

Pfund's Method

For Finding Index of Refraction of Amorphous Candy

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Summer 2005

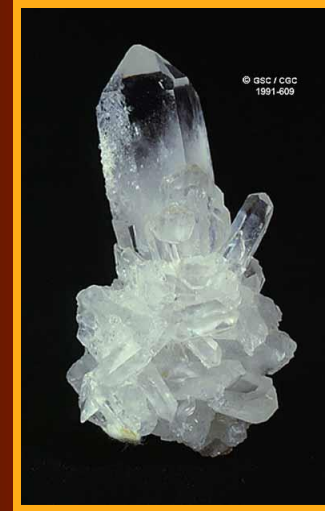
Advisors: Professor Himanshu Jain and Dr. Bill Heffner

Introduction

- This slide show will teach you how to make candy and test its index of refraction. It is a great introduction to glass science.
- The background information will draw on physical and chemical concepts to introduce glass science. And the experiment will solidify your knowledge of glass science.
- This slide show is filled with helpful hints and videos to help your experiment run smoothly the first time through.
- The supplies you need are common and inexpensive. You probably have a lot of them in your kitchen already.

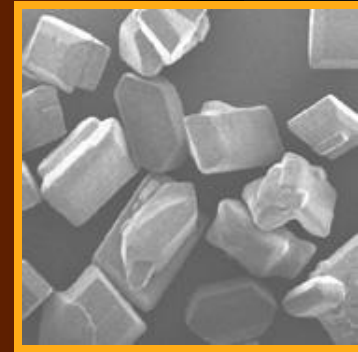
How is Candy like Glass?

- Candy without crystals is glass. A glass is an amorphous solid.
- Glass and candy have a tendency to crystallize under certain conditions, namely when cooled too slowly.
- Glass and candy contain the same types of components
 - Glass former: SiO_2 (a.k.a. silicon dioxide or quartz crystal) for glass, $\text{C}_{12}\text{H}_{24}\text{O}_{12}$ (a.k.a. sugar or sucrose) for candy.
 - Glass modifier: Na_2CO_3 for sodium silicate glass, H_2O for candy, reduces melting temperature and decreases chemical durability. (Source: Jain, Himanshu and Isha Jain, "Learning the Principles of Glass Science and Technology from Candy Making." Lehigh University. No Date. Lehigh University. 5 Aug. 2005 <http://www.lehigh.edu/~inmatsci/faculty/candy_making.pdf>.)
 - Other stuff: Corn syrup (mostly glucose, $\text{C}_6\text{H}_{12}\text{O}_6$) helps prevent crystallization in candy because glucose molecules are a different size than sucrose molecules. "Crystals form something like Legos locking together, except that instead of Lego pieces, there are molecules. If some of the molecules are a different size and shape, they won't fit together, and a crystal doesn't form." (Source for Quote: Science of Candy: Science of Sugar. Date of Posting Unknown. Exploratorium. 3 August, 2005 <http://www.exploratorium.edu/cooking/candy/sugar.html>.)



Sabina, Anna P.

"Quartz Crystal." No date. Online image. Earth Sciences Sector. 3 August 2005. <http://ess.nrcan.gc.ca/esic/gallery/gems_e.php>.

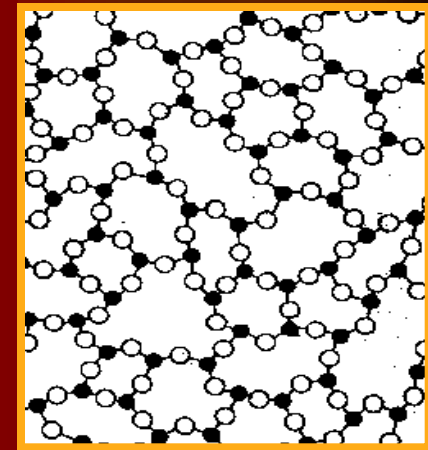
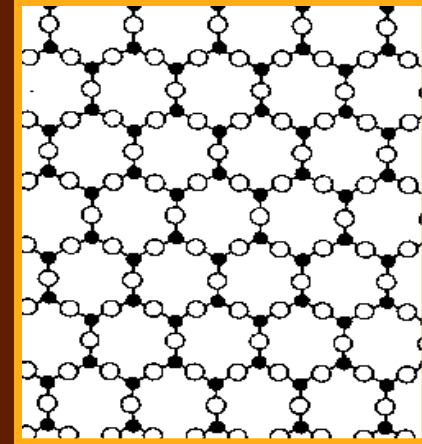


"Sugar Crystals Under a Microscope." No date. Online Image. Exploratorium. 2 August, 2005. <<http://www.exploratorium.edu/cooking/candy/sugar.html>>

What is glass?

- Glass is an amorphous solid.
- “Amorphous” means “not crystalline.”
- Crystalline solids have molecular structure that is repeated periodically whereas glass has no periodic structure.

“Molecular arrangement in a crystal.” No date. Online image. <http://math.ucr.edu/>. 3 August, 2005. <<http://math.ucr.edu/home/baez/physics/General/Glass/glass.html>>.



“Molecular arrangement in a glass.” No date. Online image. <http://math.ucr.edu/>. 3 August, 2005. <<http://math.ucr.edu/home/baez/physics/General/Glass/glass.html>>.

The Story of Glass Formation

- This graph of volume vs. temperature for glass tells a story.
- By looking at this curve, you can learn about:
 - $T_{s'}$ melting temperature.
 - $T_{g'}$ glass transition temperature.
 - Viscosity.

