Resistance, Power, and Voltage Examples

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A Quick Concept and Units Review

This “review” got a little long, but it is probably ok, because it is helpful to reiterate and expand.

We have introduced fundamental concepts of energy, charge, and voltage, usually denoted E, q, and $\mathcal{V}$. When we have a small amount of charge and we want to emphasize that it is small, or incremental, or changing, we usually write, Δq, and similarly for a small amount of energy we usually write, ΔE.

The entire concept of voltage is that if Δq of charge moves through an increase $\mathcal{V}$ of voltage, then the energy required is $\Delta E = \mathcal{V}\Delta q$. Voltage is the proportionality constant between the amount of charge you move, and the amount of energy required.

It is very much like height and mass. It requires $\Delta E = \Delta m g h$ of energy to raise a small mass Δm a height h. Also, if we let it fall though that same height h, the energy $\Delta E = \Delta m g h$ is released. You often have to intelligently think about signs in these types of formulas.

ASIDE: You might ask where was the energy stored when it raised. It is stored in the “gravitational field.” Similarly, the energy required to move a charge through a potential is stored in the “electric field.” Going further and trying to answer such questions with anything more than a few tantalizing buzzwords would take us quite a bit beyond the minimum amount of physics that we need for this course.

In the gravitational formula the extra constant g that has shown up is the acceleration of gravity in the vicinity of the Earth. There is no such constant in the voltage formula. The reason is that we choose our units for voltage precisely so that there is no conversion factor. If we measured height in Joules/kilogram, there would be no conversion formula in the gravitational formula either, but we measure height in meters, and so there is.

The three units of energy associated with E, q, and $\mathcal{V}$ are the Joule (abbreviated J), Coulomb (abbreviated C), and the Volt (abbreviated V). You can see from the formulas that

$1\,\mathrm{V} = \frac{1\,\mathrm{J}}{1\,\mathrm{C}}$

We then introduced three more concepts, power, current, and resistance, usually denoted P, I, and R. Resistance first appeared in Ohm's Law (which I always have to repeat is not a law, it is a property of some materials):

$$\mathcal{V} = IR$$

The corresponding units were the Watt (abbreviated W), the Ampere (abbreviated A), and the Ohm (abbreviated Ω).

$$1\,\mathrm{W} \equiv \frac{1\,\mathrm{J}}{1\,\mathrm{s}}$$

$$1\,\mathrm{A} \equiv \frac{1\,\mathrm{C}}{1\,\mathrm{s}}$$

$$1\,\Omega \equiv \frac{1\,\mathrm{V}}{1\,\mathrm{A}}$$

Go back to where these concepts were introduced, and you will see that what the units must be, and that it is going to be convenient to have the new units, which are just ratios of the fundamental units.

How Much Power Does a Resistor Consume?

Even though we have only have a very small number of fundamental concepts and definitions, surprisingly, we now have enough equations that we can start combining them to make new formulas!

Let's think for a moment about a resistor with current, I, flowing through it. We follow a little bit of charge, Δq, in that current flowing through the resistor. The resistor resists the passage of Δq, and it requires energy,

$$\Delta E = \Delta q \mathcal{V}$$

to get the charge, Δq, through.

By the way, in our circuits, the energy required is supplied by AA batteries, and the energy required to push the charge through the resistors is lost from them out of the circuit as heat. The battery will do this until it exhausts the chemicals in it. Its voltage will start declining from its nominal rated value of 1.5V, and eventually we declare the battery to be "dead" and buy more.

Next we use $\mathcal{V} = IR$ (Ohm's Law) in our formula and we have

$$\Delta E = \Delta q I R$$

Now we do an odd thing. We ask "how long did it take Δq to pass through the resistor?" I don't know (actually I kind of do, but let's pretend we don't), and just call the time Δt. This is the time it took for Δq to pass through and for the energy ΔE to be supplied by the battery and lost from the resistor. The odd thing is that we divide both sides of the equation by Δt. We then have:

$$\frac{\Delta E}{\Delta t} = \frac{\Delta q}{\Delta t} IR$$

Now we recall the very definitions of power and current (they are rates of energy and charge), and the equation becomes:

