The Physics of Movie Sound

Outcomes:

1. To describe how the quantum energy concept explains black-body radiation and the photoelectric effect. (327-9)
2. To explain qualitatively and quantitatively the photoelectric effect. (327-10)
3. To explain how scientific knowledge evolves as new evidence comes to light and as laws and theories are tested and subsequently restricted, revised or replaced. (115-7)
4. Summarize the evidence for the wave and particle models of light. (327-11)
5. Analyze and describe examples where technological solutions were developed based on scientific understanding. (116-4)
6. Analyze technological systems to interpret and explain their structure. (116-7)

Introduction

"Going to the movies today is a very different experience from going to the movies 70 years ago – the picture is clearer, most of the movies are in color, and the admission price is a lot higher. But the biggest change is probably the sound experience" (Harris, p. 1). If you have ever had the chance to view an old silent movie, you probably realize what a difference sound makes. Today's moviemakers invest a lot of time and money in sound effects and in the overall quality of the soundtrack. This commitment to quality sound is what makes going to the theater such an enjoyable experience. But have you ever wondered how the sound you hear is produced in harmony with the images on the screen?

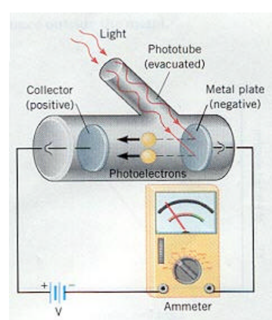
Theory

History

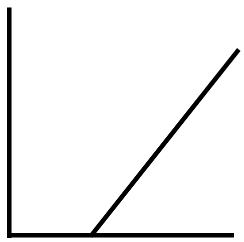
In 1889, Thomas Edison and his associates first began experimenting with synchronizing sound to the images viewed. The first commercial film to have accompanying recorded sound was "Don Juan" released by Warner Brothers in 1926. In the following year they released "The Jazz Singer" which had music, sound effects and a few lines of dialogue. Since then, movie sound has come a long way, due in large part to technological developments based on physics principles like the photoelectric effect.

Photoelectric Effect

The photoelectric effect is the phenomenon whereby when light shines on a metal surface, electrons are emitted from the surface. (This effect can be observed in other materials, but is most easily seen with metals.) It can be observed by using a photocell as shown in the diagram (Particles and Waves).



A metal plate and a smaller electrode (collector), are placed inside an evacuated glass tube called a photocell. The metal plate and collector are connected to an ammeter and to a voltage source. The ammeter will read zero when the photocell is in the dark, indicating that no current is present. But when light of sufficiently high frequency is shone on the plate, the ammeter shows that current is present. We can imagine electrons ejected from the plate by the light source and flowing across the tube to the collector to complete the circuit. The following diagram illustrates that if the frequency of light is less than the 'cutoff frequency' f_o, then no electrons will be ejected. The diagram also shows that if the frequency of the light is increased, the maximum kinetic energy of the electrons increases linearly.



The photoelectric effect can best be explained with Einstein's photon theory. In a beam of light all photons have the same energy given by $E = hf$ where h is Planck's constant (h =6.626 x 10^{-34} J·s) and f is frequency in Hertz. According to Einstein an electron is ejected from a metal by a collision with a single photon in the beam of light. In doing so, all of the photon energy is transferred to the electron and the photon ceases to exist. However some minimum energy W_o (called the work function) is necessary to get the electron out of the metal. If the frequency of the light is so low that hf is less than W_o, then the photons will not be able to eject any electrons. However, if $hf > W_o$, then electrons will be ejected, and energy will be conserved in the process. So the energy put in by the photon (hf) must equal the kinetic energy of the ejected electron (E_K) plus the energy required to get the electron out (W). Thus,

$$hf = E_K + W$$.

Assuming that W is the work function W_o, then the kinetic energy of the electron would be its maximum so,

$$hf = E_{K(\max)} + W_o$$

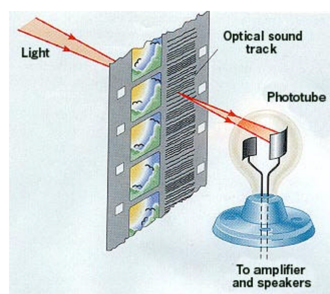
W_o is typically expressed in electron volts (eV) where 1 eV = 1.6x10^{-19} J. If electrons require more than the bare minimum (W_o) to get out of the metal, then the kinetic energy would be less than the maximum. An understanding of the photoelectric effect led to major developments in movie sound technology – from analog to digital.