Volume vs. Temperature for Glass

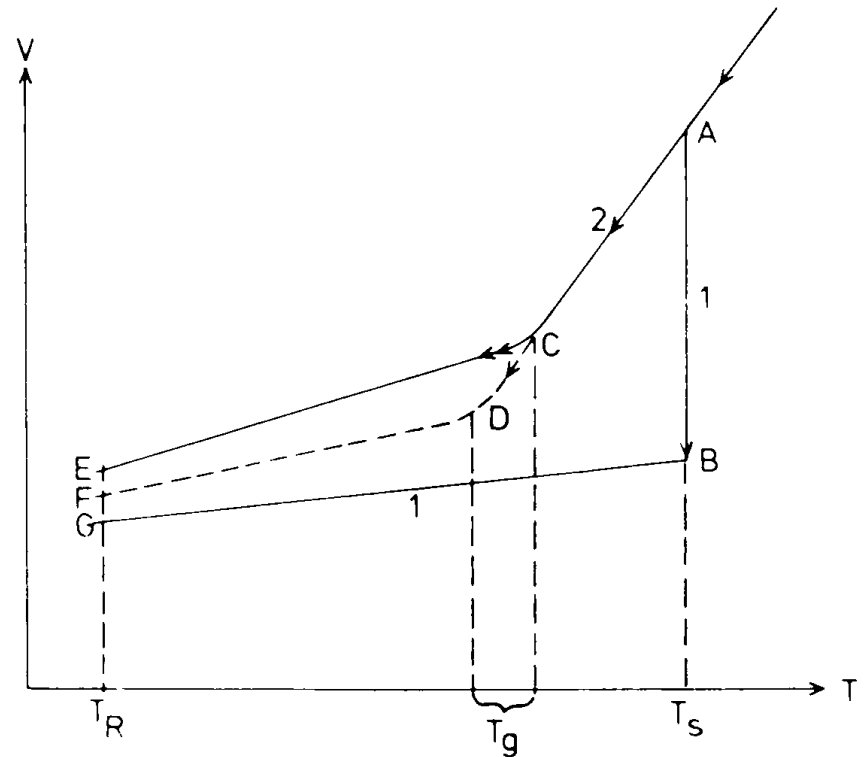


Fig. 2.2 Volume change during the cooling process of a melt forming: (1) a crystal structure; (2) a glass structure.

Background Information: The Story of Glass Formation

- We usually start making glass by melting crystals. (We can also start by melting glass. This is the case with recycling.)
- The region highlighted in yellow shows how the volume of a crystal increases as it is heated.
- The rate of increase remains the same until the crystals reach T_s , the melting temperature.

Volume vs. Temperature for Glass

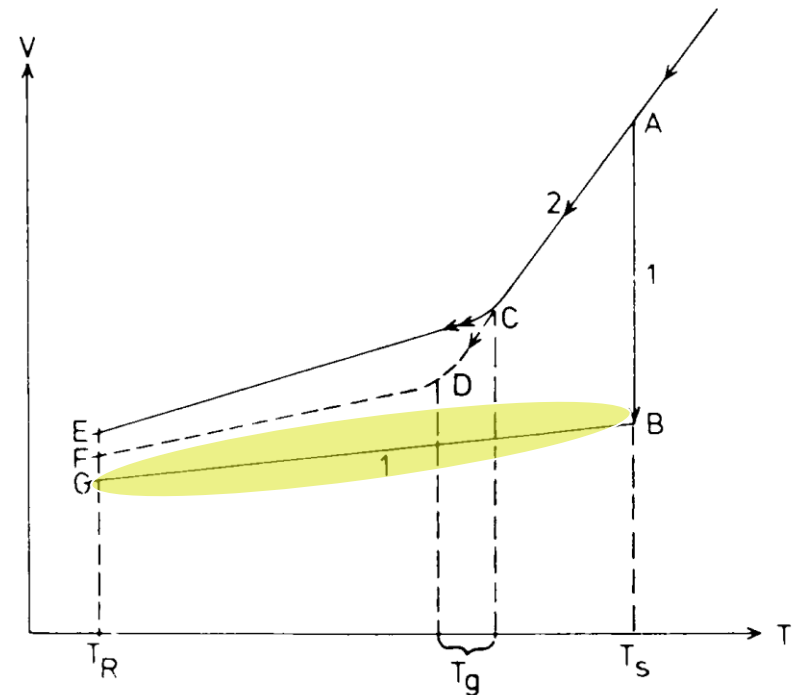


Fig. 2.2 Volume change during the cooling process of a melt forming: (1) a crystal structure; (2) a glass structure.

Background Information: The Story of Glass Formation

- At the melting temperature, T_s , the material undergoes a phase transition. The solid crystals become a liquid melt.
- The region highlighted in yellow shows the phase transition.
- The region highlighted in blue shows the volume of the melt at different temperatures.