$$P = I \cdot IR = I^2 R$$

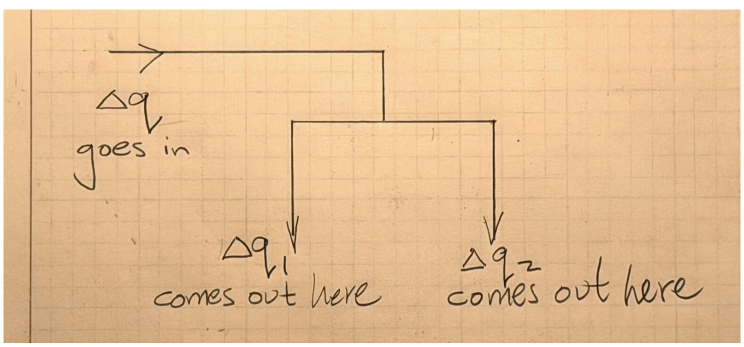
Using Ohm's Law one more time, this time arranged as $I = \frac{\mathcal{V}}{R}$, we get an equivalent formula:

$$P = \left(\frac{\mathcal{V}}{R}\right)^2 R = \frac{\mathcal{V}^2}{R}$$

So now you have two very nice answers to the question, how much power does a resistor consume:

$P = I^2 R$ or equivalently $P = \frac{\mathcal{V}^2}{R}$

Kirchhoff's First Law



Remember that charge cannot pile up anywhere in a circuit. We did an example to see how ludicrously and incomprehensibly large amount of force it would take to bring even two half-Coulomb charges to within an eight of an inch of each other.

Since charge cannot pile up, for the above drawing, there is an equation among Δq, Δq_1, and Δq_2. It is:

$$\Delta q = \Delta q_1 + \Delta q_2$$

Now we do the same odd thing. We ask "how long did it take the small amount of charge, Δq, to separate into Δq_1 and Δq_2?" We call the answer to that, whatever it is, is the small amount of time, Δt. Then we divide both sides of the equation by Δt:

$$\frac{\Delta q}{\Delta t} = \frac{\Delta q_1}{\Delta t} + \frac{\Delta q_2}{\Delta t}$$

Then we realize that the ratios appearing in this equation are exactly the definitions of the currents I, I_1, and I_2, and so we have:

$$I = I_1 + I_2$$

There are lots of ways of writing Kirchhoff's First Law, depending on how many wires meet at a junction — here we have just three, one coming in and two coming out. Also it depends on how you label the currents going in and out. For the moment, $I = I_1 + I_2$ is more than enough to know and love as "Kirchhoff's First Law."

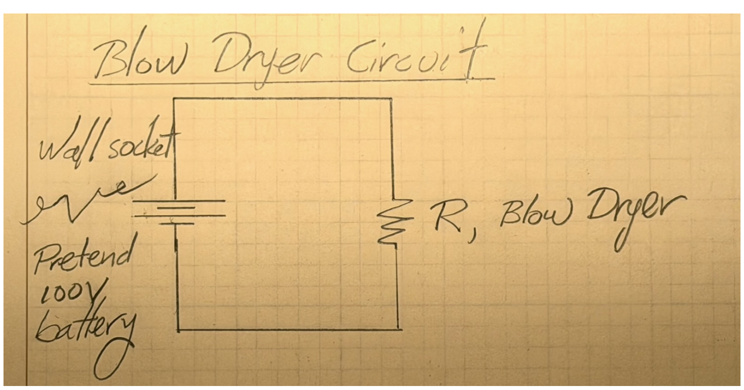
Blow Dryer Example

A blow dryer makes heat by letting current push through a resistor. Let's figure out what more precisely what must be inside it. Of course, in addition to the resistor, there is a fan motor that pushes the heat coming out of the resistor out of the blowdryer and onto your hair, but we are going to ignore the motor.

For simplicity, let's assume that the wall socket that the blow drier is plugged into delivers 100 V. Imagine on the other side of the wall is just a 100V battery, not the an attachment to the entirety of Southern California Edison's network.

Aside: Southern California Edison actually delivers "AC voltage" or "AC power" and we will get into what that is later. Steady voltage is called "DC." "DC" is short for "direct current" and "AC" is short for "alternating current." Assuming the wall socket supplies 100 V DC just like a big battery would is good enough for the moment.

The blow dryer is the same as our simplest possible circuit! The very first one we built with our kits.

