circuit drops the rest: 9 − 5.35 = 3.65 V. The current on the 800 Ω resistor is:

$$\begin{aligned} I &= V/R \\ &= 3.65/800 \\ &= 0.00456\,\mathrm{A} \end{aligned}$$

   The current on the 600 Ω resistor is:

$$\begin{aligned} I &= V/R \\ &= 3.65/600 \\ &= 0.00608\,\mathrm{A} \end{aligned}$$

   Now the power for each resistor is simply voltage times current. For the 500 Ω resistor:

$$P = 5.35 * 0.0107 = 0.0572\,\mathrm{W}$$

For the $800\,\Omega$ resistor:

$$P = 3.65 * 0.00456 = 0.0166\,\mathrm{W}$$

For the $600\,\Omega$ resistor:

$$P = 3.65 * 0.00608 = 0.0222\,\mathrm{W}$$

All of these power dissipations are less than 1/8 of a watt (0.125 W), so they are all within spec.

Chapter 11

Integrated Circuits and Resistive Sensors

1. **Question:** Calculate the amount of current flowing through each element of the circuit in Figure 11.5. You can presume that the LM393 uses about 1 mA for its own (internal) operation, and that the LED is a red, 1.8 V LED. What is the total amount of current used by the circuit?

   Solution: 9.4 mA

   Explanation: Let's start by analyzing the voltage divider created by R1 and R2. It connects directly to the positive and ground on the battery, so we know the total voltage across the divider (9 V). The operation of the LM393 utilizes negligible amounts of current, so we can ignore the amount of current coming out of the voltage divider to the LM393. The resistors are in series, so their resistance adds up to $1,000 + 1,000 = 2,000\,\Omega$. Therefore, we can find the current with Ohm's Law:

   $$\begin{aligned} I &= V/R \\ &= 5/2,000 \\ &= 0.0025\,\text{A} = 2.5\,\text{mA} \end{aligned}$$

   The second voltage divider is similar, but has a total resistance of $2,000 + 4,000 = 6,000\,\Omega$. Therefore, the current going across this voltage divider is:

   $$\begin{aligned} I &= V/R \\ &= 5/6,000 \\ &= 0.00083\,\text{A} = 0.83\,\text{mA} \end{aligned}$$

   The voltage coming into `1IN+` is greater than the voltage coming into `1IN-`, so that means that the LM393 output is positive. When the output is positive, it actually disconnects (when it is negative, `1OUT` connects to directly to ground). Therefore, no current flows into `1OUT`.

   This allows all of the current to flow through the LED. The LED utilizes 1.8 V, leaving $5 - 1.8 = 3.2$ V remaining for the resistor. The resistor is $2,000\,\Omega$, so the current flowing through this part of the circuit is:

   $$\begin{aligned} I &= V/R \\ &= 3.2/2,000 \\ &= 0.0016\,\text{A} = 1.6\,\text{mA} \end{aligned}$$

   Therefore, the first voltage divider is using 2.5 mA, the second voltage divider is using 0.83 mA, the LED circuit is using 1.6 mA, and the internal operation of the LM393 uses 1 mA (per the problem statement). Therefore, the total current used by this circuit is $2.5 + 0.83 + 1.6 + 1 = 5.93$ mA.

2. **Question:** Take the circuit in Figure 11.5 and swap which voltage divider is attached to `1IN+` and `1IN-`. Now calculate the total amount of current used by this circuit.

   Solution: 10 mA

   Explanation: If the inputs to the LM393 are swapped, this would not change the current usage of the voltage dividers, or the internal operation of the LM393. However, in this configuration, the output (`1OUT`) is negative. In the case of the LM393, this connects the output to ground.

   Therefore, the LED will not light up because the voltage will get to zero before it hits the LED. Thus, the voltage across R5 will be the entirety of the 5 V. Therefore, the new current calculation will be:

   $$\begin{aligned} I &= V/R \\ &= 5/2,000 \\ &= 0.0025\,\text{A} = 2.5\,\text{mA} \end{aligned}$$

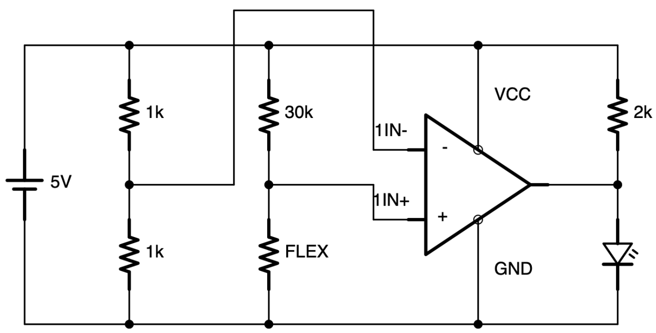
   Therefore, using the results from the previous question, we can see that the total current usage is $2.5 + 0.83 + 2.5 + 1 = 6.83$ mA.

3. **Question:** The Spectra Flex Sensor is a resistive sensor that changes its resistance when bent. When it is

straight, it has a resistance of $10\,\mathrm{k\Omega}$. When it is bent, it has resistances of $60\,\mathrm{k\Omega}$ and above. Draw a circuit that turns on an LED when the resistor is bent. Use a resistor symbole for the flex sensor, but label it as `FLEX`.

Solution:

Explanation: You can create a circuit to do this using the same voltage comparator circuit as before, but with one of the voltage dividers replaced with the circuit shown:



In this circuit, when the Flex sensor is straight, the middle voltage divider will go lower than the divider on the left, turning the output negative (i.e., connecting it to ground). When the Flex sensor is bent, the middle voltage divider will go higher than the divider on the left, turning the output positive (i.e., disconnecting the output from the circuit and allowing the current to flow through the LED). Thus, putting a variable resistor as part of a voltage divider will convert the changing resistance into a changing voltage.