Analog Sound

Analog sound refers to sound that is encoded as a long fluctuating stream of information. In the early days of cinema, 'sound on disc' technology consisted of a record player playing a wax record. The record was played on a turntable that synchronized sound to the film by controlling the speed of the projector. In the early 1930's sound on disc was replaced by 'sound on film'. The soundtrack was actually encoded on the film, though several frames away from the corresponding images. Sound on film uses either optical or magnetic technology.

Optical

In the optical process a transparent strip is recorded along one side of the film. The strip varies in width according to the frequency of the sound. As the film passes the audio reader (typically located below the lens of the projector) an exciter lamp produces a bright source of light which is focused by a lens through the transparent strip.



(Particles and Waves)

The light that passes through the film shines on a photocell, which then changes it to electric current. The amount of current produced by the photocell is determined by the amount of light it receives. The wider parts of the strip allow more light thereby producing more current. The electric current produced by the photocell is directly proportional to the intensity of light that reaches it. Since the width of the strip is changing, so is the amount of light. This results in a variable electric current that is sent to a pre-amplifier, which then boosts the signal to the amplifier for distribution to the speakers. The same result can be achieved by using a strip that varies in transparency instead of width. When using the transparency method though, the natural 'graininess' of the film can create background noise.

In the 1930's the entire soundtrack was played on a single speaker located behind the movie screen. Today we have surround sound where we hear sound coming from three or more directions. In surround sound there is more than one audio track on the film. The sound on each track can be sent to different speakers around the theater. For the listener, it creates the experience of actually being present at the event. Dolby Stereo® used three front channels and a surround sound channel with an advanced noise reduction process. "Dolby stereo is the analog sound standard, thanks to its superior sound quality" (Harris, p. 3).

Magnetic

In the 1950's, magnetic recording of soundtracks became popular. In this method sound is recorded on a stripe of metallic oxide coating located along the edge of the film. Even though magnetic recordings allowed as many as six discrete tracks of sound on a film, it was more expensive than optical recordings. Magnetic recordings also did not last as long as optical ones. Today optical track technology is the preferred choice for analog recordings. It is also utilized in digital sound systems.

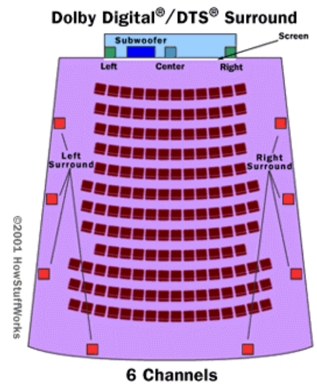
Digital Sound

Most theaters today boast of digital surround sound systems. In digital sound recordings, sound is encoded as a series of 1's and 0's just as in computer programs. This method allows for encoding more information in a limited space, thus producing more precise audio tracks. Digital sound cannot be recorded on videotape or broadcast on conventional cable. It is, however, the method used in encoding DVD's. The three major digital systems are,

1. Digital Theater Systems (DTS)
2. Dolby Digital
3. Sony Dynamic Digital Sound (SDDS)

Digital Theater Systems (DTS)

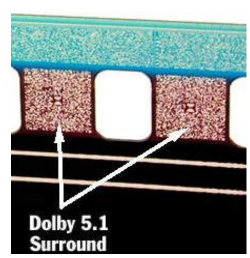
Digital theater sound was used in the 1993 movie Jurassic Park. In this system six separate audio channels are encoded onto one or two CD's. The theater has a CD player and a decoder that splits the channels up and plays them on different speakers arranged throughout the theater.



The CD is synchronized with the pictures by a time code on the film. This time code (a series of dots and dashes along the side of each frame) is read by an optical reader mounted on the projector. This reader shines light on the film with a light emitting diode (LED). Light passing through the film hits a photocell, which then sends pulses of current to the DTS processor. The dash pattern corresponds to a pattern encoded on the CD. The processor ensures that the two codes are synchronized so that the sound and the picture match (Harris).

Dolby Digital

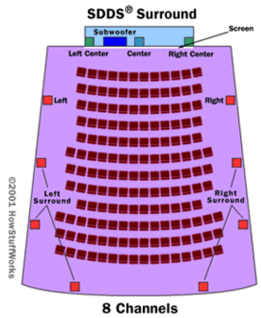
In Dolby Digital sound recordings, digital information is encoded as tiny patterns on the film in the space between the sprocket holes.



