



Spectra of Lights: An Interactive Demonstration with Diffraction Gratings

Grades: 4th – 12th grade

Purpose: Students will explore the properties of different types of light bulbs using diffraction grating glasses to reveal the light's unique spectra or "fingerprint". The goal of the activity is for students to learn about types of lights and why we do or don't like to use them based on their effects on people, animals, and the environment. Students will be involved in a discussion of several types of lighting technologies, their properties and how they affect our environment.

This activity is commonly used in conjunction with the "Light Shielding Demonstration" to highlight a crucial part of the light pollution problem. While the "Light Shielding Demonstration" reveals how changing the shielding components of a lamppost can save energy, the primary goal of the "Spectra Demonstration" is to show how the energy efficiency of a specific type of lamp, as well as the lamp's appropriate lighting role, is related to the lamp's spectrum and physical properties.

Content Objective: Students will...

- Use diffraction grating glasses to view the spectra of various lights
- Ask and answer questions about what they see
- Identify good/bad lights through their spectra
- Recite the name of a type of bulb and a few of its properties

Time to do activity: This activity can take anywhere from 30 minutes to one hour depending on the speed of the presenter, the ages of the students, and the detail used in the presentation.

Materials Provided By Kit:

- ✓ Incandescent Light Bulb
- ✓ Compact Fluorescent Lamp (CFL)
- ✓ Light Emitting Diode Lamp (LED)
- ✓ Neon Light
- ✓ Light bulb sockets
- ✓ Diffraction glasses (one pair for each student)

Materials that Could Improve Activity:

- ✓ Halogen Light Bulb (Flood Light)
- ✓ Bug Light
- ✓ UV Lamp
- ✓ Power strip
- ✓ Extension chord
- ✓ Kitchen towel (for unscrewing hot light bulbs)



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Prerequisites: This activity is commonly used in after the “Light Shielding Demonstration” to highlight a crucial part of the light pollution problem. While the “Light Shielding Demonstration” reveals how changing the shielding components of a lamppost can save energy, the primary goal of the “Spectra Demonstration” is to show how the energy efficiency of a specific type of lamp, as well as the lamp’s appropriate lighting role, is related to the lamp’s spectrum and physical properties.

Integration: This lesson could be integrated into a unit on light or energy and highlights the connections between science, technology and society as outlined in the country’s science standards. It also pairs well with lessons on environmentalism and human responsibility. Additional readings and research projects could be assigned to address reading standards and improve students’ research methods.

Preparation: Recommended preparations for this activity include becoming familiar with “Background Information” below and setting up the various lights using the information under “Lesson Sequence” “Preparations” below.

Background Information:

- **Emission:**

Every atom is composed of protons, neutrons, and electrons. The protons and neutrons reside in the nucleus of the atom, while the electrons are distributed in orbitals that surround the nucleus. The model of an electron orbital has drastically changed of the last 90 years, and we now understand electron orbitals to be accurately represented by complex probability distribution functions, which are a result of the wave nature of the electron. Although the modern picture of the electron orbital is complex, it is only necessary to comprehend one detail of electron orbitals in order to understand **emission** – the process of an atom releasing electromagnetic radiation (EMR). The key is that different electron orbitals are linked to specific energies. Some electron orbitals are higher in energy, while others are lower in energy. Electrons can be “excited” to higher energy orbitals in a variety of ways, including an electric voltage supplied by an electrical outlet. When an electron “falls” from its excited state in the higher energy orbital to a lower energy orbital, the energy the electron has lost must be conserved. The energy is conserved by the atom releasing a photon, a packet of EMR, where the change in energy of the electron is equal to the energy contained in the emitted photon. (EMR is electro-magnetic radiation.)

The energy of a photon is a function of its wavelength; the lower the wavelength of the photon, the higher its energy. Because an atom is composed of many different electron orbitals, each of which are associated with specific energies, many different electron transitions are possible. This means that photons of various energies can be produced by a single atom. Because the photon’s energy is related to its wavelength, atoms can emit EMR of a wide range of wavelengths, including short wavelength Ultraviolet (UV), longer wavelength visible light, and even longer wavelength infrared radiation (see Figure 1).



