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Teacher's Guide

Refraction of Light: A forensic analysis

Grade Level: High school

Subject area(s): Physics

Time required: (2 – 3) 50 minute class periods (depending on which activities are done)

Learning Objectives: Using two demonstrations and an inquiry-based activity, students will comprehend the principles of the refraction of light and its application in forensic science.

Summary: This lesson uses forensic science investigations to help students understand the refraction of light. Using The Marching Band Analogy, the students firsts "experience" how wavelengths of light can slow and bend. This activity provides an excellent analogy to understanding the cause of light refraction. The forensic portion of the lesson has students solve a crime scene by identifying glass using the index of refraction. Students also learn that the refraction of light occurs at the nanoscale as the visible light range is 380 to 740 nm.

Pre-requisite Knowledge: Students should have some prior recognition of the refraction of light phenomenon such as a straw in a glass of water

Lesson Background: *Glass and its properties*: Glass is a non-crystalline amorphous solid material usually made of some percentage of silica. In science terms, the definition can go beyond this to include all solids that have a non-crystalline, amorphous, structure at the atomic scale (the nanoscale). These glasses also exhibits a glass-liquid transition when they heated near the liquid state. Nearly all commercial glasses fall into one of six basic categories based on chemical composition. Within each category (except for fused silica) there are numerous distinct compositions.

1. *Soda-lime glass*: most common type; composition is 60 -75% silica, 12-18% soda, and 5 - 12% lime. Also referred to as *crown glass.*
2. *Lead glass:* composition is at least 20% lead oxide, silica. This glass has high electrical insulating properties and is used in thermometer tubing, art glass and crystal glasses. *Flint glasses* were lead glasses containing around 4–60% lead oxide; however, the manufacture and disposal of these glasses are sources of pollution because of their high lead content. In modern flint glasses, the lead is replaced with other additives such as titanium dioxide and zirconium dioxide without significantly altering the optical properties of the glass.
3. *Borosilicate*: Composition is at least 5% boric oxide, silica. This glass has high resistance to temperature change and is used in light bulbs, headlights, lab ware, and bake ware. It is also referred to as pyrex

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4. *Aluminosilicate glass*: Composition is aluminum oxide, similar to Pyrex, but with better chemical durability. When coated with an electrically conductive film it can be used as a resistor in electronic circuits.
5. *96% Silica glass*: Composition is borosilicate glass processed to remove almost all of the non-silicate elements. It has a heat resistance of up to 900 °C and was used on the space shuttle.
6. *Fused Silica glass*: Composition is pure silicon dioxide in the non-crystalline state. This is the most expensive and most difficult to make. This glass can sustain temperatures up to 1200 °C for a short period of time. It was used on the windows of the space shuttle.

Other Types of Glass:

1. *Float glass*: Float glass gets its name because the Soda-Lime Glass is cooled on top of a bath of molten tin. Windows are typically made from this type of glass.

2. *Tempered glass*: Glass which strengthened by introducing stress through rapid heating and cooling of the glass surface. It does not shatter but rather fragments and is used in the side and rear windows of automobiles.

3. *Laminated glass*: This glass consists of two sheets of ordinary glass bonded together with a plastic film. Windshields of automobiles are made with laminated glass.

Forensics and the Indices of Refraction

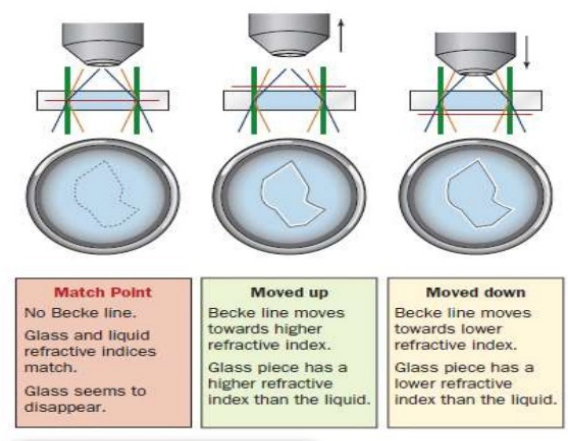
In forensic science, the term material evidence refers to anything manufactured such as glass, fibers, paint, etc. Usually there is quite a bit of material evidence left at a crime scene and it can be a great source of information to connect a suspect or a victim to that particular location.