The actual values of the resistor do not matter nearly as much as their ratios. On the left divider, it only matters that the resistors are equal (so the voltage is divided in half). On the middle divider, it only matters that the non-Flex resistor value is *between* the straight and the bent resistance, so that as it goes between straight and bent the voltage will swing above and below the voltage of the left voltage divider.

4. **Question:** Build the circuit in Figures 11.7 and 11.8.

   Solution: On this circuit, be sure to test it in a variety of light levels.

5. **Question:** If you wanted to wait until the room was even darker before the LED went on, how would you change the circuit?

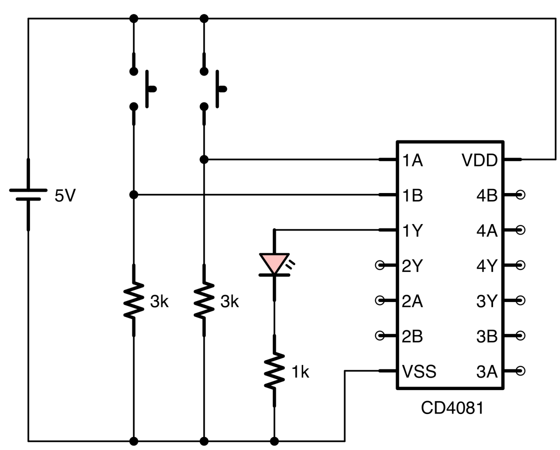
   Solution: The photoresistor works by increasing resistance in the dark. If you increase the resistance of R3, then you increase the amount of darkness required to move the voltage above the reference voltage from the other voltage divider and activate the circuit.

Chapter 12

Using Logic ICs

1. **Question:** Draw the circuit in Figure 12.3 yourself. Identify the function of each resistor.

   Solution: The circuit is repeated below:

   The 3k resistors are pull-down resistors. The 1k resistor is a current-limiting resistor for the LED.

2. **Question:** Build the circuit in Figure 12.3 (don't forget that the power source should be 5 V).

   Solution: When built, the circuit should only light up the LED when *both* the buttons are pushed down.

3. **Question:** If you assume that a negligible amount of current flows through the inputs of the AND gate, and that the output functions as a 5 V voltage source (and the LED is red), how much current flows through each resistor when all of the buttons are pressed? What, then, is the total current used by the circuit if you ignore the logic gate?

   Solution: The pull-down resistors each have 1.67 A of current, and the current-limiting resistor has 3.2 mA of current. Therefore, the total current is 6.54 mA.

   Explanation: When a button is pressed, there is a $3,000\,\Omega$ pull-down resistor connecting the power to ground. Therefore, we can use Ohm's Law to find the current usage:

   $$\begin{aligned} I &= V/R \\ &= 5/3,000 \\ &= 0.00167\,\text{A} = 1.67\,\text{mA} \end{aligned}$$

   Therefore, *each* of the button circuits are using this amount of current.

   Then, when both the inputs are positive, the output goes to 5 V. This is dropped 1.8 V by the red LED, leaving 3.2 V for the resistor. Therefore, the current going through the resistor is:

   $$\begin{aligned} I &= V/R \\ &= 3.2/1,000 \\ &= 0.0032\,\text{A} = 3.2\,\text{mA} \end{aligned}$$

   Therefore, the total amount of current in this circuit is $1.67 + 1.67 + 3.2 = 6.54$ mA.

4. **Question:** Measure the actual current that flows through each resistor. If you are having trouble pushing the buttons while you measure the current, just replace the buttons with wires for this test.

   Solution: Your currents should roughly match the answers to the previous question.

5. **Question:** Measure the current that it used by the AND gate itself. You can do this by measuring the supply current of the AND gate. Measure it both when its output is true and false.

   Solution: This measurement will vary depending on the brand of AND gate you are using. However, usually it is less than 1 mA when the output is off. It should increase by about the output current (3.2 mA) when the output is on.

6. **Question:** Draw a schematic of a circuit that has two buttons (B1 and B2) which light up an LED if either button is pressed. Use the logic gate shapes for the schematic.

7. **Question:** Draw a schematic of a circuit that has two buttons (B1 and B2) which light up an LED if neither button is pressed. Use the logic gate shapes for the schematic.

8. **Question:** Draw a schematic of a circuit that has four buttons (B1–B4) which light up an LED if either B1 and B2 are pressed or if B3 and B4 are pressed. Use the logic gate shapes for the schematic.

9. **Question:** Look at the construction of the different gates from NAND gates in Figure 12.11. Copy down the OR gate construction four times, and trace how the output is generated for each possible set of inputs (true/true, true/false, false/true, false/false). Show the inputs and outputs on each NAND gate. Compare the outputs to the truth table for the OR function in Figure 12.1.

10. **Question:** Take the circuit in Figure 12.3 and draw a schematic to use pull-up resistors on the inputs rather than pull-down resistors. How will this change the behavior of the circuit?

11. **Question:** Let's say that we want to create a door buzzer so that someone outside a door can push a button to be let in. However, the person inside also wants a switch to be able to disable the buzzer. The buzzer can be thought of as a simple device that buzzes when any positive voltage is applied. Draw a circuit diagram of this setup using logic gates. The buzzer can be drawn as a resistor labelled "buzzer" (don't forget to connect the other side to ground!).

Chapter 13

Introduction to Microcontrollers

1. **Question:** Practice modifying and uploading the Blink program to the Arduino Uno. Change the numbers given to `delay` to different values, and see how that affects the operation of the program.

   Solution: Changing the value for the delay should cause the light to noticeably blink at different rates.

2. **Question:** The ATmega328/P is only one of many different microcontrollers available in the AVR family. Research online to find one or two other AVR chips and what different features they have.

   Solution: There are many different types of AVR chips. Some of the others include the ATTiny series, the ATmega series, and the XMEGA. These chips generally differ by available memory, number of pins, and add-on subsystems.