Volume vs. Temperature for Glass

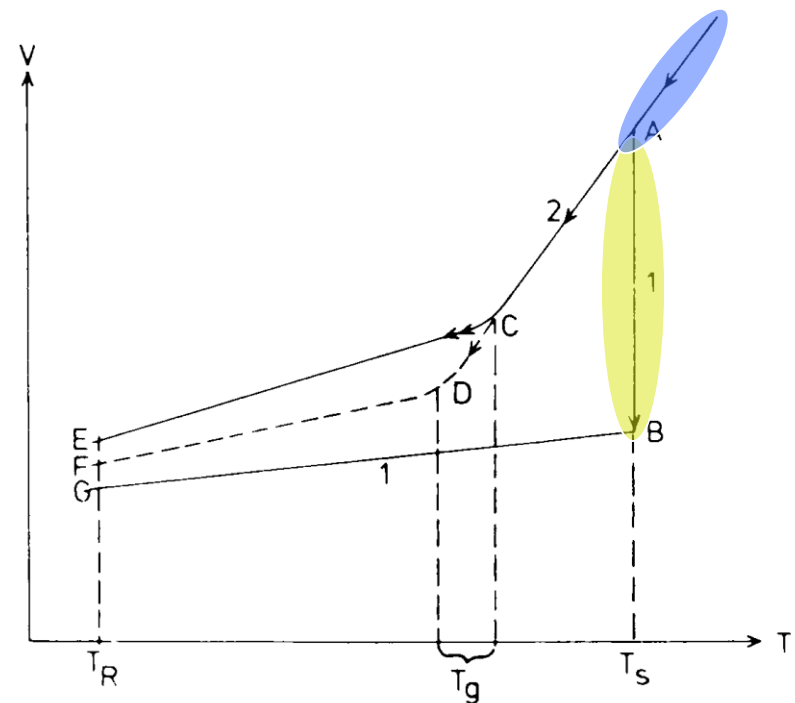


Fig. 2.2 Volume change during the cooling process of a melt forming: (1) a crystal structure; (2) a glass structure.

Background Information: The Story of Glass Formation

- Upon cooling, at T_s , the melt can turn into a crystal, or it can begin to turn into a glass. (Other things can happen, too, but for simplicity's sake, I'll say no more.)
- If it is cooled quickly enough, then it will become a glass.
- T_s is highlighted in red.

Volume vs. Temperature for Glass

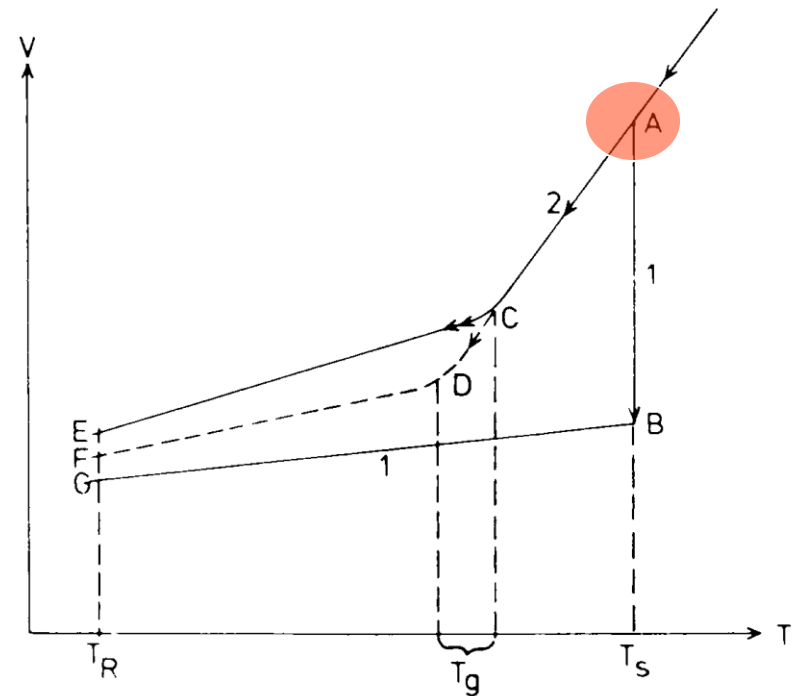


Fig. 2.2 Volume change during the cooling process of a melt forming: (1) a crystal structure; (2) a glass structure.

Background Information: The Story of Glass Formation

- This is super cool! Sometimes the melt doesn't form a solid right away the melting temperature. If the material is still fluid below the melting temperature, we call it a supercooled liquid. The supercooled liquid usually follows the path highlighted in red.
- As the supercooled liquid becomes cooler, the viscosity becomes greater.
- Viscosity is resistance to flow.

Volume vs. Temperature for Glass

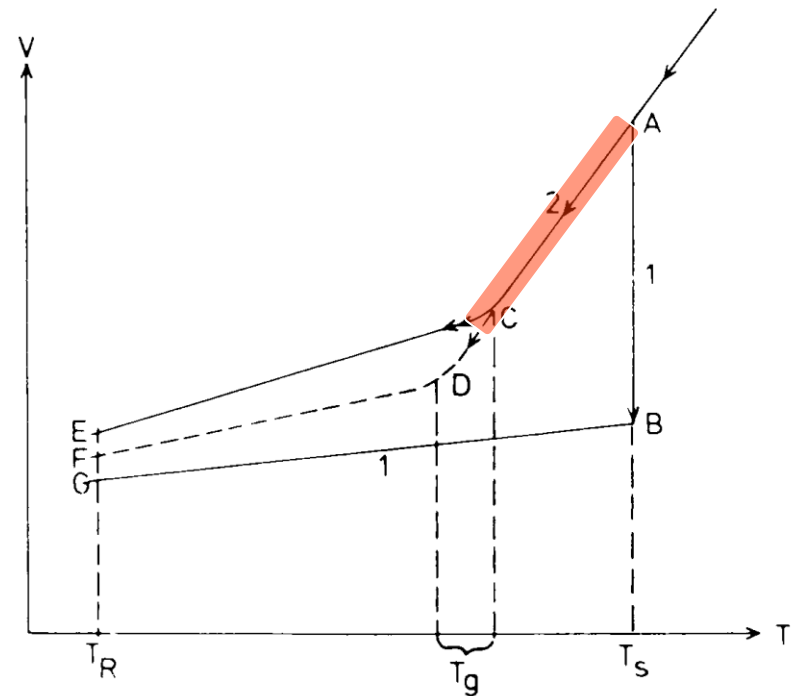


Fig. 2.2 Volume change during the cooling process of a melt forming: (1) a crystal structure; (2) a glass structure.