There are several ways to analyze chips of glass at a crime scene. A few common ways is to test the density of the sample, melting points, shape and appearance under a microscope (optical or Scanning Electron Microscope), chemical analysis, and identifying optical properties such as the index of refraction.

Since different types of glass have different indices of refraction, they can be identified by submerging them into heated oils of various indices of refraction. The oil is heated because glass will change its refractive index as its temperature increases. Once heated at the correct temperature, several techniques can be applied to determine the index of refraction: 1) use a laser to measure the light refraction; 2) use a refractometer; or 3) use an optical microscope.

Cargille Liquids are standard liquids used in many laboratories to identify particles by microscopic immersion techniques. The indices can usually be found to the precise number of +/- 0.01 to +/- 0.0002; typically +/- 0.05. The FBI has a data base of over 200 refractive indexes for different glass types and compositions. This lab is not designed to increase temperature of the glass so exact indices will not be found. In addition, Cargille Liquids are very expensive (usually $60 - $135 for 1 oz of liquid) so we will be using common oils such as vegetable, olive, baby oil, etc.

A Becke line is a bright halo observed near the border of a particle immersed in a liquid of a different refractive index. Submerging the glass into various Cargille liquids (index known) under a microscope the Becke line is observed until it disappears and the index of refraction is identified. This may be observed with the extension activity. A good explanation and image of the Becke line can be found at:
https://micro.magnet.fsu.edu/optics/timeline/people/becke.html



In the figure, the match point indicates no Becke line as the glass and refractive indices match. In the middle example, the Becke line moves towards a higher refractive index because the glass has a higher refractive index that the liquid. The moved down part of the image indicates that the Becke line has moved to a lower refractive index because the glass has a lower refractive index that the liquid.

Image from Slide Share:
https://www.slideshare.net/SangeethaBalakrishna2/glass-72819548/11

Vocabulary and Definitions:

- *Reflection* – the return of light, heat or sound from a surface
- *Diffraction* – the spreading of waves around an object or obstacle
- *Transmission* – in light it is light is the movement of electromagnetic waves through a material
- *Interference* - the net effect of when two or more light, sound, or electromagnetic waves combine. The waves are of the same frequency and combine to reinforce or cancel each other out.
- *Refraction* – When a wave passes from one medium to another, it changes the direction of a wave by a change in its speed.
- *Photon* - a particle of light or the smallest discrete bundle (quantum) of electromagnetic energy (light). It is the basic unit of all light.

Materials for introduction:

- Beaker with water
- Straw or pencil

Materials for forensic activity: (for 8 groups of 4 students):

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Part A

- 8 vials or beakers to hold clear gel spheres also a Bio Gel Plant Crystals and water Gel Crystal Soil.
- Gel growing spheres (clear, round or square)
    - Sources:
        - https://www.teachersource.com/category/s?keyword=growing+spheres
        - https://www.stevespanglerscience.com/store/jelly-marbles-clear-spheres.html
        - https://www.amazon.com/Pound-Bag-Water-Beads-Clear/dp/B0050ZNWYG/ref=sr_1_8?keywords=clear+growing+beads&qid=1554816978&s=toys-and-games&sr=1-8

Part B

- 8-16 three-compartment petri dishes or 24 - 48 small partitioned containers for each group depending on the number of glass samples to be analyzed (2 or 3). Small, plastic petri dishes work very well.
- Acetone or alcohol to clean the glass between trials – mark for identification. (Do this over a sink or a disposal container)
- Water to clean the acetone from the glass between trials – mark for identification. (Do this over a sink or a disposal container)
- Paper towels or clean, cloth rags to clean and dry glass samples – suggest flour sack towels as they leave less lint behind.
- 8 tweezers (minimum) – at least one pair per group; dissecting tweezers will work if they can be borrowed from the Biology Department
- 8 - 12 glass samples – minimum of 2 per group. The types of glass samples are listed below in the Indices of Refraction table. Mark each bag housing the sample with a particular number (1, 2; A, B) so it is easy to identify each sample.
- 3 types of refractive solutions – These solutions should be poured into each lab groups' containers. The type of solutions used will be based on the type of glass samples used, therefore refer to the Indices of Refraction below. Mark each container with a particular letter (I, II, and III) so the index of refraction of the solution can easily be identified.