3. **Question:** The AVR family is only one of many microcontroller families. Research one or two other microcontroller families and look at what features are claimed for each. Examples of other microcontroller families include: PIC, STM32, MSP432, and the Intel Quark.

   Solution: This is an open-ended question. Features that would be interesting to focus on are power consumption, working voltage, available memory, ease of programming, extra features, size, and other characteristics.

4. **Question:** Go to the `arduino.cc` website and look at the different types of Arduinos that are available. What makes them different? Why might you choose one for a project over another?

   Solution: While Arduino continually comes out with new variants, some popular variants include the Arduino Uno, the Leonardo, the 101, the Nano, the MKR series, the M0, the Due, and others. These differ from each other based on size, the microcontroller family (AVR, Intel, etc.), the specific microcontroller (which varies based on RAM, speed, power consumption, extra features, etc.), and the extras packed onto the board. The MKR series, for instance, combines the microcontroller with different kinds of networking features. Also, some of them vary by the working voltages used as well. Some variants such as the Lilypad are geared towards wearable devices.

Chapter 14

Building Projects with Arduino

1. **Question:** Which Arduino pin do you use when supplying an unregulated voltage (i.e., a voltage above the 5 V that the Arduino runs at)?

   Solution: The V_{IN} pin is used to provide an unregulated voltage to the Arduino.

2. **Question:** What Arduino pins would you use to extract power out from an Arduino connected to a power supply?

   Solution: You would use the 5 V pin for a regulated five volt output, and the GND pin for ground.

3. **Question:** What is the voltage of an output pin set to HIGH?

   Solution: An output pin set to HIGH puts out 5 V.

4. **Question:** What is the maximum current that should be sourced by any particular Arduino pin?

   Solution: Each output pin should only have up to 20 mA of current coming out of it.

5. **Question:** If you have a red LED attached to an Arduino output pin, what is the minimum size of resistor that you need?

   Solution: 160 Ω

   Explanation: Since each output pin can only output 20 mA of current, we can use Ohm's Law to figure out the minimum size of resistor. The red LED will eat up 1.8 V of voltage. That leave $5 - 1.8 = 3.2$ V remaining. Therefore, Ohm's Law states:

   $$\begin{aligned} R &= V/I \\ &= 3.2/0.02 \\ &= 160\,\Omega \end{aligned}$$

   Therefore, the resistor needs to be at least 160 Ω.

6. **Question:** If an Arduino input pin is completely disconnected from a circuit, what state does the Arduino read it as?

   Solution: If a pin is completely disconnected from a circuit, it could read any value—either HIGH or LOW.

7. **Question:** How much current does an Arduino input use?

   Solution: Arduino inputs can be thought of as mere voltage sensors, not using up any serious amount of current.

8. **Question:** What is the best way to wire a button to an Arduino?

   Solution: Buttons should be wired to Arduinos with pull-down (or pull-up) resistors, in order to make sure that the input pin is always physically connected to the circuit, and therefore has a valid value.

9. **Question:** What is an advantage of storing a program in a microcontroller even if the logic could be built directly in hardware?

   Solution: Storing a program in a microcontroller allows *changes* in logic to be performed without remanufacturing. Additionally, the microcontroller can often be cheaper (and smaller) than the device built without them.

Chapter 15

Analog Input and Output on an Arduino

1. **Question:** What do you have to do in order to a resistive sensor in order to read the value of the sensor on the analog input?

   Solution: You need to create a voltage divider with the resistive sensor to convert the resistance into a voltage that can be read on the analog input.

2. **Question:** In the code that dimmed the lights, how would we slow down the dimming process?

   Solution: After each dimming level is set, there is a `delay()` function called. Increasing the amount of time that we delay will slow down the dimming process.

3. **Question:** Modify the darkness sensor circuit and code so that it will output a dimmed (analog) value to the LED.

   Solution: This will require moving the output from Pin 2 (which is digital only) to a pin that supports PWM (such as Pin 3). This will also require changing the code from using `digitalWrite()` to turn the LED on to using `analogWrite()`.

4. **Question:** Further modify the darkness sensor circuit so that, at different darkness levels, the LED has different levels of brightness.

   Solution: There are many ways to accomplish this. The simplest one, using the tools that you already know, is to have multiple `if` statements check for various light levels, and use a different value for `analogWrite()` for each of them. A more sophisticated (but actually simpler) way of doing this would be to divide the value of `analogRead()` by 4, and use the result as the value for `analogWrite()`.

5. **Question:** Think of your own modifications to the circuits in this chapter. Come up with a new way of putting together the pieces that you have learned to create some amount of modified functioning. Implement this new design.

   Solution: Examples of what you could do include: (a) having a button which turns the whole project on or off, (b) having multiple lights which come on at different light/dark levels, (c) having a button which controls the dimming of an LED. The possibilities are endless.

Chapter 16

Capacitors

1. **Question:** Convert 23 F to microfarads.

   Solution: 23 F = 23, 000, 000 µF

   Explanation: 1 F = 1, 000, 000 µF. Therefore, to convert we multiply by 1, 000, 000.

2. **Question:** Convert 15 µF to farads.

   Solution: 15 µF = 0.000015 F

   Explanation: 1 µF = 0.000001 F. Therefore, to convert we multiply by 0.000001.

3. **Question:** Convert 35 pF to farads.

   Solution: 35 pF = 0.000000035 F

   Explanation: 1 pF = 0.000000001 F. Therefore, to convert we multiply by 0.000000001.

4. **Question:** Convert 0.0002 F to microfarads.

   Solution: 0.0002 F = 200 µF

   Explanation: 1 F = 1, 000, 000 µF. Therefore, to convert we multiply by 1, 000, 000.

5. **Question:** Convert 0.0030 µF to farads.

   Solution: 0.0030 µF = 0.000000003 F

   Explanation: 1 µF = 0.000001 F. Therefore, to convert we multiply by 0.000001.