Background Information: The Story of Glass Formation

- T_g is the glass transition temperature. At T_g , the glass becomes hard enough to be considered a solid.
- T_g is actually a range, not just one temperature. You can see that the slope is changing in the T_g region.
- When the temperature of the material is below T_g , we can call it a glass.

Volume vs. Temperature for Glass

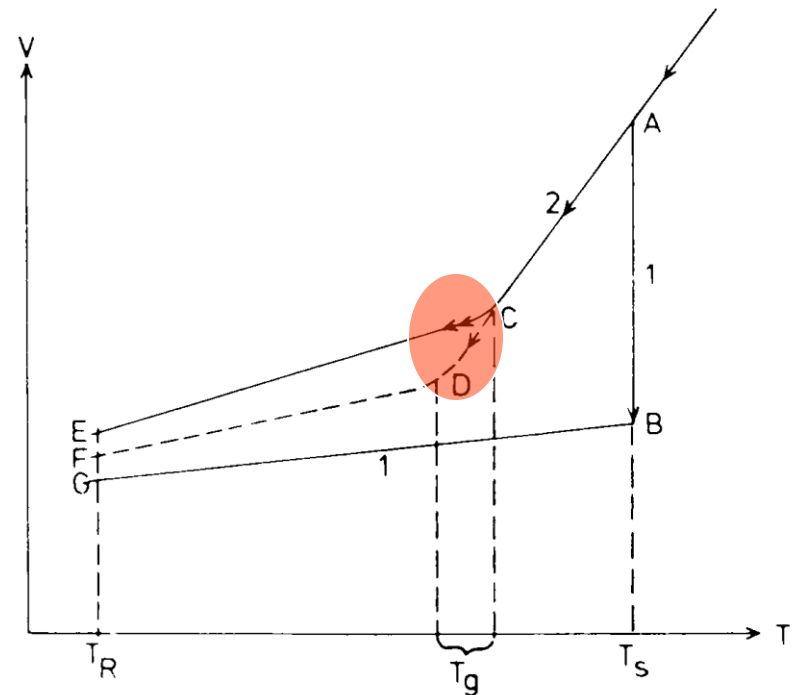
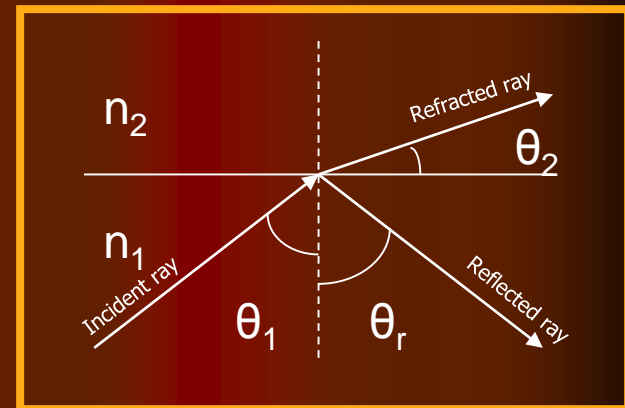


Fig. 2.2 Volume change during the cooling process of a melt forming: (1) a crystal structure; (2) a glass structure.

Background Information: Snell's Law

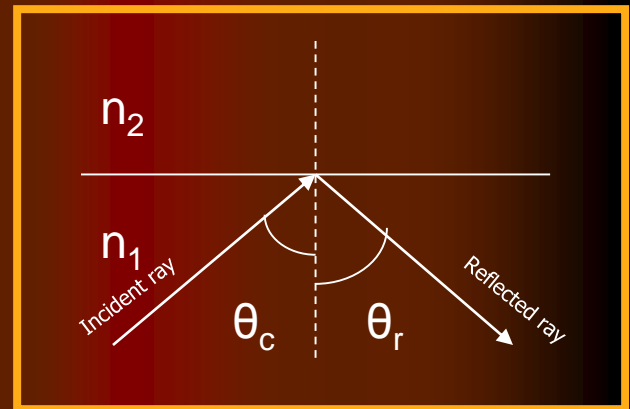
- The dotted line is the normal. All angles are measured from the normal.
- Snell's law says that $n_1 \sin \theta_1 = n_2 \sin \theta_2$.
- The reflected angle equals the incident angle, $\theta_1 = \theta_r$.