An LED is shone through this pattern as the film passes through the projector. On the other side of the film the light does not hit a photocell but a charge coupled device, and is finally interpreted as an audio signal.

Sony Dynamic Digital Sound (SDDS)

In Sony Dynamic Digital Sound there are five separate channels at the front of the theater, as well as left and right surround channels.



Digital information is encoded with a pattern of light and dark areas on the outside edge of the film. A laser passes light through transparent areas of the film, through a lens that magnifies the light, to fall on an array of photocells on the other side. Wherever there are dark areas on the film, the photocells in that area do not receive any light. Photocells that do receive light emit a small amount of current. The processor reads each cell as a 1 or a 0 based on whether or not it is generating current. As the film goes by a constant stream of binary information is sent to the processor. The processor then interprets the digital pattern as sound.

Conclusion

The proliferation of sound technology over the last 70 years has been phenomenal – from black and white silent movies to those rich in color and sound. While we may lament the increasing admission fees, perhaps we really are getting our money's worth.

Questions

1. What are the three main types of digital sound?
2. How is a photocell used in producing movie soundtracks?
3. What is the maximum kinetic energy and speed of an electron ejected from a sodium surface whose work function is W_o =2.28 eV when illuminated by light of wavelength 410 nm?
4. **Research:** How is a photocell used in an automatic garage door opener?

References

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Activities

Activity 1:
Check out this website to download a virtual lab on the photoelectric effect.
http://www-ed.fnal.gov/projects/photoe_lab/teachers_notes.html

Activities

Activity 2: Designing a Photoelectric Cell

Note that the HOBO system referred to throughout this lab can be substituted with Vernier software (voltage and light sensors) or the LabPro system.

Introduction:
Have you ever pondered what makes those automatic doors at supermarkets open and close? When we step in front of the door our bodies block a beam of light, which triggers the opening of the door. A photoelectric cell detects the presence or absence of light. The purpose of this lab is to build a simple photoelectric cell and to test the effect on the cell of varying the intensity of the light shining on it.

Materials:
A HOBO RH, Temp, Light, External data logger (HO8-004-02)
A voltage input cable (CABLE-2.5-STEREO)
250-ml beaker
Lead (II) nitrate
Nitric acid
Copper plate (roughly square with side length equal to the diameter of the beaker)
Lead plate (same size as copper plate)
Lamp or flashlight
Bunsen burner

Hypothesis:
Will voltage depend on the intensity of the light? If it does, then how will these two factors be related?

Theory:
When light strikes a metal surface, it has the potential to scatter an electron in the process. This is called the photoelectric effect and occurs when the light photon striking the metal possesses enough energy to excite the electron so that it jumps out of its orbit. Just how much energy is enough depends on the properties of the metal. If there is a convenient electrolytic medium surrounding the metal plate (in this lab, lead (II) nitrate is used, but salt water could be used as a simple alternative), then these scattered electrons can move, thereby creating an electric current. In this lab, scattered electrons travel through the lead (II) nitrate over to the lead plate and then up through the voltage sensor. The fact that there is a current automatically implies an associated voltage. White light is a combination of all wavelengths of visible light. As wavelength gets smaller, frequency increases (since $f\lambda = c$, where c is the speed of light, a constant) and increasing frequency implies increasing energy (specifically $E = hf$, where h is called Planck's constant and is equal to 6.626×10^{-34} J-s). It is likely that the longer wavelengths of the visible spectrum (the reds and oranges) will not carry enough energy to excite the electrons, but the shorter wavelengths (blues and violets) might. A very interesting aspect of the photoelectric effect is this idea that it is the energy of the photons that matters. If you shine very intense infrared light on a copper plate, you probably won't be able to observe any electron scattering at all. But if you shine a dim ultraviolet light on that same plate, you most likely will get results. Shining white light on the copper plate in this experiment will produce scattering because a portion of white light is high-energy blue and violet light. Increasing the intensity of the light will increase proportionately the number of high-energy photons and therefore should lead to more electrons being scattered and, consequently, a higher voltage.