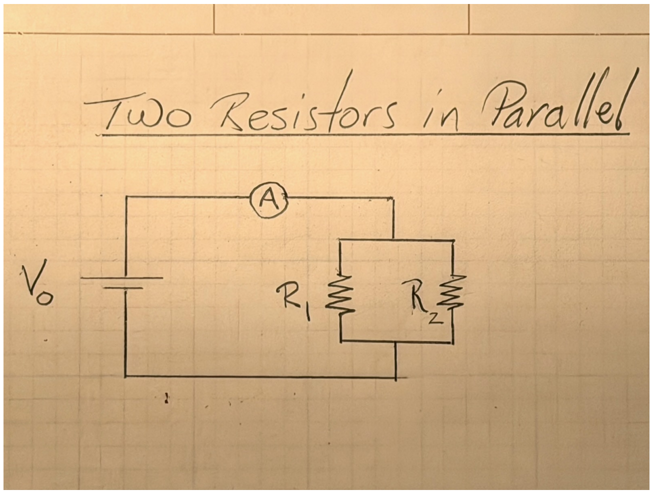


Blow Dryer Problems

1. Rearrange one of the equations in the section titled “How Much Power Does a Resistor Consume?” to get a formula for R in terms of P and $\mathcal{V}$. HINT: Which equation only involves R, P, and $\mathcal{V}$? That is the one to rearrange.
2. Plug in $P = 1$ kW for a typical blow dryer and $\mathcal{V} = 100\ V$ to your formula. What is R?
3. Rearrange Ohm’s Law to solve it for I.
4. With your values for $\mathcal{V}$ and R what do you get for I?
5. If you run the blow dryer for 6 minutes, simply knowing the time and the rated power of the blow dryer of 1 kW, how many Joules have been delivered to you by Southern California Edison.
6. Southern California Edison doesn’t write their bill in Joules. They use the kilowatt-hour (kWh) as their billing unit.
7. How many kWh were you supplied when you ran a blow dryer for 6 minutes. HINT: 6 minutes was conveniently chosen to be $\frac{1}{10}$ of an hour. Just put $t = 0.1$ h and $P = 1$ kW into $E = P \cdot t$.
8. Southern California Edison now charges 35¢ on average per kWh. It can go as high as 74¢ during peak demand in the late afternoon in the summer. Let’s suppose you blow dry your hair when everybody else is blow-drying theirs in the morning, and the rate is 50¢ per kWh. How much did your 6 minutes of blow-drying cost you?
9. If secretly on the other side of the wall is not a 100V battery, but hamsters in treadmills turning generators, and there are 50 hamsters struggling to maintain 100V at the rate your blowdryer is drawing it, and each of them needs one M&M per minute to keep going on its treadmill, how many M&Ms were consumed in the six minutes that you ran your blowdryer?

   ASIDE: Of course it’s a silly example, but it helps you think concretely about quantities and rates, because you can visualize M&Ms far more easily than kWh. One of the troubles with learning electronics is that our eyes cannot see charge, and so we have to simply imagine it flowing around circuits at various rates, dividing at some junctions, and recombining at others.
10. If you use a monster 2kW blow dryer, but use it for only 3 minutes, how many kWh were you supplied?

Parallel Resistors Example



The last circuit we built in class is above. We used two 47kΩ resistors for R_1 and R_2.

Parallel Resistors Problems

1. If the voltage $V_0 = 6 * 1.6$ V for 6 very fresh AA batteries, what is the voltage across resistor R_1. HINT: It isn't 4.8 V.
2. What is the voltage across resistor R_2?
3. What is the current, I_1, through resistor R_1?
4. What is the current, I_2, through the resistor R_2?
5. The current that goes to and through both of the resistors comes from the battery. Call it I. What must I be per Kirchhoff's First Law?
6. If the battery supplies this for 10 minutes, how many milliaamp-seconds have supplied.
7. Convert your answer to Coulombs and round it to a pleasing two-significant-digit value.
8. Could we say that the battery has supplied about one-quarter of a Coulomb?
9. Knowing that the batteries are in series in the plastic compartment you loaded them into, how many Coulombs did each battery have to supply? HINT: It ain't 1/6 of what you got in 8.
10. An Energizer Ultimate AA battery is rated to supply 3000mAh which is the same as 3 Ah. How many Coulombs is that?

Conclusion

You are starting to have the tools to analyze circuits. Right now we just have batteries and resistors. They have simple and predictable behavior. Circuits get more interesting as other types of components are introduced, like capacitors, diodes, and transistors. All in good time!