6. **Question:** If a voltage of 6 V is applied to a 55 µF capacitor, how much charge would it store?

   Solution: 0.00033 coulombs

   Explanation: The equation for charge is $Q = C \cdot V$, where C is the capacitance in farads, and the result is in coulombs. Therefore, begin by converting the capacitance to farads. 1 µF = 0.000001 F, so 55 µF = 0.000055 F. The equation then becomes:

   $$\begin{aligned} Q &= C \cdot V \\ &= 0.000055 \cdot 6 \\ &= 0.00033 \end{aligned}$$

   Therefore, the capacitor will be holding 0.00033 coulombs of charge.

7. **Question:** If a voltage of 2 V is applied to a 13 pF capacitor, how much charge would it store?

   Solution: 0.000000026 coulombs

   Explanation: The equation for charge is $Q = C \cdot V$, where C is the capacitance in farads, and the result is in coulombs. Therefore, begin by converting the capacitance to farads. 1 pF = 0.000000001 F, so 13 pF = 0.000000013 F. Therefore, the equation becomes:

   $$\begin{aligned} Q &= C \cdot V \\ &= 0.000000013 \cdot 2 \\ &= 0.000000026 \end{aligned}$$

   Therefore, the capacitor will store 0.000000026 coulombs worth of charge.

8. **Question:** If a 132 µF capacitor is holding 0.02 coulombs of charge, how many volts will it produce when it begins to discharge?

Solution: 151.5 V

Explanation: The equation for charge in a capacitor is $Q = C \cdot V$ where Q is in coulombs and C is in farads. This can be rearranged to solve for voltage, giving $V = \frac{Q}{C}$. Then, we convert 132 µF to farads. Since 1 µF = 0.000001 F, then 132 µF = 0.000132 F. Therefore, the equation becomes:

$$\begin{aligned} V &= \frac{Q}{C} \\ &= \frac{0.02}{0.000132} \\ &\approx 151.5 \end{aligned}$$

Therefore, when the capacitor begins to discharge, it will discharge at 151.5 V.

9. **Question:** if a 600 pF capacitor is holding 0.03 coulombs of charge, how many volts will it produce when it begins to discharge?

Solution: 50, 000 V

Explanation: The equation for the voltage when discharging a capacitor is $V = \frac{Q}{C}$, where the charge is in coulombs and the capacitance is in farads. We will start by converting 600 pF to farads. Since 1 pF = 0.000000001 F, then 600 pF = 0.0000006 F. Therefore, the equation becomes:

$$\begin{aligned} V &= \frac{Q}{C} \\ &= \frac{0.03}{0.0000006} \\ &= 50000 \end{aligned}$$

Therefore, this would generate 50, 000 V when it began to discharge. Note that this is probably beyond the physical capacity of such a device, and, even if you could charge it up that much, it would discharge almost instantaneously, kind of like a static electricity shock (which has almost the same amount of voltage).

10. **Question:** If a 121 µF capacitor is connected to a battery. After some fluctuation, the capacitor has 0.00089 coulombs of charge stored in it and the battery is reading 8.9 V. Is the capacitor going to be charging or discharging at this point?

Solution: The capacitor will be charging.

Explanation: To know if the capacitor will be charging or discharging, find out first how much charge the capacitory *could* store at the supplied voltage. If the charge in the capacitor is less than the potential charge at that voltage, then that means that charge would be flowing in. If the charge in the capacitor is greater than the potential charge at that voltage, then the charge will flow out into the circuit.

At 8.9 V, the amount of charge for a 121 µF (0.000121 F) capacitor is:

$$\begin{aligned} Q &= C \cdot V \\ &= 0.000121 \cdot 8.9 \\ &= 0.0010769 \end{aligned}$$

Therefore, at 8.9 V, the charge in the capacitor should go to 0.0010769 coulombs. The actual charge in the capacitor is 0.00089 coulombs, which is *less* than the charge should be at that voltage. Therefore, the charge is flowing into the capacitor.

Chapter 17

Capacitors as Timers

1. **Question:** If I have an RC circuit with a resistor of $10\,\Omega$ and a capacitor of $2\,\mathrm{F}$, what is the RC time constant of this circuit?

   Solution: 20 seconds

   Explanation: The RC time constant is just the resistance (in ohms) multiplied by the capacitance (in farads). Therefore, multiply $10 \cdot 2 = 20$. The time constant is 20 seconds.

2. **Question:** In the previous question, how many seconds does it take to charge my capacitor to approximately 50% of supply voltage?

   Solution: 14 seconds

   Explanation: Figure 17.1 shows how many time constants it takes to charge a capacitor to a certain percentage of supply voltage. Like most things in electronics, it won't be exact. However, in the figure you can see that 0.7 time constants will yield 50.3% of the supply voltage. Since the time constant was 20 seconds, the amount of time to charge 50% is $0.7 \cdot 20 = 14$ seconds.

3. **Question:** If I have an RC circuit with a resistor of $30,000\,\Omega$ and a capacitor of $0.001\,\mathrm{F}$, what is the RC time constant of this circuit?

   Solution: 30 seconds

   Explanation: The RC time constant is just resistance (in ohms) multiplied by capacitance (in farads). In this case, that yields $30,000 \cdot 0.001 = 30$ seconds.

4. **Question:** In the previous question, what percentage of the way is the capacitor's voltage charged after 60 seconds?

   Solution: 86.5%

   Explanation: Since the RC time constant is 30 seconds, 60 seconds would be two RC time constants. Figure 17.1 shows that two time constants yields an 86.5% voltage charge.

5. **Question:** If I have an RC circuit with a resistor of $25\,\mathrm{k\Omega}$ and a capacitor of $20\,\mathrm{\mu F}$, what is the RC time constant of this circuit?