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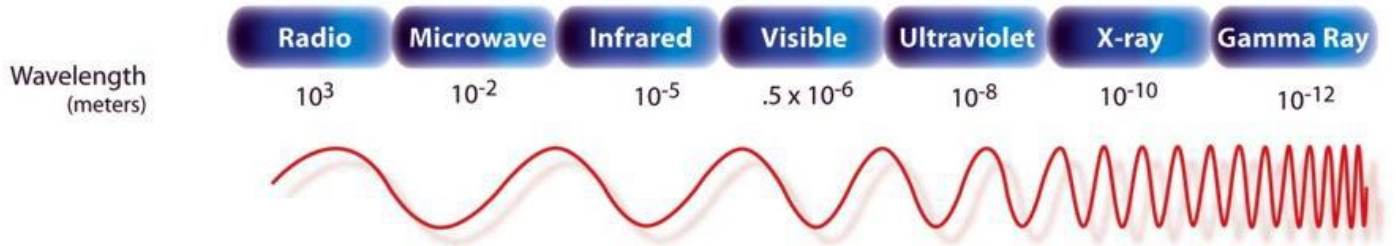


Figure 1: The electromagnetic spectrum, with the wavelengths of the associated photons

Although every type of atom has many different electron orbitals, the specific orbital structure is unique to each atomic element. Therefore, because the different electron transitions for each element are unique, so is the collection of different wavelengths of EMR that is emitted during the electron transitions. In other words, the EMR emitted by a certain type of atom has a specific “signature” of wavelengths unique to that atom. For instance, a hydrogen atom emits photons with wavelengths of 122 nanometers (UV), 486 nanometers (visible light), and 1000 nanometers (infrared), among many others.

Another type of emission that does not directly depend on an electron transiting between orbitals, but instead results from the energy contained in a hot object, is known as **incandescence**. Unlike the electron orbital emission described above, which produces only select wavelengths of light, emission by incandescence produces essentially *all* of the wavelengths of the electromagnetic spectrum at varying intensities. The brightness of each wavelength depends on the temperature of the object.

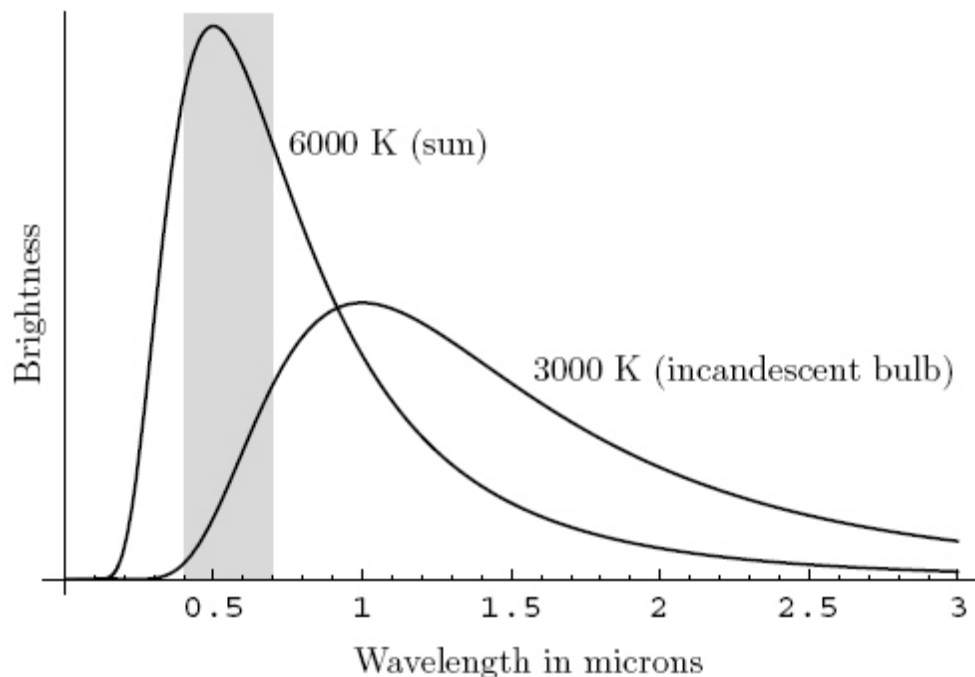


Figure 2: The brightness of the various wavelengths of EMR of two different incandescent objects



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Consequently, the “signature” of wavelengths for an incandescent source is quite different than that of other light sources which produce light due to the “falling” of electrons to lower energy orbitals. It is often impossible to tell, just by looking with the unaided eye, if a light source contains all of the wavelengths of visible light, or just a few. How can we analyze the mixture of wavelengths emitted by a source to determine if it operates via incandescence, or by other means.