Reflection and Refraction. $n_1 > n_2$

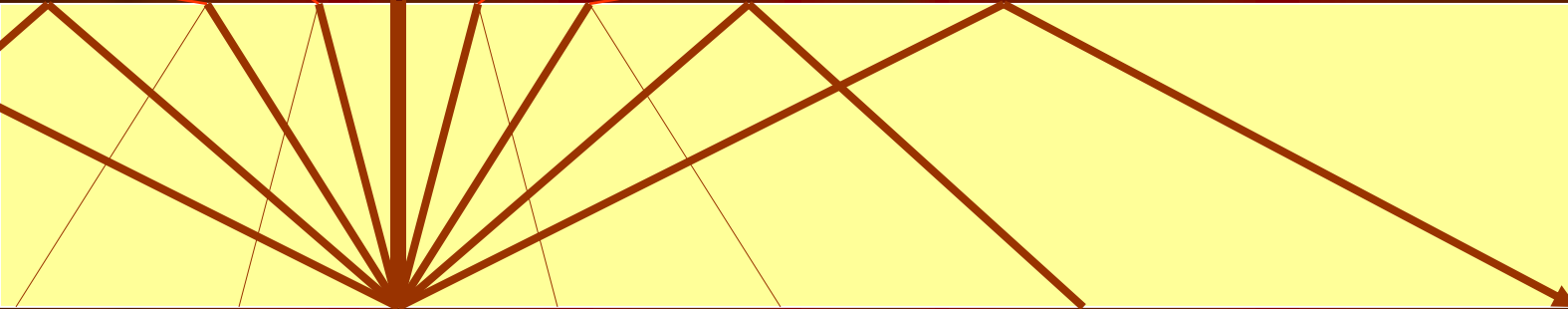
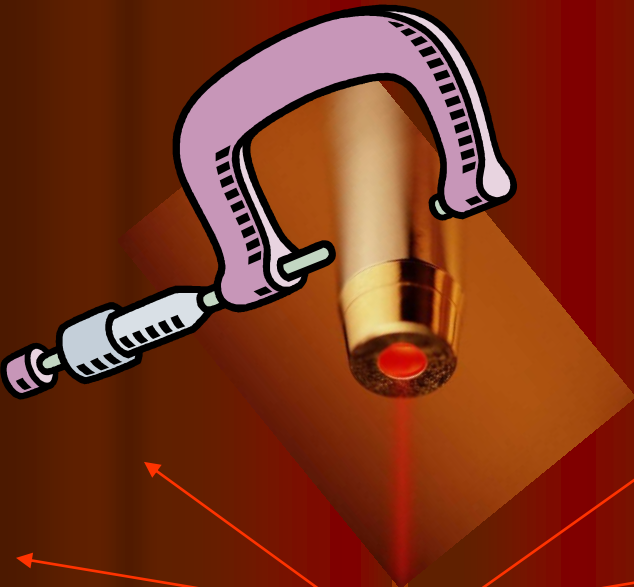
Background Information: Total Internal Reflection

- If θ_2 is greater than 90° then no light is refracted. The incident angle that would cause this 90° angle of refraction, θ_2 , is called the critical angle, θ_c .
- $n_1 \sin \theta_1 = n_2 \sin \theta_2$ becomes $n_1 \sin \theta_c = n_2 \sin 90^\circ$.
- So the critical angle is $\sin \theta_c = n_2 / n_1$



Critical Angle and Reflected Angle.
 $n_1 > n_2$.

