Review: What makes a bulb light up?

- The critical ingredient is closing a circuit so that current is forced through the bulb filament
  - more on filaments and what is physically going on later
- The more the current, the brighter the bulb
- The higher the voltage, the brighter the bulb
- Power "expended" is $P = VI$
  - this is energy transfer from chemical potential energy in the bulb to radiant energy at the bulb

Bulb Design Basics

- Bulb contains a very thin wire (filament), through which current flows
- The filament presents resistance to the current
  - electrons bang into things and produce heat
  - a lot like friction
- Filament gets hot, and consequently emits light
  - gets "red hot"
Everything is Aglow

- All objects emit "light"
  - Though almost all the light we see is reflected light
- The color and intensity of the emitted radiation depend on the object's temperature
- Not surprisingly, our eyes are optimized for detection of light emitted by the sun, as early humans saw most things via reflected sunlight
  - no light bulbs, TVs
- We now make some artificial light sources, and ideally they would have same character as sunlight
  - better match to our visual hardware (eyes)

Color Temperature

<table>
<thead>
<tr>
<th>Object</th>
<th>Temperature</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>You</td>
<td>~ 30°C ~ 300 K</td>
<td>Infrared (invisible)</td>
</tr>
<tr>
<td>Heat Lamp</td>
<td>~ 500°C ~ 770 K</td>
<td>Dull red</td>
</tr>
<tr>
<td>Candle Flame</td>
<td>~ 1700°C ~ 2000 K</td>
<td>Dim orange</td>
</tr>
<tr>
<td>Bulb Filament</td>
<td>~ 2500°C ~ 2800 K</td>
<td>Yellow</td>
</tr>
<tr>
<td>Sun’s Surface</td>
<td>~ 5500°C ~ 5800 K</td>
<td>Brilliant white</td>
</tr>
</tbody>
</table>

The hotter it gets, the “bluer” the emitted light
The hotter it gets, the more intense the radiation

The “Blackbody” Spectrum

- Frequency (Hz)
  - Wilkinson: 4.4 x 10^14 Hz
- Wavelength (nm)
  - 750 nm
- Temperature (°C)
  - 750°C

Blackbody spectra on logarithmic scale

- Sun peaks in visible band (0.5 microns), light bulbs at 1 μm, we at 10 μm.
  - (note: 0°C = 273°K; 300°K = 27°C = 81°F)
Bulbs aren’t black! Blackbody??!!

- Black in this context just means reflected light isn’t important
- Hot charcoal in a BBQ grill may glow bright orange when hot, even though they’re black
- Sure, not everything is truly black, but at thermal infrared wavelengths (2–50 microns), you’d be surprised
  - even white paint is practically black
  - metals are shiny, though
- This property is called emissivity:
  - radiated power law modified to \( P = \sigma A T^4 \), where \( \sigma \) is a dimensionless number between 0 (perfectly shiny) and 1.0 (perfectly black)
  - \( \sigma \), recall, is 5.67 \times 10^{-8} \) in MKS units, \( T \) in Kelvin
- Why do we use aluminum foil?

What Limits a Bulb’s Lifetime

- Heated tungsten filament drives off tungsten atoms
  - heat is, after all, vibration of atoms: violent vibration can eject atoms occasionally
- Tradeoff between filament temperature and lifetime
  - Brighter/whiter means hotter, but this means more vigorous vibration and more ejected atoms
  - “Halogen” bulbs scavenge this and redeposit it on the filament so can burn hotter
- Eventually the filament burns out, and current no longer flows – no more light!
- How “efficient” do you think incandescent bulbs are?
  - Ratio between energy doing what you want vs. energy supplied
  - Efficiency = (energy emitted as visible light)/(total supplied)

Predicting Brightness in Bulb Networks

- This is a very instructive (and visual) way to learn about the behavior of electronics, how current flows, etc.
- The main concept is Ohm’s Law:
  \[ V = IR \]
  - voltage = current \times resistance
- We’ve already seen voltage and current before, but what’s this \( R \)?
- \( R \) stands for resistance: an element that impedes the flow of current
  - measured in Ohms (\( \Omega \))
- Remember the bumper-cars nature of a bulb filament? Electrons bounce off of lattice atoms
  - this constitutes a resistance to the flow of current

Interpretation of Ohm’s Law

- The best way to think about Ohm’s law is:
  - when I have a current, \( I \), running through a resistance, \( R \), there will be a voltage drop across this: \( \Delta V = IR \)
  - “voltage drop” means change in voltage
- Alternative interpretations:
  - when I put a voltage, \( V \), across a resistor, \( R \), a current will flow through the resistor of magnitude: \( I = V/R \)
  - If I see a current, \( I \), flow across a resistor when I put a voltage, \( V \), across it, the value of the resistance is \( R = V/I \)
- Ohm’s Law is key to understanding how current decides to split up at junctions
  - try to develop a qualitative understanding as well as quantitative
Bulbs in Series

- Each (identical) light bulb presents a "resistance" to the circulating electrical current.
- Adding more bulbs in series adds resistance to the current, so less current flows.

Which bulb is brighter? WHY?

Answer

- There is only one current flowing, and it goes through both bulbs. They will therefore shine with equal brightness.
  - Imagine exchanging bulbs. Does this change anything?