- **Diffraction gratings:**

A diffraction grating is a tool used to separate EMR (usually visible light) based on its wavelength. Some commercial diffraction gratings, such as those made by Rainbow Symphony, Inc, are useful for demonstrating to a large audience how a light source really contains a signature spectrum.



Figure 3: Diffraction Grating slides and glasses

By holding this type of diffraction grating up to one’s eye to view to a light source, the repeating groove structure within the grating causes each of the specific wavelengths of light to obtain a maximum intensity at a particular angular deflection from the source. In other words, all of the wavelengths that are emitted by a source are completely separated. Therefore, the “signature” of the light is recovered in what scientists call an emission spectrum.

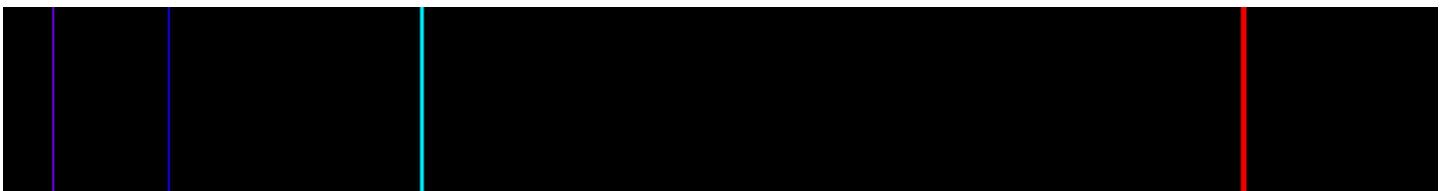


Figure 4: Hydrogen atom emission spectrum. Note only certain wavelengths are produced



Figure 5: Incandescent emission spectrum. All visible light wavelengths are produced

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- **Incandescent bulb:**

When an incandescent light bulb is screwed into a live socket, electricity is conducted through the metallic screw thread, up a wire, through the filament (typically tungsten), and back down a wire through the electrical foot contact. The movement of charge through the filament causes atoms to bump into each other, heating up the filament. Electrons are bumped into higher energy levels and as they fall back down into lower energy levels, they emit photons and the tungsten glows. The gas inside the light bulb allows the filament to glow without burning. Without the gas, the filament would simply burn up.

The bulb also produces a lot of waste radiation (infrared) that we can't see, which makes it quite inefficient. The "*luminous efficacy*" of a lamp is determined by the ratio of the power of the visible light emitted by the lamp to the total power it consumes. Incandescent bulbs often consume a lot of power and only give off a relatively small amount of visible light compared to infrared, which means their luminous efficacy is very low!

Because the filament is so hot, the glass bulb can get quite hot as well (as high as 400 °F). The lamp's high temperature is another way (besides the continuous and complete spectrum) to tell that a lamp is not efficiently using energy. Approximately 90% of the electrical power consumed by an incandescent lamp is turned into heat, rather than visible light – which is not a good thing for a LIGHTbulb!

