Teacher's Guide

Light Extraction by Changing Composition of Material

Grade Level: High school

Subject area: Physics

Time required: (2) 50 minute classes

Learning Objectives:
Through hands-on experimentation:
- understand the refractive index of different materials;
- determine how to maximize refractive index;
- determine effect of concentration and particle size/color on refractive

Summary: This activity has been designed to have students explore light emitting diodes (LED) and the importance of index of refraction in improving LED efficiency. This activity investigates the tune-ability of a polymer's index of refraction by using a macromodel LED. This activity will be a macromodel because the size of nanoparticles is smaller than the smallest wavelength of visible light. Using different glitter particle sizes or concentrations of glitter will model the use of nanoparticles. The macromodels will be gelatin molds infused with glitter varying size, color, and concentration to examine impact on refraction.

Lesson Background Information:

"*Nothing can travel faster than the speed of light.*"
"*Light always travels at the same speed.*"

These two misleading statements are generally quoted as results of Einstein's Theory of Relativity. The fact of the matter is that the speed of light in a vacuum is always the same: 3.0×10^8m/s, and light travels the fastest in a vacuum. In any medium, the particles present in the medium scatter the light and the speed changes depending on the composition of the medium through which the light is traveling. Many waves behave the same way by slowing down in different media. This property of the material is called the *index of refraction* and is expressed as a ratio of the speed of light in a vacuum and the speed of light in the medium.

$$\text{index of refraction } (n) = \frac{\text{speed of light in a vacuum } (c)}{\text{speed of light in a medium } (v)}$$

Table 1: Index of Refraction of some common materials.[1]

Material	Index of Refraction (*n*)
Vacuum	1.0000
Air	1.0003
Water	1.33
Ethanol	1.36
Crown glass	1.52
Heavy flint glass	1.65
Diamond	2.42

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A fact about *light waves*: A soap bubble appears iridescent in white light when the thickness of the soap film is about the same as a wavelength of light.[1]

Materials with increased index of refraction are needed in industry for anti-reflective coatings in photonic devices, such as light emitting diodes (LEDs) and image sensors. LEDs are a particular type of diode that convert electrical energy into light using semiconductors and electroluminescence. The light from the LEDs primary optic is too broad for most applications, lacking intensity over distance. The LED uses a small semiconductor crystal with reflectors and other parts to make the light brighter and focused into a single point. The wavelength of the light depends on the energy band gap of the semiconductors used.

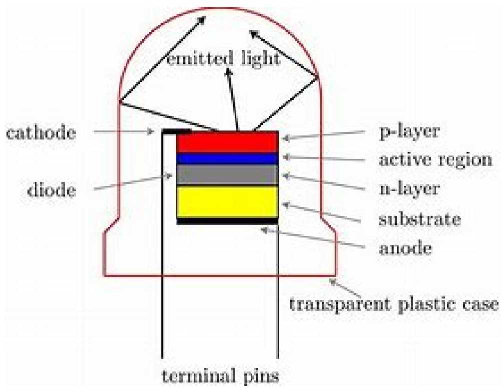

Figure 1. Diagram of a light emitting diode. https://commons.wikimedia.org/wiki/File:LED_Device.jpg

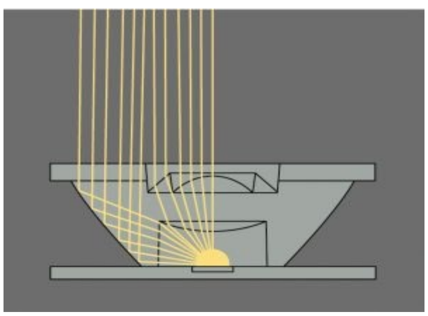

Figure 2. Diagram of the reflection from a LED reflector that uses a total internal reflection lens made from a polymer. galery/lighting-reflectors.html -

Since these materials have a high index of refraction, design features of the devices such as special optical coatings and die shape are required to efficiently emit light. LED research has led to the development of many high efficiency products but there is still a need for optical encapsulants with high refractive index to increase efficiency. The silicone materials used presently have a refractive index of 1.5, and scientists are in constant search for materials to increase this refractive index. Introduction of nanoparticles with higher refractive indices have the potential to increase the refractive index of the composite. High efficiency LEDs cannot be used without a protective encapsulant which decreases the brightness but also increases the optical size of the LED. The higher refractive index results in the bending of light at a higher angle into the encapsulant thus increasing the optical ~~size~~ brightness or output. For a typical polymer, encapsulation decreases the brightness by a factor of about two.[2]

Industrial and academic researchers have been trying to manufacture these products with low cost. Mixing a material that has a high refractive index into a medium is known to increase the index of refraction of that medium. LEDs are encapsulated in polymers or silicone (*n* = 1.5)[3].