   Solution: 0.25 seconds

   Explanation: This is just like the other time constant problems, except that we have to change units. The units for the RC circuit are ohms and farads. Since $1\,\mathrm{k\Omega} = 1,000\,\Omega$, then $25\,\mathrm{k\Omega} = 25,000\,\Omega$. Likewise, since $1\,\mathrm{\mu F} = 0.000001\,\mathrm{F}$, then $20\,\mathrm{\mu F} = 0.00002\,\mathrm{F}$.

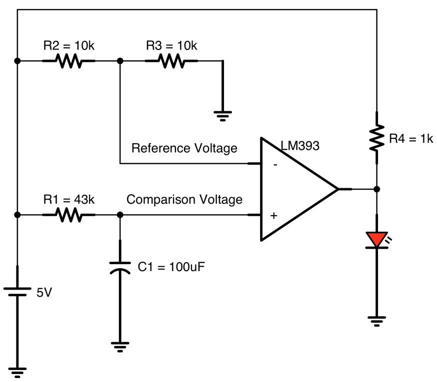
   Now we just need to multiply them together. $25,000 \cdot 0.00002 = 0.5$ seconds.

6. **Question:** Give a resistor and capacitor combination that will yield an RC time constant of 0.25 seconds.

   Solution: Any resistor/capacitor combination that, when multiplied together, yields 0.25 will suffice. A simple example would be to halve *one* of the component values from the previous problem. For instance, I could keep the $25\,\mathrm{k\Omega}$ resistor but change the capacitor to $10\,\mathrm{\mu F}$.

7. **Question:** Reconfigure the circuit in Figure 17.2 to wait for 3 seconds. Draw the whole circuit.

   Solution: There are an infinite number of ways to modify this solution to achieve your goal. An example one is:



Explanation: The way that the circuit works is by comparing the comparison voltage to the reference voltage. Since the reference voltage is produced by a voltage divider, we can see that the output of the voltage divider will be 50% of voltage, or 2.5 V. Therefore, when the comparison voltage rises above 2.5 V, the comparator will fire. According to Figure 17.1, the capacitor will be 50% full (thus making the comparison voltage over 2.5 V after 0.7 time constants.

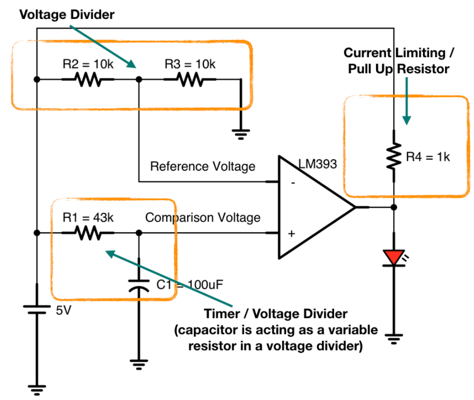
Therefore, since we are wanting a waiting period of 3 seconds, we can solve for the time constant C like this:

$$3 \text{ seconds} = 0.7 \cdot C$$
$$\frac{3 \text{ seconds}}{0.7} = C$$
$$4.3 \text{ seconds} = C$$

Therefore, we need a time constant of 4.3 seconds. The time constant is found by multiplying the resistance times the capacitance. Therefore, R1 and C1 can be *any* values that multiply to be approximately 4.3. In the example above, we merely changed the resistor to be $43,000\,\Omega$ ($43\,\text{k}\Omega$), because $43,000 \cdot 0.0001 = 4.3$.

8. **Question:** Redraw the previous circuit, and circle each basic resistor circuit pattern and label it.

   Solution: Using the circuit from the previous question, it should be labeled as follows:



Explanation: This circuit uses three resistor circuit patterns. The reference voltage is set using a voltage divider circuit. The timing circuit itself is a voltage divider as well, even though it includes a capacitor. The capacitor acts as a sort of variable resistor, increasing the voltage across it as it fills. Thus, the voltage coming out from between the resistor and the capacitor changes based on how full the capacitor is. Finally, the resistor attached to the LED is a pull-up resistor. Pull-up resistors also function as current-limiting resistors (however, simply labeling it as a pull-up resistor is sufficient).

Chapter 18

Introduction to Oscillator Circuits

Figure 18.2 will be used as the basis for the problems in this section.

1. **Question:** Copy Figure 18.3 to a piece of paper including the current flows on charge and discharge.

   Solution: See Figure 18.3.

   Explanation: During the charging phase, current flows from the positive all the way into the capacitor. This is shown with the line that is on the interior of the circuit. During the discharge phase, Pin 7 goes low, and therefore current flows into Pin 7 from *both* the power supply *and* from the capacitor.

2. **Question:** Why is R1 important? What would happen if we just replaced it with a wire?

   Solution: During the discharge phase, R1 acts as a current-limiting resistor. It would create a short-circuit from power to ground if it was just a wire.

   Explanation: Remember, there is no intelligence in a circuit. The power supply only knows how to supply power. Therefore, during the discharge phase, the power supply *will continue to supply power just as before*. When Pin 7 goes to zero volts, not only does the charge from the capacitor start to flow in that direction, but also the power from the supply. If there is no resistor here, then it becomes a short-circuit from supply to ground. Additionally, since this power is entirely wasted, R1 also limits the amount of waste that occurs during the discharge phase.

3. **Question:** Why are there two different pins on the NE555 connected to the capacitor? What type of circuit (that we have discussed in this book) do you think they are connected to inside the chip?

   Solution: One compares for voltage *above* a certain level, and the other compares for voltage *below* a certain level. Since they are checking for voltage, they are probably voltage comparator circuits.

   Explanation: The NE555, in its standard configuration, allows the capacitor to charge until it is two thirds full, and then discharges it until it is only one third full. It has to detect for each of these conditions. Therefore, it has two separate sensing inputs, one for each condition. $Threshold$ watches for the high voltage (and switches it from "charge" to "discharge" when it goes over), and $\overline{Trigger}$ watches for the low voltage (and switches it from "discharge" to "charge" when it goes under). Since it is watching voltage levels, it is likely using a voltage comparator in the chip to measure these voltages.