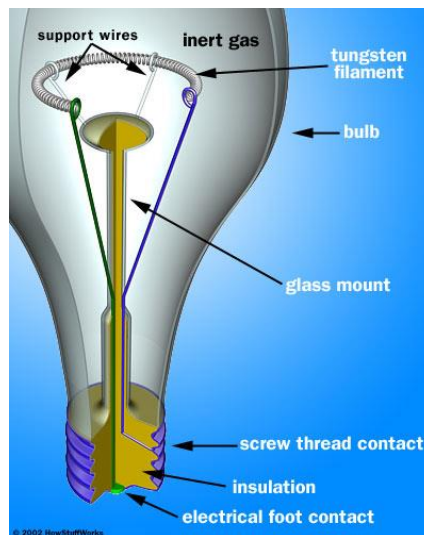


Figure 6: The structure of an incandescent light bulb



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- **CFL bulb:**

Instead of a glowing filament, CFLs contain argon and mercury vapor housed within a tube. They now come in many shapes, sizes and colors. They also have an integrated “ballast”, which produces an electric current to pass through the vaporous mixture, exciting the gas molecules. When stimulated by electric current, mercury vapor inside a CFL produces ultraviolet light, which is re-radiated as visible light when it strikes the fluorescent compound, known as phosphor, painted on the inside of the bulb. No other element has proved as efficient in this process, so even though the amounts of mercury used in bulbs has decreased over time, a small amount of mercury is still required for CFLs to function properly. Since CFLs contain mercury, it is important that they are disposed of properly. Some home improvement stores may offer recycling programs.

CFLs use significantly less energy -- 75 percent less energy than incandescent light bulbs. That means CFLs require less wattage to produce an equivalent amount of light. For example, you could use a 20-watt CFL and enjoy the same amount of light as a 75-watt incandescent. If every home in the United States of America made one such swap, enough energy would be saved in one year to light more than 3 million homes (source: Energy Star).

- **LED lamps:**

The spectrum is produced either by a single Light-emitting-diode, or LED and a combination of phosphors, or several different LEDs. Much of the specifics behind how a LED operates are beyond the scope of this activity, including *why* the spectrum appears continuous (which is best explained by band theory). However, the general mechanism of operation can be described.

A LED is essentially a sandwich of compounds called semiconductors. Semiconductors can either be natural elements (such as Si or Ge) or carefully engineered compounds. The sandwich of the compounds creates a flow of electrons, which leads to a production of photons of a certain wavelength, depending on the electronic structure of each of the compounds.

In the LED/phosphor case, usually a blue LED gives off light which is then absorbed by the phosphors to produce the other colors of the spectrum. In the multiple LED case, there are many different types of LEDs that, in combination, produce all of the colors of the spectrum.

This technology is remarkably energy efficient, although not very cost efficient. LEDs are now being integrated into many aspects of technology, including HD televisions, and of course, flashlights.



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- **Neon light:**

This light functions similarly to the CFL only that instead of mercury vapor, it utilizes some type of noble gas – typically neon, hence the name “Neon” light. Just like the CFL, most neon lamps are usually coated in phosphors, and the emission spectrum is once again a combination of both the wavelengths due to phosphor emissions and due to the noble gas. Although it is essentially impossible to observe any of the specific wavelengths when the light is viewed unshielded, a neon light of many different colors produces a very impressive image through diffraction gratings. These lights are often used for store signs, and are most well-known for lighting up the sky of Las Vegas. Though they are highly efficient in terms of energy consumption, shielding them effectively can be a problem, so they are large contributors to sky glow and glare.

- **Halogen light:**

Think of this light as a hotter, bigger version of the incandescent lamp, with one small twist. In a halogen lamp, a small amount of a halogen gas is added to the bulb. This trace amount of gas induces a set of chemical reactions known as the “halogen cycle.” The cycle acts to redeposit tungsten onto the filament that has previously sublimated, which greatly extends the life of the filament.

A drawback to the halogen cycle is that it must be conducted at high temperatures in order to function – even higher temperatures than are present in incandescent bulbs. Therefore, although the life of the bulb is extended compared to an incandescent lamp, the high bulb temperatures of halogen lamps leads to similar conversion rates of power to waste heat.

Though inefficient compared to a CFL, a halogen lamp is quite inexpensive for how much light total light it can produce. This is evident in the sheer number of halogens used in society (from car headlights to outdoor spot lights to pool lighting, etc.)

- **Bug light:**

Bug lights are available in incandescent or CFL formats. They are typically red or yellow in color. When seen through diffraction gratings, we see that they do not emit much if at all in the blue-violet range. The bug light utilizes only a few types of phosphors to give light in the green, red, orange, and yellow regions of the visible spectrum.