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Much research is occurring to increase the light extraction from LEDs by adding nanoparticles to these media. Nanoparticles (1-100 nm) don't have a noticeable effect on the transmission of the visible light because their size is smaller than visible light (380 nm-740 nm). Amorphous TiO_2 at 30% concentration showed light transmittance of 94% at 450 nm and refractive index of 1.63[4].

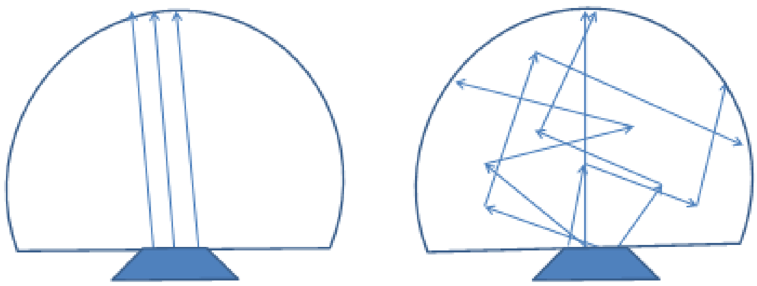

Figure 1: Role of nanoparticles in increasing the optical size of an LED

LEDs began commercial use around 1962 and were first used in remote control devices. Because of their low energy consumption and long life, LEDs have become the standard in lighting including household lights, automobile lights, traffic signals etc. You may want to ask students to compile a list of LED uses that they encounter in their daily lives.

Sources

1. CRC. *Handbook of Chemistry and Physics*. 93rd Ed., 2012-13, CRC Press, p. 10-248.
2. Wierer, J., Aurelien D and Megens M. "III-nitride photonic-crystal light-emitting diodes with high extraction efficiency." *Nature Photonics*, Vol. 3, 163- 169, 2009.
3. Gabrielli L., Cardenas J., Poitras C. and Lipson M. "Silicon nanostructure cloak operating at optical frequencies" *Nature Photonics*, Vol. 3, 461 - 463 (2009).
4. Lem, K; Nguyen, D; Kim, H; Lee, D. "Preparation and Characterization of the Transparent Hybrids of Silicone Epoxy Resin and Titanium Dioxide Nanoparticles via Sol-Gel Reactions" *Journal of Nanoscience and Nanotechnology*, Volume 11: 8, 7202-7205(4), 2011.
5. Scully, T., "LED Optics Explained". https://www.ledsupply.com/blog/led-optics-explained/ Accessed August 2019.

Pre-requisite Knowledge: Students should know what light is, how it travels, and how refraction occurs.

Materials per class period

Access to a refrigerator is required for this activity

- Dark paper cups to make photodetector, one per group (if you cannot find dark cup paint it using black paint)
- Photodetector one per group
- One needle to make tiny holes in paper cup
- Printed photodetector guide, one per group

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- Lamination sheets for photodetector guide.
- Plastic wrap (Saran wrap)

Materials per group of 3

- styrofoam cup
- 1 pack of unflavored gelatin
- 1 cup water
- hot plate or kettle to boil water
- plastic spoon
- Mini Half-Sphere Cake Silicone Mold/ Baking Pans
- different sizes/colors of glitter
- balance
- weighing boats/papers
- craft sticks/wood splints for mixing the glitter into the gelatin
- clock, watch, or stopwatch
- photodetector
- multimeter with leads
- set of alligator clips
- laser light pen
- graph paper
- metric ruler

Source/Website	Material
Digi-Key Corporation (800) 858-3616 http://search.digikey.com/scripts/DkSearch/dksus.dll?Detail?name=PDV-P5001-ND	• photodetectors (part number PDV-P500; ~$2.25 each)
SK Science Kit & Boreal Laboratories (800) 828-7777 http://sciencekit.com/key-chain-laserpointer/p/IG0024470/	• keychain red laser pointers (These are sometimes less expensive at retail stores.)
All Electronics (888) 826-5432 http://www.allelectronics.com	• digital multimeters, multiple colored jumper test leads with insulated alligator clips
Online or craft stores	• glitter of different sizes (very fine to chunky) and colors can be purchased online or at craft stores.
www.amazon.com https://www.amazon.com/Cavity-Silicone-Polymer-handmade-Chocolate/	• 15 cavity Mini Half Sphere Silicone Cake Baking Pan

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Safety Information: Never shine laser light into anyone's eyes, including reflected laser light; it will harm a person's retina and can cause permanent blindness. Hot water and water vapor can cause severe burns.