Advance Preparation

- Have the students read the section on refraction of light in their textbooks to gain a further understanding of the topic.

- The crystal gel spheres grow in water and have the same index of refraction as water. Only a few of the crystals (10 to 15) should be placed in each container with the water. The crystals should soak in the water for at least 8 hours.

- Glass samples: It is recommended to have samples cut professionally (at a hardware store or glass shop or to buy pre-cut samples (watch crystals, art glass etc.). If the glass is cut in-house all rough edges should be smoothed out with a file or sandpaper.

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- Indices of Refraction for particular glass and solutions are listed below. Note that some of the indices can vary due to manufacture process and contamination. It is strongly suggested that the oils are tested before the lab is presented to the students. Also, mixtures of various oils may be needed. For example, for Pyrex: 4 parts Wesson Vegetable Oil and 1 part Baby Oil works very well. It is suggested that the identifying liquids vary so the students can easily identify the glass

- The indices of refraction provided to the students should be altered to a specific solution once the samples and solutions have been chosen and tested. The number of samples and solutions can be changed depending on the teacher's resources. I used Pyrex (with baby oil), frame glass (with immersion oil) and grape seed oil as my control.

Material	Index of Refraction	Material	Index of Refraction
Acetone	1.36	Patchouli Oil	1.507 -1.512
Baby Oil	1.45	Sandal Wood Oil	1.485 – 1.520
Canola Oil	1.465 – 1.467	Silicone Oil	1.5 – 1.52
Castor Oil	1.475 – 1.485	Tea Tree Oil	1.475 – 1.4820
Cinnamon Bark Oil	1.55 – 1.58	Vegetable Oil	1.47
Clove Oil	1.543	Water	1.33
Corn Oil	1.4735 – 1.4785	*Acrylic Glass (Lucite)	1.49 – 1.5
Flax Seed Oil	1.48	Crown Glass (Soda-lime)	1.52 - 1.62
Grape Seed Oil	1.471 – 1.478	Flint Glass (Lead Glass)	1.523 – 1.925
Mineral Oil	1.4616 – 1.4627	*Plexiglass	1.488
Microscope Oil (Immersion Oil)	1.515	Pyrex Glass (Borosilicate)	1.474

*** Do not use Acetone as the cleaning agent.**

Safety Information:

- Always wear Safety Glasses.
- Never pick up pieces of glass without tweezers.
- Tweezers can be very sharp so caution students to be aware of their surroundings and how the tweezers are held.
- Caution not put fingers in the solutions.

Directions for the Activity:

Introduction:

Introduce the concept of the refraction of light by showing the class a clear glass of water with a straw or pencil inside it. This something that the students should have seen before, but have them discuss what they see such as the difference in the size of the straw/pencil in and out of the water; how the straw/pencil appears broken, etc. Have them recall the types of wave interactions they have previously learned (reflection, diffraction, transmission, interference and refraction) and how they relate to light and the demonstration.