Why does this bulb use only the phosphors that don't produce blue and violet light? Most insects are attracted to blue and violet visible light, as well as UV radiation. Their eye structure is different than humans and it allows them to perceive UV radiation as visible light. Insects are only attracted to lights that they can see, so any light that minimizes production of those wavelengths will not attract bugs. A



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standard CFL bug light does this by allowing the phosphors to absorb any of the UV emitted by the excited Mercury atoms within the bulb.

- **UV Lamp:**

This type of lamp is mainly used in this demonstration to provide contrast to the bug light from before. This light produces the wavelengths of EMR that the bug light does not produce – UV and violet. It makes sense, then, that this type of lamp would attract insects. In fact, this kind of light is similar to “bug zappers” which are specifically designed to draw in insects. Don’t be surprised if a few moths fly toward the light while you’re doing your demonstration!

Aside from its insect attracting properties, a very large portion of the EMR emitted from this type of bulb is in the UV region of the spectrum. These high energy waves will immediately cause a few interesting effects amongst the audience, including making everything that is a light color fluoresce brightly. This is the same process that makes the phosphors in a CFL glow – the compounds in an object absorb UV light, exciting the electrons to high energy orbitals. The electrons then relax down to another lower energy orbital releasing energy as visible light, which gives the appearance of a “glowing” object.



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Lesson Sequence:

Preparations:

Start by setting up a variety of light sources. Four lamps are supplied in the kit: an incandescent, a CFL, an LED and a neon lamp. If more can be added, a good lamp variety should include an incandescent (both clear and coated), a halogen, a compact fluorescent, a bug light (a CFL works best), a portable neon light, an Ultraviolet lamp such as an "Avon Derma-Spec Skin Imager", and an LED bulb or LED flashlight. All of these lamp types are inexpensive and relatively easy to obtain. Mercury vapor and sodium discharge lamps are good additions, but are more expensive. Make sure all of the lights that are set up are switched off, and pass out diffraction gratings to the audience (such as the linear diffraction gratings mentioned above). Briefly explain what a diffraction grating is and what it is used for. A helpful comparison is that the separated light (the spectrum) created by the grating appears as a rainbow of colors – something very familiar to most children.

Next, ask the audience if they know what the ridges on their fingers are called. One student should figure out that they are called „finger prints“. With that, you can briefly explain how “each lamp, depending on how it operates and the chemicals it uses in order to function, exhibits a unique fingerprint in the form of its spectrum.” Explain how the spectrums for different lights are not the same, just as no two fingerprints are the same. The spectrums can vary in both the number of colors and the color separation.

Engage:

This part of the learning cycle will begin when each light source is turned on and students see the light's spectra or “finger print” through their diffraction gratings or glasses. Turn on the lamps one at a time, and let the audience examine them with their spectrum. The following two questions should be asked for each bulb:

“What colors do you see?”

“Are the colors separated or right next to each other?”

Explore:

As a classroom activity, students can use crayons or colored pencils to draw the colors and locations of the lines they see like in Figures 4 and 5. Alternatively, students could use normal pencils and label the colors of the lines or write “rainbow” across the bar if they see the entire visible spectrum.



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Explain:

The length and depth of this section will vary depending on the age of the audience. Spectra are often referred to as the lamp's 'finger print' for elementary age children. Many of the attributes listed in the background information section can be shared at this time. The following are "script" tips for each bulb.

Incandescent:

- The audience should see a continuous and complete spectrum, because the lamp obviously (from the name) operates via incandescence. Ask the audience how they think this lamp produces its light. The audience may or may not know right away, but if they don't, the clear incandescent bulb helps give them a hint.
- Turn off the coated bulb and turn on the clear incandescent bulb. The audience should see the same spectrum colors; because this is the same type of light (It's as if you were to clone yourself; your clone would have your same finger prints as you do). The glowing hot tungsten filament should be immediately visible. The filament, which can be as hot as 5000 °F, is the hot object that produces the light.
- Demonstrate to the audience that after a few seconds, it is impossible to touch the glass bulb for very long without burning your finger. We can think of an efficient bulb as producing very little heat and an inefficient bulb producing a lot of heat. **NOTE: This is often the better way to explain inefficiency to students, as it relies on a familiar physical property, instead of discussing "invisible" infrared radiation. Remember, infrared is not the same thing as heat!**
- If the audience has significant knowledge about electromagnetic radiation (EMR), then more details can be discussed as covered in the background information section. This could also serve as an introduction to EMR.