Vocabulary: *Before* beginning the lab, review the meaning of these terms:

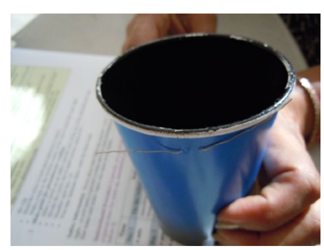
- *Wave* A disturbance or variation that transfers energy progressively from point to point in a medium and that may take the form of an elastic deformation or of a variation of pressure, electric or magnetic intensity, electric potential, or temperature.[2]
- *Wavelength* The distance between two successive, repeating parts of a wave.[1]
- *Wavespeed* The speed at which a wave passes any fixed point over time; expressed as speed = frequency × wavelength.[1]
- *Reflection* The return of any wave from a barrier in such a way that the angle at which a given ray is returned is equal to the angle at which it strikes the surface. When the reflecting surface is irregular, light is returned in irregular directions; this is diffuse reflection.[1]
- *Refraction* The bending of an oblique ray of wave when it passes from one medium to another.[1]
- *Critical angle* The minimum angle of incidence at which a light ray is totally reflected within a medium.[1]
- *Total internal reflection* The total reflection of light traveling in a medium when it strides on the surface of a less dense medium at an angle greater than the critical angle.[1]

In addition to reviewing the vocabulary, explore with the class these questions to provoke thought and to review their prior knowledge:

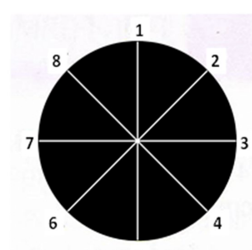
1. You have a light bulb with low output. What can you use to increase the light from this bulb?
   You may use mirrors for reflection which would help increase the light in room.
2. How may you increase the area covered by light?
   Move the light source away from a wall to a more central location which would result in more area covered.

Advance Preparation:

1. *Make the photodetectors.*
   - Using a needle, poke two tiny holes about 0.5 cm apart and 1.0 cm from the rim in the paper cup
   - Insert the photodetector's leads through these holes with the photodetector being inside the cup.
   - Bend the wires to hold photodetector in place.
   - Make a hole in the bottom center of the cup to insert the laser light.

2. *Make guide for photodetector readings.*
   - Print the photodetector guide (at end of lesson).
   - Laminate for future use.



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- You need one photodetector per group.

3. Calculate concentrations of glitter
    - Test the type of glitter you have for maximum and minimum concentration by making gels. The concentration will be determined by the formula: Concentration = grams of glitter/ grams of gel
    - This will vary depending on the make and size of glitter.

Suggested Instructional Procedure:

Time	Activity
Day 1	
20 min	Introduce students to the topic of LEDs, reflection, and refraction (see Resources for helpful sites). Assign each group a different variable like the type of the glitter, the particle size of the glitter or the concentration of glitter particles. Depending on the class level you may decide to test only one variable with all the groups. Based on the variable, demonstrate the calculation of glitter in each mold. Based on your own calculation for the glitter type you are using, assign students the concentration values.
30 min	Distribute student worksheet Students will follow Day 1 procedure. Store the student gels in refrigerator after covering with plastic wrap.
Day 2	
4 min	Review terms and ask students warm-up questions in the *Vocabulary* section.
40 min	Have students follow procedures to measure the light extraction of the gels with the introduced glitter particles.
3 min	Assign homework: graph the data and answer conclusion questions.
3 min	Clean up.

Teaching Strategies: This investigation needs students to work in groups of three. At least two students need to use the setup for the experiment and one student needs to record the data. Prior to beginning the activity, list any last minute details that the students must remember, including reiterating all safety precautions regarding the danger of eye damage with the laser and burns with the hot water.

Procedure Checkpoints:

- The students should work in groups of three.
- Different groups can investigate different variables like the type of the glitter, the particle size of the glitter or the concentration of glitter particles.
- Two groups will share one mold.