Reminder: Ohm’s Law

- There is a simple relationship between voltage, current, and resistance:

\[ V = I \times R \]

Ohm’s Law

V is in Volts (V)
I is in Amperes, or amps (A)
R is in Ohms (Ω)
Numerical examples of Ohm's Law ($V = IR$)

- How much voltage is being supplied to a circuit that contains a 1 Ohm resistance, if the current that flows is 1.5 Amperes?
- If a 12 Volt car battery is powering headlights that draw 2.0 Amps of current, what is the effective resistance in the circuit?

Answer #1:

(How much voltage is being supplied to a circuit that contains a 1 Ohm resistance, if the current that flows is 1.5 Amperes?)

- Use the relationship between Voltage, Current and Resistance, $V = IR$.
- Total resistance is 1 Ohm
- Current is 1.5 Amps

So $V = IR = (1.5 \text{ Amps})(1 \text{ Ohms}) = 1.5 \text{ Volts}$

Answer #2:

(If a 12 Volt car battery is powering headlights that draw 2.0 Amps of current, what is the effective resistance in the circuit?)

- Again need $V = IR$
- Know $I$, $V$, need $R$
- Rearrange equation: $R = \frac{V}{I}$
  - $(12 \text{ Volts})/(2.0 \text{ Amps})$
  - $= 6 \text{ Ohms}$

Conductors are at Constant Voltage

- Conductors in circuits are idealized as zero-resistance pieces
  - so $\Delta V = IR$ means $\Delta V = 0$ (if $R = 0$)
- Can assign a voltage for each segment of conductor in a circuit

- Batteries in parallel add energy, but not voltage
- Batteries in series add voltage
Multi-bulb circuits

Rank the expected brightness of the bulbs in the circuits shown, e.g. A>B, C=D, etc. WHY?!

Answer:

- Bulbs B and C have the same brightness, since the same current is flowing through them both.
- Bulb A is brighter than B and C are, since there is less total resistance in the single-bulb loop, so

\[
A > B=C.
\]

Adding Bulbs

- Where should we add bulb C in order to get A to shine more brightly?

Answer

- The only way to get bulb A to shine more brightly is to increase the current flowing through A.
- The only way to increase the current flowing through A is to decrease the total resistance in the circuit loop.
- Since bulbs in parallel produce more paths for the current to take, the best (and only) choice is to put C in parallel with B:
A more complex example!

Predict the relative brightness of the bulbs.

Answer

- The entire current goes through bulb F so it’s going to be the brightest.
- The current splits into 3 branches at C,D,E and they each get 1/3 of the current.
- The current splits into 2 branches at A,B and they each get half the current, so

F > A = B > C = D = E

If I disconnect bulb B, does F get brighter or fainter?

Answer

- By disconnecting B, the resistance of the (AB) combination goes up, so the overall current will be reduced.
- If the current is reduced, then F will be less bright.
Power Dissipation

- How much power does a bulb (or resistor) give off?
  - \( P = VI \)
  - but \( V = IR \)
  - so \( P = IR \) and \( P = \frac{V^2}{R} \) are both also valid
- Bottom line: for a fixed resistance, power dissipated is dramatic function of either current OR voltage

How about multiple resistances?

- Resistances in series simply add
- Voltage across each one is \( \Delta V = IR \)

![Image of resistances in series](image)

Total resistance is \( 10 \Omega + 20 \Omega = 30 \Omega \)
So current that flows must be \( I = \frac{V}{R} = \frac{3.0 V}{30 \Omega} = 0.1 A \)
What are the Voltages across \( R_1 \) and \( R_2 \)?

Parallel resistances are a little trickier....

- Rule for resistances in parallel:
  \[ \frac{1}{R_{\text{tot}}} = \frac{1}{R_1} + \frac{1}{R_2} \]

![Image of parallel resistances](image)

Can arrive at this by applying Ohm’s Law to find equal current in each leg. To get twice the current of a single 10 \( \Omega \), could use 5 \( \Omega \).

A Tougher Example

- What is the voltage drop across the 3 resistors in this circuit?

![Image of a tougher example circuit](image)
Answer

• First, need to figure out the current that flows in the circuit. This depends on the total resistance in the loop.
• Combine the parallel resistors into an equivalent single series resistor, the parallel pair are equal to a single resistor of 10 Ohms.
• The total resistance in the loop is $5 + 10 = 15$ Ohms.
• So the total current is $I = \frac{V}{R} = \frac{3}{15} = 0.2$ Amps.
• Voltage across $R_1$: $V = IR = 0.2 \times 5\,\Omega = 1$ Volt.
• Voltage across $R_2$: $V = IR = 0.2 \times 10\,\Omega = 2$ Volt.
• Note that the sum of the voltage drops equals battery voltage!

Complex Example

• Say battery is 5.5 Volts, and each bulb is 6.
• AB combo is 3\,\Omega.
• CDE combo is 2\,\Omega.
• total resistance is 11\,\Omega.
• current through battery is 5.5V/11\,\Omega = 0.5$ A.
• A gets 0.25 A, so $\Delta V = 1.5$ V.
• C gets 0.1667 A, so $\Delta V = 1.0$ V.
• F gets 0.5 A, so $\Delta V = 3.0$ V.
• note voltage drops add to 5.5 V.

Assignments

• Read pp. 224–231, 332–333, 407 for this lecture.
• Next Q/O (#2) due next Friday: only submit one this week if you missed it last week.