4. **Question:** Why is the charging time of the NE555 always at least a little longer than the discharging time?

   Solution: The circuit uses both R1 and R2 to charge, but *only* uses R2 to discharge. Therefore, the resistance for discharging will always be less than the resistance for charging.

5. **Question:** Why does the NE555 stay in the on state a little longer when the circuit is first turned on?

   Solution: Generally, the NE555 oscillates between filling and discharging the capacitor from one third to two-thirds full. When first turned on, the capacitor will (presumably) be *fully* discharged, so it will take some amount of time for that first charge cycle to occur, because it is charging from zero instead of from one third full.

6. **Question:** Let's say that we wanted our circuit to be on for 2 seconds and off for 1 seconds. Keeping the same capacitor, what values should we use for R1 and R2 to accomplish that?

Solution: R1 would be 144300.2 Ω and R2 would be 144300.1 Ω. In terms of standard components, using a 150 kΩ resistor for each one would be sufficient.

Explanation: Since the discharge phase (when the output is off) only uses one resistor (R2) we will beging considering the discharge phase. The total time is 1 seconds. Since we are using a NE555 timer, this time will cover 0.693 time constants. The time constant is given by the resistance multiplied by the capacitance. Since the capacitor is a 10 µF capacitor, the full equation is:

$$\begin{aligned} R \cdot 0.00001 \cdot 0.693 &= 1 \\ R &= \frac{1}{0.00001 \cdot 0.693} \\ R &\approx 144300.1 \end{aligned}$$

Therefore, R2 will be approximately 144300.1 Ω. We now do a similar operation to find R1. However, the "on" phase of the oscillation will utilize both R1 and R2, and will take two seconds. Therefore, we can solve for R1 as follows:

$$\begin{aligned} 0.00001 \cdot (144300.1 + R) \cdot 0.693 &= 2 \\ 144300.1 + R &= \frac{2}{0.00001 \cdot 0.693} \\ R &= \frac{2}{0.00001 \cdot 0.693} - 144300.1 \\ R &\approx 144300.2 \end{aligned}$$

So R1 will be approximately 144300.2 Ω.

Resistors are not actually available in these values. Therefore, you would likely choose a 150 kΩ resistor for each of these.

7. **Question:** Let's say that we wanted our circuit to be on for 10 seconds and off for 3 seconds. Keeping the same capacitor, what values should we use for R1 and R2 to accomplish that?

8. **Question:** The factory called and said that they were out of the capacitor we wanted for the circuit, and instead only had a 23 µF capacitor that we could use. Recalculate the previous problem using this new capacitor value.

9. **Question:** How much current is our output sourcing from the chip?

10. **Question:** When the chip first turns on (and thus the capacitor is empty and at 0 V) how much current is the RC circuit in Figure 18.2 using?

Chapter 19

Producing Sound with Oscillations

1. Why is the input voltage signal to the 555 timer smooth, but the output is square?
2. Will increasing the resistance of R1 and R2 make the pitch higher or lower?
3. Can you think of a way to modify the circuit so that the pitch of the sound can be adjusted while the circuit is on?
4. Given the circuit in Figure 19.3, what power would be delivered to your headphones if you were using an 8 Ω speaker instead of the 16 Ω speaker? What about a 100 Ω speaker?
5. The frequency of the A note above middle-C on the piano is 440 Hz. Design a modification to this circuit that will yield this frequency.
6. The output of the 555 is 1.7 V less than the power supply used. What is the effect on the wattage to the headphones if we change the power supply to be a 9 V power supply?

Chapter 20

Inductors

1. **Question:** If I want a circuit to block DC current but allow AC current, should I use an inductor or a capacitor?

   Solution: Capacitor

   Explanation: Capacitors allow AC current but block DC current.

2. **Question:** If I want a circuit to allow DC current but block AC current, should I use an inductor or a capacitor?

   Solution: Inductor

   Explanation: Inductors allow DC current but block AC current.

3. **Question:** Why are inductors used so much in systems that interact with the outside world?

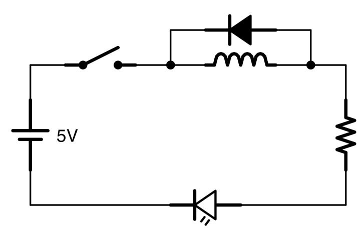
   Solution: Inductors create a magnetic field which can be used to move other components.

4. **Question:** Why does inductive kick happen?

   Solution: In an inductor, the magnetic field is maintained through current flow through the inductor. If the current decreases, the magnetic field cannot be maintained, and the flux is converted to a voltage. A sudden decrease in current will cause an equally sudden build-up in voltage. This is the inductive kick.

5. **Question:** Draw a schematic of an inductor where the positive side of the inductor has a switch and the negative side is connected to an LED and a resistor. Add in a snubber diode to protect the LED from the effect of turning off the switch.

   Solution:

6. **Question:** What is the purpose of the snubber diode?

   Solution: The snubber diode reduces the effect of the inductive kick by giving the current a pathway back through the inductor. This allows generated voltages/currents to be bled off slowly throught the inductor itself.

7. **Question:** If I have an inductor that is 5 H and has a steady current going through it of 2 A, what is the size of the magnetic flux in the inductor's magnetic field?

   Solution: 10 webers

   Explanation: The equation governing the behavior of an inductor is given by Equation 20.1, $\phi = L \cdot I$, where L is given in henries and I is in amperes. Therefore, since the units match, we can calculate as follows:

   $$\begin{aligned} \phi &= L \cdot I \\ &= 5 \cdot 2 \\ &= 10 \end{aligned}$$

   Therefore, the inductor is holding 10 webers of flux.