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Procedure for the Activity:

Found in Student Worksheet below

Assessment:

Students will be able to:

- Record appropriate quantitative and associated qualitative raw data including units, process the raw data correctly, present processed data appropriately and, where relevant, include errors and uncertainties.
- State a conclusion with justification based on a reasonable interpretation of the data, evaluate weaknesses and limitations, and suggest realistic improvements with respect to identified weaknesses and limitations.
- Understand the effect of changed composition of optically transparent materials on index of refraction and its implications.

Resources: You may wish to use these resources either as background or as a resource for students to use in their inquiry-based design.

1. A good online applet showing how light refracts due to angle of incidence and wavelength of light: http://micro.magnet.fsu.edu/primer/java/scienceopticsu/refraction/refractionangles/index.html
2. Refraction of light PowerPoints online (free download): https://www.slideshare.net/search/slideshow?searchfrom=header&q=refraction+of+light "Anti-Reflective Coating" *Wikipedia* Wikimedia Foundation, Inc.1 June 2011*Web*. 15 June 2011. http://en.wikipedia.org/wiki/Anti-reflective_coating
3. "Atoms, Electrons and Photons" *The Energy Groove* n.d.*Web*.22 June 2011. http://www.energygroove.net/atoms.php>
4. "Iridescent Colors Caused by Interference: Iridescence". *Causes of Color* n.d. *Web*. 29 June 2011. http://www.webexhibits.org/causesofcolor/15.html
5. Mark Foster. "Physics Definitions." (accessed August, 2012) http://mark.foster.cc/school/phys100.html
6. Nanowerk. "High light-extraction efficiency from high-refractive-index semiconductors." (accessed October, 2012) http://www.nanowerk.com/news/newsid=16229.php
7. Kubo et al., "Tunability of the Refractive Index of Gold Nanoparticle Dispersions." Nano Letters Volume 7 (2011): 3418-3423
8. You Tube – numerous videos are available on how LEDs work and their development
9. Learn about LED lighting - https://www.energystar.gov/products/lighting_fans/light_bulbs/learn_about_led_bulbs
10. How LEDs Work - https://electronics.howstuffworks.com/led.htm

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Next Generation Science Standards

PS3.A.4

Electrical energy may mean energy stored in a battery or energy transmitted by electric currents.

HS PS4-3 Evaluate the claims, evidence, and reasoning behind the idea that electromagnetic radiation can be described either by a wave model or a particle model, and that for some situations one model is more useful than the other.

HS-PS4.B.1: Electromagnetic radiation (e.g., radio, microwaves, light) can be modeled as a wave of changing electric & magnetic fields or as particles called photons. The wave model is useful for explaining many features of electromagnetic radiation, and the particle model explains other features.

PS4.A.1

The wavelength and frequency of a wave are related to one another by the speed of travel of the wave, which depends on the type of wave and the medium through which it is passing.

PS4.B.3

Photoelectric materials emit electrons when they absorb light of a high-enough frequency.

PS4.C.1

Multiple technologies based on the understanding of waves and their interactions with matter are part of everyday experiences in the modern world (e.g., medical imaging, communications, scanners) and in scientific research. They are essential tools for producing, transmitting, and capturing signals and for storing and interpreting the information contained in them.

Cleanup: Wipe the photodetector guide cards with wet towel. Dispose of all the gels in a regular trash can. Unplug the leads from the multimeter and store.

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Student Worksheet
(with answers in red)

Light Extraction by Changing Composition of Material

Introduction:

"*Nothing can travel faster than the speed of light.*"
"*Light always travels at the same speed.*"

These two misleading statements are generally quoted as results of Einstein's Theory of Relativity. The fact of the matter is that the speed of light in a vacuum is always the same: 3.0×10^8m/s, and light travels the fastest in a vacuum. In any medium, the particles present in the medium scatter the light and the speed changes depending on the composition of the medium through which the light is traveling. Many waves behave the same way by slowing down in different media. This property of the material is called the *index of refraction* and is expressed as a ratio of the speed of light in a vacuum and the speed of light in the medium.