Activities

Activity 2: Designing a Photoelectric Cell (Cont'd)

Procedure:
The first step is to form cuprous oxide from the copper plate. Heat the copper plate above the Bunsen burner until a layer of black cupric oxide covers the entire surface. There is a layer of cuprous oxide beneath this black stuff. Place the plate in the nitric acid until the black cupric oxide has dissolved leaving behind the red layer of cuprous oxide. In the beaker you should now put together 100 ml of an approximately 0.5 M solution of lead (II) nitrate in water. Place the lead and copper plates in the beaker so that they are about halfway submerged. Attach one of the voltage sensor's clips to the copper plate and the other clip to the lead plate. Launch the HOBO to record light intensity and voltage at half-second intervals. Attach the voltage sensor to the HOBO and position the data logger so that the light sensor is facing the lamp. Turn off the lights in the room and focus the lamp on the copper plate. Turn the light on for about ten seconds and then turn it off for another ten seconds. Place the light source two meters from the beaker and turn the light back on. Every ten seconds move the light a little bit closer, perhaps 20 cm at a time. Is there anything else you want to try? Try shining the light from a distance of about a meter and then have someone walk in front of it. Walk slowly since the HOBO is only making measurements every half-second. Can you think of applications in the real world that work in this fashion? When you're ready, display and analyze your results.

Analysis:
How does voltage vary with light intensity? Is this relationship linear? Does voltage react instantaneously to changes in light intensity, or is there a delayed repsonse? When you moved the light source towards the beaker, the HOBO should have recorded light intensity, increasing as the inverse square of distance. In other words, moving the light source halfway to the beaker should increase light intensity by a factor of four. Is this relationship reflected in the voltage measurement? One source of error is the fact that the light sensor is outside of the beaker and a good deal of light will be absorbed or reflected before striking the copper plate. How significant is this error? What are some other sources of error and what could you do to minimize them?

Something Extra:
Get some color filters and vary the frequency of the light shining on the copper plate. You could also use an ultraviolet lamp and perhaps an infrared lamp. Does a higher frequency of light imply a greater voltage? Is there some frequency at which no electrons are scattered? Be careful when choosing your filters to make sure they provide approximately monochromatic light. Also make a note of the effect of the filters on intensity.

Activities

Activity 3: Make a solar cell in your kitchen

Adapted from: **http://www.angelfire.com/ak/egel/solcell.html**

A solar cell is a device for converting energy from the sun into electricity. The high-efficiency solar cells you can buy at Radio Shack and other stores are made from highly processed silicon, and require huge factories, high temperatures, vacuum equipment, and lots of money. If we are willing to sacrifice efficiency for the ability to make our own solar cells in the kitchen out of materials from the neighbourhood hardware store, we can demonstrate a working solar cell in about an hour.

Our solar cell is made from *cuprous oxide* instead of silicon. Cuprous oxide is one of the first materials known to display the *photoelectric effect*, in which light causes electricity to flow in a material. Thinking about how to explain the photoelectric effect is what led Albert Einstein to the Nobel prize for physics, and to the theory of relativity.

Materials:

1. A sheet of copper flashing from the hardware store. This normally costs about $5.00 per square foot. We will need about half a square foot.
2. Two alligator clip leads.
3. A sensitive micro-ammeter that can read currents between 10 and 50 microamperes.
4. An electric stove. An 1100 Watt one-burner electric hotplate will also work.
5. A large clear plastic bottle of which you can cut the top off. I used a 2 liter spring water bottle. A large mouth glass jar will also work.
6. Table salt. We will want a couple of tablespoons of salt.
7. Tap water.
8. Sandpaper or a wire brush on an electric drill.
9. Sheet metal shears for cutting the copper sheet.

How to build the solar cell

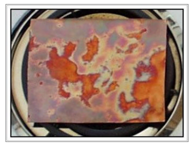
The burner looks like this:

The first step is to cut a piece of the copper sheeting that is about the size of the burner on the stove. Wash your hands so they don't have any grease or oil on them. Then wash the copper sheet with soap or cleanser to get any oil or grease off it. Use the sandpaper or wire brush to thoroughly clean the copper sheeting, so that any sulphide or other light corrosion is removed. Next, place the cleaned and dried copper sheet on the burner and turn the burner to its highest setting.

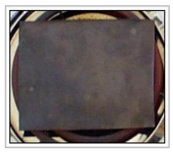
Activities

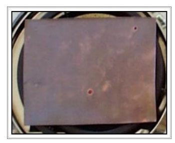
Activity 3: Make a solar cell in your kitchen (Cont'd)
Adapted from: **http://www.angelfire.com/ak/egel/solcell.html**

As the copper starts to heat up, you will see beautiful oxidation patterns begin to form. Oranges, purples, and reds will cover the copper.