8. **Question:** If I have an inductor that is 7 µH and has a steady current going through it of 3 mA, what is the size of the magnetic flux in the inductor's magnetic field?

Solution: 0.000000021 webers

Explanation: The equation for flux is $\phi = L \cdot I$, where L is in henries and I is in amperes. Therefore, we need to convert into proper units to use the equation. Since 1 µH = 0.000001 H, 7 µH = 0.000007 H. Since 1 mA = 0.001 A, 3 mA = 0.003 A. Therefore, the equation becomes:

$$\begin{aligned} \phi &= L \cdot I \\ &= 0.000007 \cdot 0.03 \\ &= 0.000000021 \end{aligned}$$

Therefore, the magnetic field has a flux of 0.000000021 webers.

9. **Question:** If I have a 4 H inductor with 0.3 Wb of flux in its magnetic field, how much current is flowing through it?

   Solution: 0.075 A or 75 mA

   Explanation: We will solve this problem by rearranging Equation 20.1 to solve for I:

$$\begin{aligned} \phi &= L \cdot I \\ I &= \frac{\phi}{L} \end{aligned}$$

   Since the units are already correct, I can now just substitute and solve:

$$\begin{aligned} I &= \frac{\phi}{L} \\ &= \frac{0.3}{4} \\ &= 0.075 \end{aligned}$$

   Therefore, the current is 0.075 A or 75 mA.

10. **Question:** If an inductor's magnetic field has 5 Wb of flux and it decreases to 3 Wb of flux over 2 seconds, what is the average voltage produced over that timeframe?

    Solution:

    Explanation: Questions involving the *change* of voltage and flux utilize Equation 20.2, which states:

$$V_{\text{average}} = -\frac{\text{change in } \phi}{\text{change in time}}$$

    Since we start with 5 Wb of flux and end with 3 Wb, therefore, we changed by −2 Wb. Since this occurred across 2 seconds, the resulting formula would be:

$$\begin{aligned} V_{\text{average}} &= -\frac{-2}{2} \\ &= 1 \end{aligned}$$

    Therefore, the average voltage produced for that time period is 1 V.

11. **Question:** If an inductor's magnetic field has 1 µWb of flux and it increases to 2 µWb of flux over 0.4 seconds, what is the average voltage produced over that timeframe?

    Solution:

    Explanation: Questions involving the *change* of voltage and flux utilize Equation 20.2. To use this equation, first we have to convert units. The standard conversion is 1 µWb = 0.000001 Wb. Therefore, the equation becomes:

$$\begin{aligned} V_{\text{average}} &= -\frac{\text{change in } \phi}{\text{change in time}} \\ &= -\frac{0.000001}{0.4} \\ &= -0.0000025 \end{aligned}$$

    Therefore, the inductor will produce a negative voltage, averaging −0.0000025 V for the duration of the 0.4 seconds.

12. **Question:** If the current flowing through a 3 H inductor drops from 7 mA to 1 mA over a period of 0.01 seconds, what is the average voltage produced over that time period?

    Solution: 1.8 V

    Explanation: To solve this, you will need *both* Equation 20.1 and Equation 20.2. Equation 20.2 requires a starting and an ending flux. However, we are not given the starting and ending flux, but rather the starting and ending current. Equation 20.1 tells us how to relate current to the amount of flux.

    First, we need to convert our units. 7 mA = 0.007 A and 1 mA = 0.001 A. Let's begin by solving for the starting flux:

$$\begin{aligned} \phi &= L \cdot I \\ &= 3 \cdot 0.007 \\ &= 0.021 \end{aligned}$$

    So the starting flux is 0.021 Wb.

Next, let's solve for the final flux:

$$\begin{aligned}\phi &= L \cdot I \\ &= 3 \cdot 0.001 \\ &= 0.003\end{aligned}$$

So, the final flux is 0.003 Wb. This means that the change in flux was −0.018 Wb across 0.01 seconds. Therefore, the average voltage over that period can be found using Equation 20.2:

$$\begin{aligned}V_{\text{average}} &= -\frac{\text{change in } \phi}{\text{change in time}} \\ &= -\frac{-0.018}{0.01} \\ &= 1.8\end{aligned}$$

Therefore, the average voltage produced by the decrease in current over that time period is 1.8 V.

Chapter 21

Inductors and Capacitors in Circuits

1. What is the time constant of a series circuit consisting of a $50\,\Omega$ resistor and a $2\,\mathrm{H}$ inductor?
2. What is the time constant of a series circuit consisting of a $10\,\Omega$ resistor and a $5\,\mu\mathrm{H}$ inductor?
3. If I have a $9\,\mathrm{V}$ battery and I connect it to a series circuit consisting of a $1\,\mathrm{k\Omega}$ resistor and a $23\,\mu\mathrm{H}$ inductor, how much time will it take before the current through the inductor reaches approximately 87% of its maximum value?
4. If I have a $5\,\mathrm{V}$ source and I connect it to a series circuit consisting of a $2\,\mathrm{k\Omega}$ resistor and a $6\,\mu\mathrm{H}$ inductor, how much time will it take before the voltage across the inductor falls below $0.25\,\mathrm{V}$.
5. If I have a circuit that has unwanted high-pitched noise, what component can I wire in series with the circuit to remove the noise?
6. If I have a circuit that has unwanted high-pitched noise, what component can I wire in parallel with the circuit to remove the noise?
7. What types of currents does an inductor (a) block and (b) allow?
8. What types of currents does a capacitor (a) block and (b) allow?
9. If I am building a radio, I need to allow through only very specific frequencies. What component or combination of components would I use to do this?