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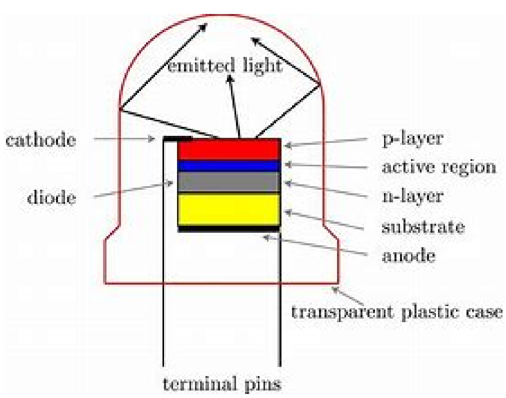

Figure 1. Diagram of a light emitting diode. https://commons.wikimedia.org/wiki/File:LED_Device.jpg

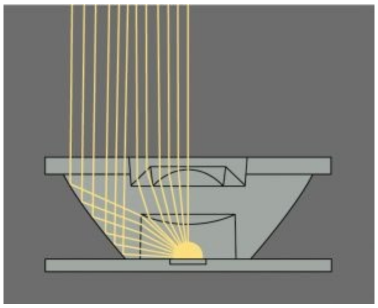

Figure 2. Diagram of the reflection from a LED reflector that uses a total internal reflection lens made from a polymer. galery/lighting-reflectors.html -

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Industrial and academic researchers have been trying to manufacture these products with low cost. Mixing a material that has a high refractive index into a medium is known to increase the index of refraction of that medium. LEDs are encapsulated in polymers or silicone (n = 1.5)[3]. Much research is occurring to increase the light extraction from LEDs by adding nanoparticles to these media. Nanoparticles (1-100 nm) don't have a noticeable effect on the transmission of the visible light because their size is smaller than visible light (380 nm-740 nm). Amorphous TiO_2 at 30% concentration showed light transmittance of 94% at 450 nm and refractive index of 1.63[4].

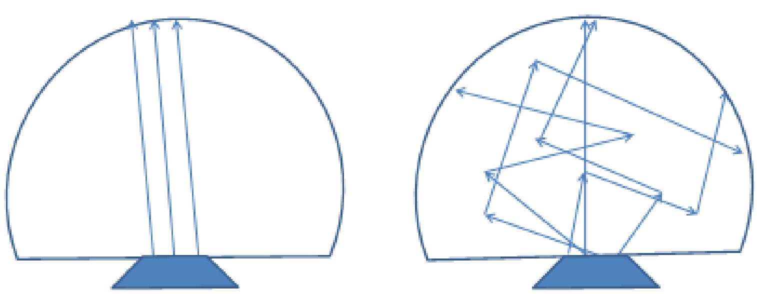

Figure 1: Role of nanoparticles in increasing the optical size of an LED

Materials per group:

- styrofoam cup
- 1 pack of unflavored gelatin
- 1 cup water
- hot plate or kettle to boil water

- plastic spoon
- mini silicone half-sphere cake mold/baking pans
- different sizes/colors of glitter
- balance
- weighing boats
- craft stick/wood splints for mixing the glitter into the gelatin
- clock, watch, or stopwatch
- photodetector
- multimeter with leads
- set of alligator clips
- laser light pen
- graph paper
- metric ruler

Procedure:

- Your group of 3 will be assigned a different variable such as glitter color, particle size of the glitter, or the concentration of glitter particles. Glitter represents a macro-model of nanoparticles.
- You teacher will indicate how many groups will share one mold.

Day 1: Preparation of gelatin

1. Each group will have one control gel – no glitter added. Depending on the variable being tested, you will be instructed on a fixed amount to weigh out of the glitter for each gel using a balance and weighing boats. If you are testing type of glitter or particle size of glitter, all concentrations must be the same. If your group was assigned the concentration variable you will have 5 different concentrations assigned by you teacher. Record your glitter variables in your data table.

2. Dissolve one packet of gelatin in one cup of hot water in a styrofoam cup. Stir to remove all the lumps using a plastic spoon. This will make 6 half-spheres. One of the half spheres will be used as control without any glitter and others will have the glitter variables.