CFL:

- The CFL should produce most of the main colors of the rainbow (except for orange in some cases), but the colors will be separated. This makes sense, as the bulb does not produce light by incandescence.
- If the bulb is not shielded, the audience will see the entire bulb image (instead of just the emission spectrum) in many different colors. Unlike the incandescent bulb whose light source was the thin filament, the entire glass exterior of the CFL is the light source.



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NOTE: For younger audiences, it is recommended to skip the in depth discussion of electron transitions and to just say that there are several chemicals, both gases and solids, that get excited, and these excitations produce the colors you see.

- The audience should have seen the separation of the colors (a different type of “finger print” than the incandescent bulbs), which is indicative of a more efficient light bulb. If you want, you can touch the bulb to your hands or face to show the audience that the bulb is indeed cool and not producing very much waste heat.

LED light:

- This is the one exception to the original assumption that a continuous spectrum usually means a light is incandescent and is inefficient. A diffraction grating does indeed show a continuous spectrum, but this is only a cleverly manufactured spectrum that is designed to resemble incandescent light.

Neon light:

- It produces separate images of the light in each phosphor emission, creating a very impressive overall image for the audience to observe.

Halogen lamp:

- When viewed through the diffraction grating, the audience should see that the spectrum is similar to the incandescent bulbs. It should be noted that the spectrums look similar because the base mechanism for producing light – the heating of a metal – is the same for all incandescent type lamps.

Bug light:

- The bug light utilizes only a few types of phosphors to give light in the green, red, orange, and yellow regions of the visible spectrum. The blue and violet regions are missing, and the audience should immediately pick up on this. This is an obvious example of how a lamp’s “finger print” can change based solely on the amount of colors visible through a diffraction grating.

UV lamp:

- The audience should see just a few violet lines for this lamp, and nothing else.
- **NOTE: Efficiency is a bit complicated for this lamp type, so it can often be left out of the discussion.** On the one hand, this type of bulb produces a lot of excess heat, but this is only due to how the bulb operates and the large amount of UV radiation coming from the bulb. The



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bulb's luminous efficacy is actually quite high, but it must be defined in a slightly different way than for the incandescent bulb. For an incandescent bulb, visible light is the target EMR, and infrared and UV are byproducts that are essentially "wasted" when considering the bulb's purpose. However, for a UV lamp, its target EMR is in the UV region, and any visible light and infrared are byproducts. A better definition for the luminous efficacy of this lamp is the ratio of the power of the UV light emitted to the power consumed. By this definition, most UV lamps are quite efficient. So just because a lamp is not producing a lot of visible light does NOT mean that the mechanism behind the production of the light is inefficient – it depends on the light's overall purpose.

Elaborate:

In a classroom, you could provide students with several types of lights and ask them to determine what types of lights they are. Alternatively, they could take the diffraction gratings home and determine the types of bulbs used in their homes or around their neighborhoods and report back in the form of a worksheet, report, or presentation.

Evaluate:

After the demonstration, point to each bulb and ask the students to tell you 2-3 facts or key features about it. If this is part of a unit on light, energy, or science and society, the objectives of the assessment should evaluate the objectives as outlined previously (e.g., use diffraction grating glasses to view the spectra of various lights, ask and answer questions about what they see, identify good/bad lights through their spectra, and recite the name of a type of bulb and a few of its properties). The depth of the assessment will depend on grade level and the depth of the activity.



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Spectra worksheet: Draw and label lines to represent the colors you see from your diffraction grating on the bars below. If you see a whole rainbow, write "rainbow" across the bar.

EXAMPLE: (You do not need to color the rest black)



Incandescent Light Bulb

Compact Fluorescent Lamp (CFL)

Light Emitting Diode Flashlight (LED)

Neon Light



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If these bulbs are available:

Halogen Light Bulb (Flood Light)

Bug Light

UV Lamp