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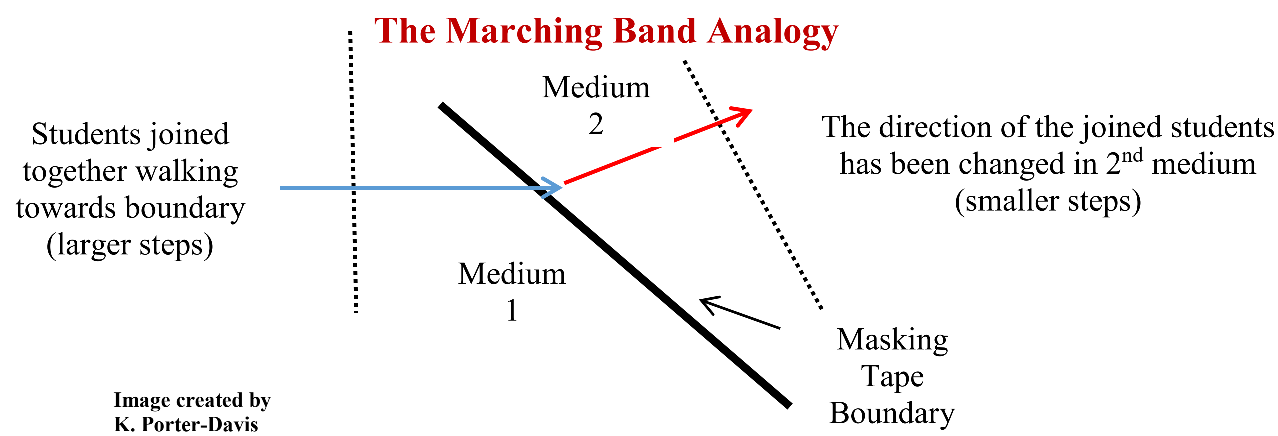
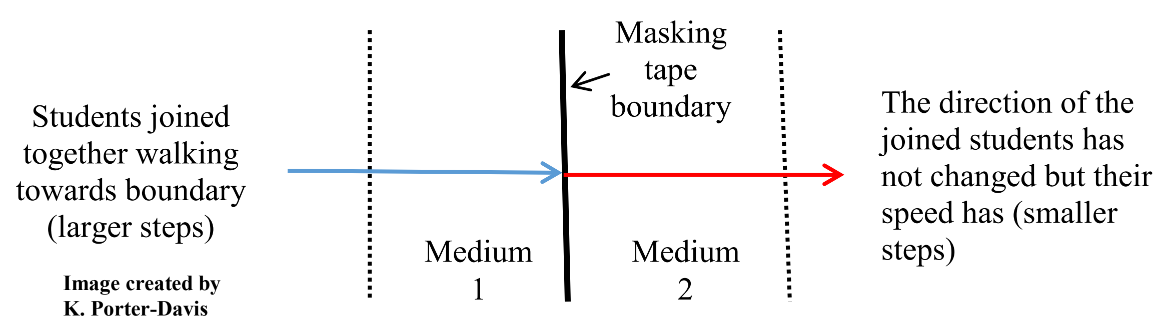
Discuss how refraction of light occurs either through an online or self-created PowerPoint with or You Tube video. Possible sources are in the Resource section of the lesson. Make sure to emphasize that refraction of light occurs on the nanoscale with the visible spectrum of light from 380 t0 740 nm. In comparison, the size of an atom's diameter ranges from 0.1 – 0.5 nm. Have the students watch the following video clip on light interactions to understand the five ways that high energy photons can interact with matter.
http://www.youtube.com/watch?v=4p47RBPiOCo&feature=player_embedded
Have the students perform the Marching Soldiers/Band Activity which demonstrates why wavelengths of light slow and bend. Point out to the students that they are portraying individual wavelengths of light in the visible light range (400 nm to 700 nm). The activity can be found at: https://www.physicsclassroom.com/class/refrn/Lesson-1/The-Cause-of-Refraction



The website goes on to explain why refraction does not occur when the light enters parallel to the normal:

A perpendicular (parallel to the normal) approach to the masking tape boundary will not result in a direction change.



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The Marching Band activity provides an excellent analogy to understanding the cause of light refraction. The line of students approaching the masking tape is comparable to a wave front of light. The masking tape represents the boundary between two media. The change in speed that occurred for the line of students would also occur for a wave of light and like the marching students, a light wave will not undergo refraction if it approaches the boundary in a direction that is parallel to the normal.

The two conditions that are needed for bending the path of the line of students are also required for the refraction of light. Light refracts at a boundary due to a change in speed and the angle of approach.

Part A: Refraction of light with gel growing spheres. Instructions for the lab are included on the Student Worksheet (teacher version with answers in red).

Part B: Forensic Lab: Identifying Glass Using the Index of Refraction. Instructions for lab are included on the Student worksheet (teacher version with answers in red).

Assessment:
Students should correctly and in complete sentences answer the questions from the student worksheet.