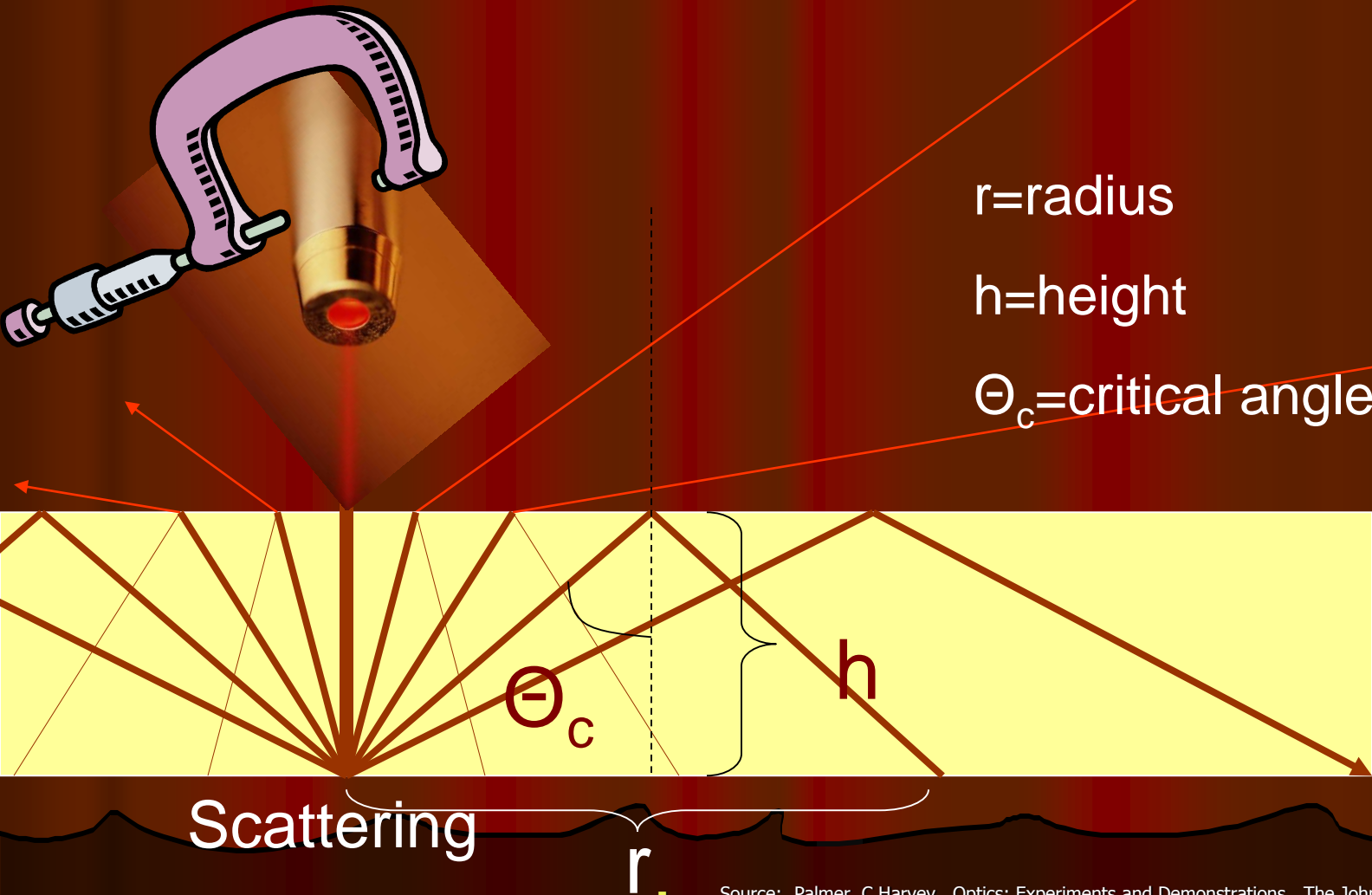
Background: How Pfund's Method Works



Scattering

This surface stuck to paper.

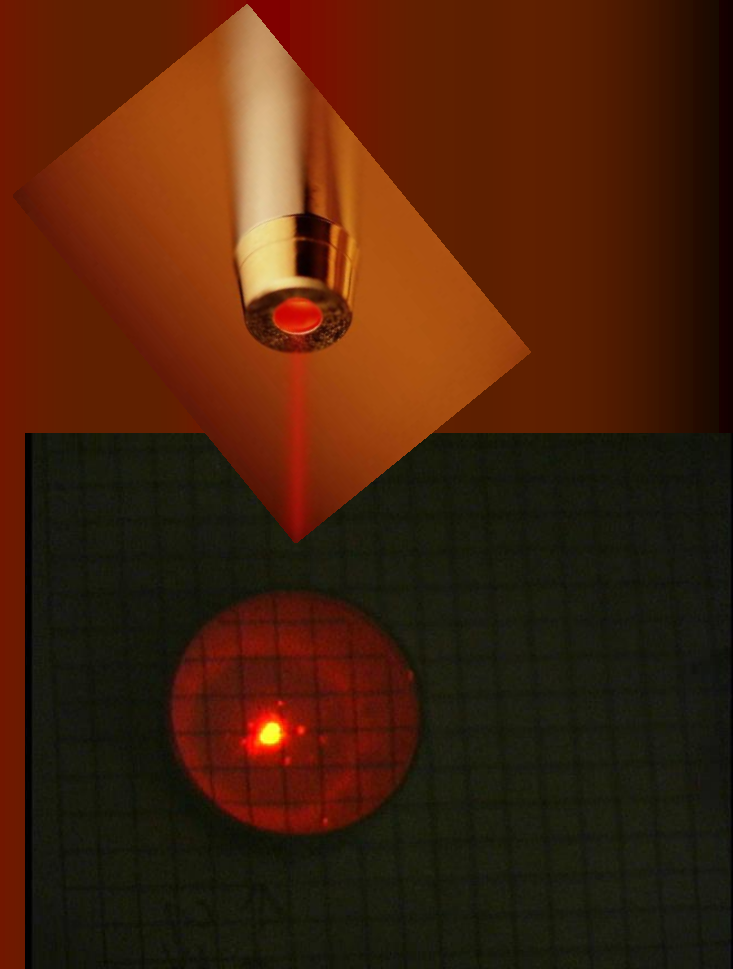
Background Information: How Pfund's Method Works



What Pfund's Method Looks Like

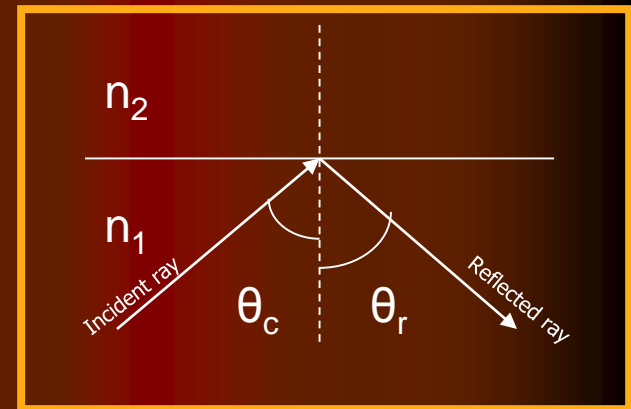
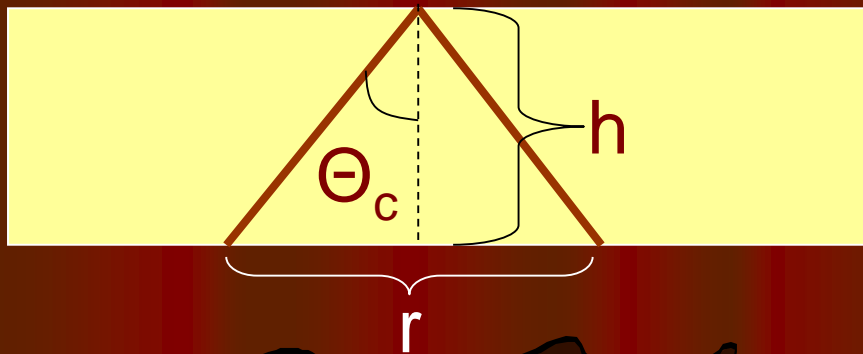
- Pfund's method looks like this.
- Why the dark ring in the center and bright ring on the outside?