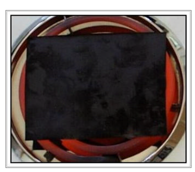
As the copper gets hotter, the colors are replaced with a black coating of *cupric oxide*. This is *not* the oxide we want, but it will flake off later, showing the reds, oranges, pinks, and purples of the cuprous oxide layer underneath.





The last bits of color disappear as the burner starts to glow red.

When the burner is glowing red-hot, the sheet of copper will be coated with a black cupric oxide coat. Let it cook for a half an hour, so the black coating will be thick. This is important, since a thick coating will flake off nicely, while a thin coat will stay stuck to the copper.



After the half hour of cooking, turn off the burner. Leave the hot copper on the burner to cool slowly. If you cool it too quickly, the black oxide will stay stuck to the copper.

As the copper cools, it shrinks. The black cupric oxide also shrinks. But they shrink at different rates, which makes the black cupric oxide flake off.

The little black flakes pop off the copper with enough force to make them fly a few inches (Note, wear safety goggles). This means a little more cleaning effort around the stove, but it is fun to watch.

Activities

Activity 3: Make a solar cell in your kitchen (Cont'd)
Adapted from: http://www.angelfire.com/ak/egel/solcell.html

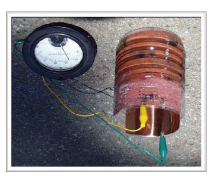
When the copper has cooled to room temperature (this takes about 20 minutes), most of the black oxide will be gone. A light scrubbing with your hands under running water will remove most of the small bits. Resist the temptation to remove all of the black spots by hard scrubbing or by flexing the soft copper. This might damage the delicate red cuprous oxide layer we need to make the solar cell work.

The rest of the assembly is very simple and quick. Cut another sheet of copper about the same size as the first one. Bend both pieces gently, so they will fit into the plastic bottle or jar without touching one another. The cuprous oxide coating that was facing up on the burner is usually the best side to face outwards in the jar, because it has the smoothest, cleanest surface.

Attach the two alligator clip leads, one to the new copper plate, and one to the cuprous oxide coated plate. Connect the lead from the clean copper plate to the positive terminal of the meter. Connect the lead from the cuprous oxide plate to the negative terminal of the meter.

Now mix a couple tablespoons of salt into some hot tap water. Stir the saltwater until all the salt is dissolved. Then carefully pour the saltwater into the jar, being careful not to get the clip leads wet. The saltwater should not completely cover the plates -- you should leave about an inch of plate above the water, so you can move the solar cell around without getting the clip leads wet.

The photo above shows the solar cell in my shadow as I took the picture. Notice that the meter is reading about 6 microamps of current. The solar cell is a battery, even in the dark, and will usually show a few microamps of current.



The above photo shows the solar cell in the sunshine. Notice that the meter has jumped up to about 33 microamps of current. Sometimes it will go over 50 microamps, swinging the needle all the way over to the right.

Activities

Activity 3: Make a solar cell in your kitchen (Cont'd)

Adapted from: http://www.angelfire.com/ak/egel/solcell.html

Theory

Cuprous oxide is a type of material called a *semiconductor*. A semiconductor is in between a conductor, where electricity can flow freely, and an insulator, where electrons are bound tightly to their atoms and do not flow freely.

In a semiconductor, there is a gap, called a *bandgap* between the electrons that are bound tightly to the atom, and the electrons that are farther from the atom, which can move freely and conduct electricity.

Electrons cannot stay inside the bandgap. An electron cannot gain just a little bit of energy and move away from the atom's nucleus into the bandgap. An electron must gain enough energy to move farther away from the nucleus, outside of the bandgap.

Similarly, an electron outside the bandgap cannot lose a little bit of energy and fall just a little bit closer to the nucleus. It must lose enough energy to fall past the bandgap into the area where electrons are allowed.

When sunlight hits the electrons in the cuprous oxide, some of the electrons gain enough energy from the sunlight to jump past the bandgap and become free to conduct electricity.

The free electrons move into the saltwater, then into the clean copper plate, into the wire, through the meter, and back to the cuprous oxide plate.

As the electrons move through the meter, they perform the work needed to move the needle. When a shadow falls on the solar cell, fewer electrons move through the meter, and the needle dips back down.