Resources:

- 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
- Free online PowerPoint provides information on glass and refraction: https://www.slideshare.net/SangeethaBalakrishna2/glass-72819548
- 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
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- "Theory and Fabrication of Integrated Circuits: GT7 – SiO2 Color Chart" *ECE Illinois* Copyright © 2007, 2008, 2009, 2010, 2011 The Board of Trustees at the University of Illinois. n.d. *Web*.28 June 2011. http://fabweb.ece.uiuc.edu/gt/gt/gt7.aspx
- "Thin-Film Battery Attains Commercial Availability" *ThinFilmsBlog* 13 December 2007 *Web.* 28 June 2011*.* http://www.thinfilmsblog.com/2007/12/thin-film-battery-attains-commercial.html
- "Types of Glass". *Corning Museum of Glass* © 2002 - 2011 Corning Museum of Glass. All Rights Reserved. n.d. *Web*. 11 July 2011 <http://www.cmog.org/dynamic.aspx?id=5658

Next Generation Science Standards

HS. Waves and Electromagnetic Radiation

- HS-PS4-4 Evaluate the validity and reliability of claims in published materials of the effects that different frequencies of electromagnetic radiation have when absorbed by matter.
- PS4.A Wave properties
- PS4.b Electromagnetic radiation

Crosscutting Concepts

- Cause and Effect

Optional activity extension:

An Optical Microscope can be used for a lab extension. Pyrex glass in Baby Oil or Vegetable Oil samples work best under the microscope when trying to demonstrate the disappearance of the Becke line. Reminder: this lab does not change the temperature of the solution so a complete disappearance of the Becke line may not be possible. If temperature change is wanted it is not suggested to use the plastic petri dishes.

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The Index of Refraction can also be useful when discussing lenses, thin-film interference and diffraction. You may want to have students choose one of these topics and design an activity to examine the connection to the Index of Refraction and these three topics.

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Student Worksheet (with answers in red)

Refraction of Light: A forensic analysis

Introduction: Do you know why refraction of light occurs and that this phenomenon happens on the nanoscale? This lesson will help demonstrate and explain the refraction of light by using a variety of activities. Your teacher will guide you through the first activities. In the final activity, you will use your knowledge about refraction to perform a forensic science investigation of glass from crime scenes. This final activity allows you to see the real-world application of the refraction of light.

Materials:

- Clear container with clear liquid
- Provided by teacher
- Tweezers
- Paper towels/cloth
- 2 glass samples
- 3 identification solutions
- 2 cleaning solutions (acetone and water)

Safety:

1. Always wear safety glasses.
2. Never pick up pieces of glass without tweezers.
3. Tweezers can be very sharp so be aware of your surroundings and how you are holding the tweezers.
4. Do not put fingers in the solutions.

Part A: What do you observe?

You will be provided a beaker or glass filled with water. Follow the directions below and answer the questions:

1. Observe your Part A. container. Describe what you see:
   Students should observe a container that seems to have just a clear liquid in it.

2. Place your hand in the container and describe what you feel:
   Students should feel the gel spheres in the liquid.

3. Explain how this demonstration relates to light refraction:
   The students should realize that they were not able to see the water marbles in the liquid because the water and gel spheres each have the same index of refraction.

4. What are the two main events to occur when light travels from one transparent media to another with different indices of refraction:
   Light changes speed and bends (if entered at an angle).
5. How, if at all, is this activity related to the nanoscale?
   Students should indicate that the visible light spectrum is 380-740nm. They can also indicate that photons of light are light quanta, which have both particle and wave properties that are on the nanoscale.

Part B: Forensic Lab: Identifying Glass Using the Index of Refraction

You are a part of a Crime Scene Investigation Unit and samples of glass from three different suspects have arrived for your analysis. It is your job to identify which suspect matches with which crime scene. One way to identify glass/acrylic fragments is to identify the index of refraction of the sample. Law enforcement uses a technique to identify glass fragments using more specific immersions liquids called Cargille Liquids. These are standard liquids used in many laboratories to identify particles by microscopic immersion techniques. The indices can usually be found to the precise number of +/- 0.01 to +/- 0.0002. Typically it is around =+/-0.05. The FBI has a data base of over 200 refractive indices for different glass types and compositions.