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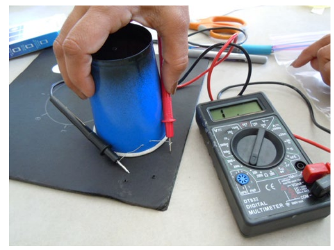
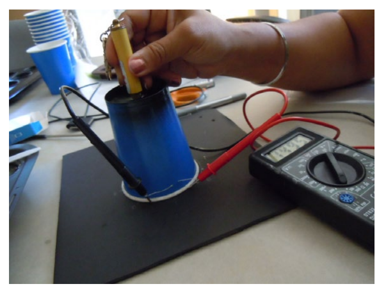
3. Pour the gelatin into the molds. Using a craft stick stir the gel in the molds every minute for 5 minutes. When the gel starts to set (begins to thicken) add the glitter particles to it.
4. Keep stirring to make sure the particles are evenly distributed.
5. Stop stirring once the gel seems to be firming and the particles are not moving to the bottom of the gel (not settling to the bottom), otherwise the gel will be lumpy. Label the mold with your group name and the variable. Leave the gel to set overnight in a refrigerator.
6. **6.** Clean up your lab stations. Put the styrofoam cup, plastic spoon, and craft stick in the trash.

Day 2: Measuring the light extraction



1. Now that the gels are set, remove them from the mold and invert one gel on the photodetector reading guide positioning it in the center.
2. Attach the multimeter probes to the photodetector wires and plug the other ends into the multimeter. The photodetector wires should not touch each other.
3. Set the multimeter to measure resistance (Ohms, Ω), and set the meter to 20 kΩ. The resistance will decrease as the illumination on the photodetector increases.



4. Measure and record the readings on the multimeter for ambient light (the light regularly in the classroom), with ambient light blocked by inverting the cup (make sure to cover the hole for the laser light), and with laser light shining directly on the photodetector. Record your readings on your Student Worksheet. *The multimeter should read about 4,000 Ω (40 kΩ) in normal light, about 14,000 Ω (140 kΩ) when the photodetector is blocked, and about 800 Ω (0.8 kΩ) with the laser light shining on it.*
5. Now invert the photodetector cup on the guide covering the gel with the photocell aligned with number 1 on the guide.

6. Set up the laser pointer to shine through the hole in the bottom of the cup (which is inverted, so the top of the cup).
7. Record the reading on the multimeter in the table on your Student Worksheets in the Record Your Observations section.
8. Rotate the cup so the photocell is aligned with number 2 and record the readings on the multimeter.
9. Repeat the procedure. Record readings for all the points.
10. Add the values together for each reading to give a final reading and record in the Total column of your table.
11. Repeat for all of your gel variables.

Record your observations

____

____

____

____

Resistance for ambient light _________

Resistance with light blocked __________

Resistance with laser shining on photodetector________

Table 1: Record the resistance for gels with different concentrations of glitter.

	Resistance At Different Angles (Ω								
Concentration g/gel	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Total**
0.0	*13.0*	*12.0*	*15.0*	*13.0*	*12.0*	*11.0*	*12.0*	*12.0*	*100.0*
0.1									
0.2									
0.5									
1.0									
2.0									

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Table 2 : Record the resistance for gels with different particle size of glitter.

	Resistance At Different Angles (Ω								
Particle size	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Total**
No Glitter	*13.0*	*12.0*	*15.0*	*13.0*	*12.0*	*11.0*	*12.0*	*12.0*	*100.0*

Table 3 : Record the resistance for gels containing different types/color of glitter

	Resistance At Different Angles (Ω								
Type of glitter	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Total**
No glitter	*13.0*	*12.0*	*15.0*	*13.0*	*12.0*	*11.0*	*12.0*	*12.0*	*100.0*

Analyze the Results:

Plot a graph on your graph paper using the resistance value as a function of the variable tested. Make sure to use the independent variable on the X- axis. If you are testing different types of glitter, make a bar graph, and if you are testing different concentrations, make a scatter plot with a best-fit line.

Draw Conclusions

1. What is the relationship between the independent and dependent variable?

   Answers will vary depending on the variable tested. Example

   A direct correlation - the dependent variable (amount of light extracted) was directly related to independent variable (concentration of glitter)

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2. Why are nanoparticles used in materials to increase the index of refraction?

   Nanoparticles are smaller than the wavelength of light and do not affect the transmission of light. Nanoparticles are also used to introduce other properties like mechanical strength and reflecting shorter wavelengths.

3. What other material can we use in this experiment to make the light transmission better?

   Optically transparent materials like glass beads can be used to increase THE REFRACTIVE INDEX OF GEL. These beads should have higher index of refraction and addition of these particles should increase the index of refraction for the medium.

Cleanup:

- Wipe the photodetector guide cards with wet towel.
- Dispose of all the gels in a regular trash can.
- Unplug the leads from the multimeter and store.

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