- Source of Pfund's Method: Optics: Experiments and Demonstrations, C. Harvey Palmer, The John Hopkins University: The John Hopkins Press: Baltimore, 1962, page 9.



What is the Index of Refraction?

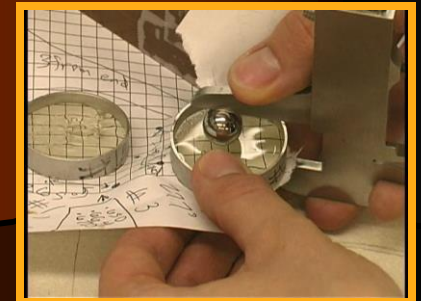
- Can you derive an equation for the index of refraction, n , in terms of the thickness, h , of the candy and the radius, r , of the dark circle? It takes some trigonometry.



$$\sin\theta_c = n_2/n_1$$

Outline of Experiment:

- Part 1: Fabricate Candy.
 - Melt sugar, water, and corn syrup in a beaker.
 - Pour into mold with graph paper on bottom.
- Part Two: Pfund's Method.
 - Measure thickness of slab and diameter of dark circle in at least two locations on each sample.
 - Calculate index of refraction.

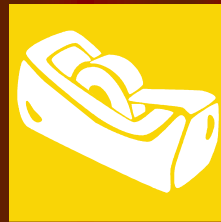


And Now for the Experiment

Pfund's Method!

Supplies:

- A Hot Plate
- Oven Mitts
- A 400mL Beaker
- 205g Sugar
- 60g Corn Syrup
- 50g Water
- A Thermometer that can read 200°F to 350°F
- 2 Metal Bars: at least 15cmx15cmx2cm (or an alternative)
- Some Thick Cardboard
- Scissors
- Tape
- Graph Paper
- A Vernier Caliper
- A Perfect Steel Ball, about 1/3-1/2 inch
- A laser



Set Up: Making the Mold

- On a flat, horizontal surface, make a mold about 10cm by 10cm using the metal bars, cardboard, scissors, tape and graph paper. Make sure you make the mold on a flat surface. See picture. Be sure to make it sturdy enough to keep candy in. Don't let the candy break loose, for this will result in a sticky situation. Also, don't tape the graph paper because the bottom surface needs to be as flat as possible. The metal bars should be heavy enough to hold the mold in place on top of the graph paper.



A mold.

July 2005.



Making a Mold.

July 2005.

Procedure: Candy Fabrication

- Stir sugar, corn syrup and water in beaker, and then heat on the highest setting. Do not stir while heating because this will make bubbles that can cause crystallization later. We don't want crystallization; we want complete amorphousness!
- Note the temperature, T_d , at which the sugar crystals dissolve (see picture).
- Pour the candy at a temperature between T_d and the temperature at which it turns dark yellow (about 310°F). Record the temperature at which you pour.
 - If the entire class is making candy, plan ahead on this part so you can graph index of refraction vs. pour temp. (Note: If the heating method is the same for everybody, then the results will be more telling.)
- Allow the candy to cool for at least an hour but no longer than a day because crystals may form, especially in a candy that is above T_g at room temperature.



Not
Dissolved.

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Dissolved.

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Procedure: Measurements

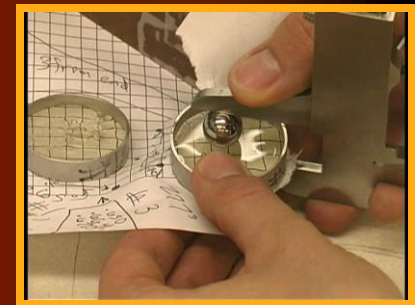
- Shine a laser into the candy, and measure the diameter of the ring produced. Take note of the place where you measured diameter. Repeat at least 3 more times in three more different locations. Use the gridlines in the graph paper for guidance.
- Using the caliper, measure the thickness of the candy in locations corresponding to the places you measured diameter. Measuring technique will be different for supercooled liquid candies and amorphous solid candies. See the pictures, and choose the method that works best for you.



Measuring Diameter.
Click for Inside Box
for Video.



Measuring Thickness
of Viscous Liquid.



Measuring Thickness
of Solid Candy.

Procedure: Calculations

- Find the index of refraction at least 4 times using the formula: $n = \sqrt{d^2 + 16h^2} / d$
- Find the average index of refraction and its standard deviation.
- If the whole class participated in this project, graph index of refraction vs. pour temperature to see how index of refraction changes with pour temperature. Note: The higher the pour temperature, the less water the candy contains.

Odds and Ends

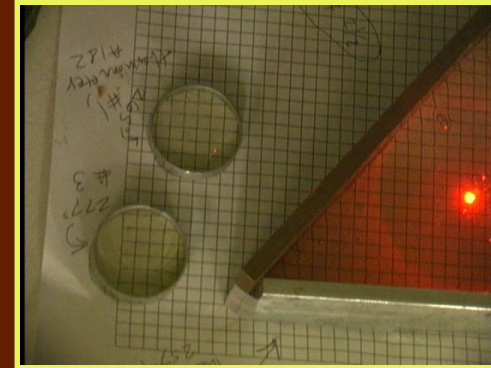
**This is
almost
The End**

$n=?$

- Here's how I found n in terms of h and d .