For this lab, you will be using commonly available oils as Cargille Liquids are rather expensive. To complete this activity, use the materials provided and follow the procedures:

1. Using the tweezers, pick up the first glass sample and place in Solution A.
2. Observe if the sample seems to disappear in the solution.
3. Write in the chart the number 1, 2 or 3 depending on how well you are able to see the sample in the solution. 1 = sample seems to disappear 2 = sample somewhat disappears 3 = clear see sample in solution. You may retry the samples to determine what number you choose.
   Students may have to retry their samples in the solutions to make a distinction of which number to put down.
4. Clean and dry the glass sample before placing it in the solution B. Very important.

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5. After the sample has been placed in each solution, indicate which solution matched best with the glass sample.
6. Repeat procedures 1-5 for the other glass sample(s) or additional solution.
7. Contact your CSI supervisor (teacher) to identify the index of refraction of your selected solutions and match the glass sample with the crime scene.
   The teacher should have the indices already prepared before students start lab.

Glass Sample	Solution A	Solution B	Solution C
1			
2			
3 (Optional)			

Crime Scenes: Match the refraction index of your samples to the crime samples.

A) A research lab was broken into and many beakers were shattered. The beakers were made of Pyrex Glass (n = 1.474).
B) A hit and run occurred and the lenses of the car's exterior lights were broken. The lenses were made of Acrylic Glass (n = 1.49 – 1.5).
C) An art gallery was robbed and the frame of the stolen painting was broken and the protective glass pane was shattered. The glass pane was made out of Crown Glass (n = 1.515 – 1.62).
D) During a home robbery a telescope was knocked over and the optical lens broke. The lens was made of Flint Glass (n = 1.523 – 1.925).

Glass Sample	Crime Scene
1	
2	
3 (optional)	

Summary Questions:

1. Identify the three conditions that must be met for refraction to occur.
   a. the angle of incidence cannot equal 0°
   b. the index of refraction for the incident material cannot equal that of the refractive material

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c. both media must be transparent

2. Why on charts displaying indices of refraction always specify what wavelength of light they were measured with?
   a. The listed Indices of Refraction are given for a specific wavelength of light in a vacuum. Not only does the speed of light but also the wavelength of the light contribute to how much light will bend upon entering a particular medium. This why a spectrum is produced when white light is incident upon a prism. Since each color of light has a different wavelength then each color of the spectrum is refracted by a different amount.

3. Why does blue light refract more than red light?
   a. The index of refraction (speed) varies with the wavelength/frequency of light. The electron has a resonant frequency near the UV region (usually 200 – 400 nm). Therefore, visible light closer to this region (blues and violets) will interact with the electron for a longer time before being remitted, which makes this color of light travel slower.

4. Why does refraction not occur if light enters parallel to the normal of the material? Refer to both the Marching Band Activity and Snell's Law.
   a. If the light approaches the medium in a direction that is perpendicular to it, then each wavelength of light meets the barrier at the same exact time. This will slow the light but not cause it to bend.
   b. Referencing the Marching Band Activity:
      i. The students changed their direction because they had reached the masking tape at different times. The first student reached the tape, slowed down, and observed the rest of the students marching ahead at the original speed. The change in direction of the line of students only occurs at the boundary when the students change speed and approach at an angle. When the students reach the barrier at the same time only the speed changes.
   c. Referencing Snell's Law:
      i. $n_i (\sin\theta_i) = n_r(\sin\theta_r)$ if $\theta_i = 0$ then $\sin\theta_i = 0$

5. Calculate the index of refraction of a material that light travels at a speed of 1.36 E 8 m/s.
   a. n = c/v; c = 3 E 8 m/s → n = (3 E 8 m/s)/(1.36 E 8 m/s) → n = 2.206

Cleanup:

Dump all excess oil into class clean-up container. **The oil should not be dumped down the sink.**

1) Rinse and dry off all containers, tweezers, and glass samples.
2) Put away materials as directed by your teacher.

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