Chapter 22

Reactance and Impedance

1. As the frequency of a signal goes up, how does that affect the reactance from a capacitor? What about with an inductor?
2. As the frequency of a signal goes down, how does that affect the reactance from a capacitor? What about with an inductor?
3. What is true about the relationship between the capacitative reactance and the inductive reactance at the resonant frequency?
4. Why is power not used up with reactance?
5. How are reactance and resistance combined to yield impedance?
6. Calculate the capacitative reactance of a 3 F capacitor at 5 Hz.
7. Calculate the capacitative reactance of a 20 µF capacitor at 200 Hz.
8. Calculate the inductive reactance of a 7 H inductor at 10 Hz.
9. Calculate the inductive reactance of a 8 mH inductor at 152 Hz.
10. Calculate the impedance of a circuit with a 200 Ω resistor in series with a 75 µF capacitor with a signal of 345 Hz.
11. Calculate the impedance of a circuit with a 310 Ω resistor in series with a 90 nF capacitor with a signal of 800 Hz.
12. Calculate the impedance of a circuit with no resistor and a 60 mH inductor with a signal of 89 Hz.
13. Calculate the impedance of a circuit with a 50 Ω resistor in series with a 75 µH inductor with a signal of 255 Hz.
14. If I have an AC circuit with an RMS voltage of 6 V and an impedance of 1 kΩ, what is the average (RMS) current of this circuit?
15. If I have an AC circuit, and I measure the AC voltage as 10 V RMS, and I measure the AC current at 2 mA RMS, what is the impedance of this circuit?
16. If I have an 80 Hz AC circuit that has an 8 V RMS voltage source in series with a 500 Ω resistor, a 5 H inductor, and a 200 nF capacitor, what is the RMS current flowing in this circuit?
17. Calculate the impedance of a circuit with a 250 Ω resistor in series with a 87 µH inductor and a 104 µF capacitor with a signal of 745 Hz.
18. What is the resonant frequency of the circuit in the previous question?
19. What is the reactance of a circuit at its resonant frequency?
20. If I have a 10 µF capacitor, what size inductor do I need to have a resonant frequency of 250 Hz?

Chapter 23

DC Motors

1. If you wanted to prevent too much current from going through a motor, what should you use for this?
2. What happens to the RPM of a motor when I reduce the voltage to my motor?
3. What should be attached to a motor to protect the other parts of the circuit when a motor is shut-off?
4. List one reason why a series resistor should not be used with a motor.
5. If I was building a robot and wanted to control the angle of a robot's arm, what type of motor could I use?
6. If I was building a machine to place components into a precise position onto a board, what type of motor should I pick to achieve that precision?

Chapter 24

Amplifying Power with Transistors

Unless otherwise specified, assume that the transistor is a BJT NPN transistor and that the beta is stable.

1. **Question:** If the base of a transistor is at 3 V and the transistor is on, what will be the emitter voltage?

   Solution: The emitter is 0.6 V less than the base, so the emitter will be $3 - 0.6 = 2.4$ V.

2. If the base of a transistor is at 45 V and the emitter is on, what will be the emitter voltage?
3. If the base of a transistor is at 5 V and the emitter, if conducting, would have to be at 4.5 V, is the transistor on or off?
4. If the base of a transistor is at 0.6 V and the emitter is at ground, is the transistor on or off?
5. If the base of a transistor is at 0.4 V and the emitter is at ground, is the transistor on or off?
6. If a transistor has a base current (I_{BE}) of 2 mA and the transistor has a beta of 55, how much current is going through the collector (I_{CE})?
7. In the previous problem, how much total current is coming out of the emitter?
8. If a transistor has a base current of 3 mA and the transistor has a beta of 200, how much current is going through the collector?
9. If the base voltage is greater than the collector voltage, what does this mean for our transistor operation?
10. The output of your microcontroller is 3.3 V and supports a maximum output current of 10 mA. Using Figure 24.7 as a guide, design a circuit to control a motor that requires 80 mA to operate. Assume that the transistor beta is 100.
11. Redesign the previous circuit so that it utilizes a stabilizing resistor on the emitter to prevent variations in the transistor beta.

Chapter 25

Transistor Voltage Amplifiers

1. What is the purpose of the resistor in the collector of a transistor amplifier?
2. What is the purpose of the resistor in the emitter of a transistor amplifier?
3. Why is there a bias voltage on the base of the transistor? Why can't the signal just be connected in directly to the base?
4. Why is the signal coupled in through a capacitor?
5. Why does the single stage voltage amplifier discussed in this chapter invert its output?
6. If the output of the two-stage amplifier is coupled into a third stage, the signal current would swing 1.85 mA in either direction. Design a third amplification stage which can handle this amount of current.

Chapter 26

Examining Partial Circuits

1. Why would we want to know what a circuit's Thévenin equivalent circuit is?

2. What are the two components of a Thévenin equivalent circuit?

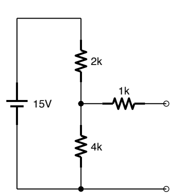
3. Think about the two-stage amplifier that you built in Chapter 25. How would you go about finding the Thévenin equivalent circuit as it is seen by the headphones?

4. Suppose I have a circuit where the output terminals have a $2\,\mathrm{V}$ drop when it is an open circuit, and have $2\,\mathrm{mA}$ of current flowing through it when it is a short circuit. Draw the Thévenin equivalent circuit.

5. If I have a Thévenin equivalent circuit of $4\,\mathrm{V}$ with an impedance of $400\,\Omega$, what will be the voltage drop of the load if I attach a $2000\,\Omega$ resistor across the output?

6. If I have a Thévenin equivalent circuit of $3\,\mathrm{V}$ with an impedance of $100\,\Omega$, what will be the voltage drop, the current, and the power of the load if I attach headphones rated at $32\,\Omega$?

7. Calculate and draw the Thévenin equivalent circuit of the circuit below:



8. Suppose I have a circuit where, when I add a load of $350\,\Omega$ I get a $7\,\mathrm{V}$ drop, and when I add a load of $2000\,\Omega$ I get an $8\,\mathrm{V}$ drop. Calculate and draw the Thévenin equivalent circuit.