- $\sin\theta_c = n_{\text{air}}/n$
- $= 1/n$
- $\sin\theta_c = (r/2)/\text{hypotenuse}$
- $\text{hypotenuse} = \sqrt{(r/2)^2 + h^2}$
- $\sin\theta_c = (r/2)/\sqrt{(r/2)^2 + h^2}$
- $= (d/4)/\sqrt{(d/4)^2 + h^2}$
- $= d/\sqrt{d^2 + 16h^2}$
- $1/n = d/\sqrt{d^2 + 16h^2}$

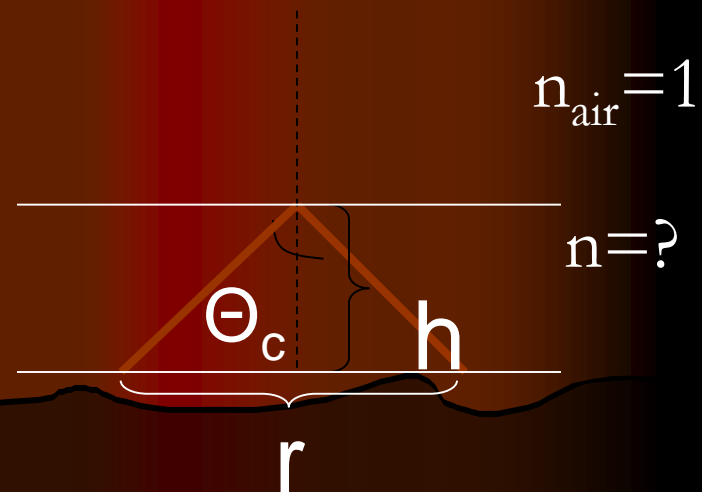
- **$n = \sqrt{d^2 + 16h^2}/d$**



d = diameter of dark ring

r = radius = $.5d$

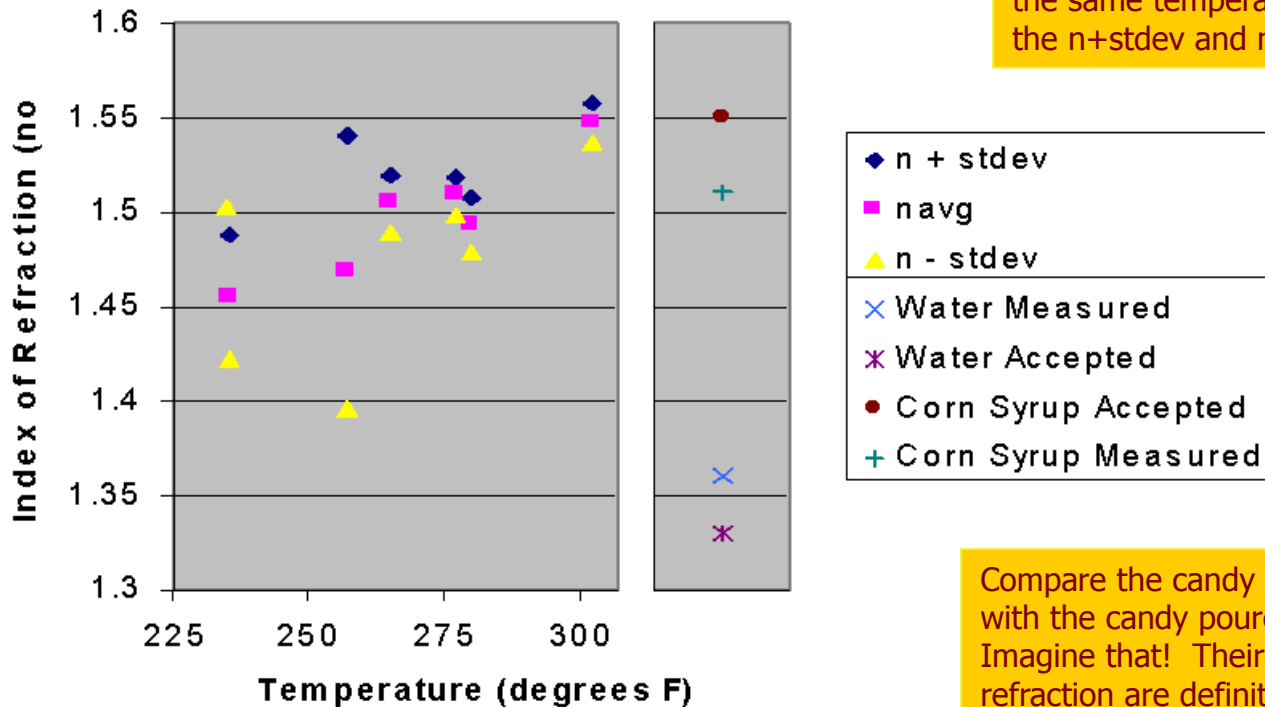
n = index of refraction of glass



Are Your Results Similar to Mine?

The navg corresponding to this point was off the charts! Oops!

Index of Refraction vs. Pour Temperature for Candy Poured from Various High Temper



About 68 percent of all samples poured using the same method at the same temperature will be within the $n+stdev$ and $n-stdev$.

Compare the candy poured at 236°F with the candy poured at 302°F. Imagine that! Their indices of refraction are definitely different.

I would love to see your results. Just email them to schneiderbusiness@yahoo.com.

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- My Teacher: Andrea Harmer, Director, Web-Based Instruction, Materials Science and Engineering, Lehigh University
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