Hypersonics STEM Curriculum

Hypersonics – Moving at a Snell's Pace

Grade	Time	Subject Area	Key Concepts
High School	70 min	Physics	Light Snell's Law

Lesson Overview

In this lesson, students will trace the path of light as it passes through a rectangular and a triangular glass refraction plate. They will use their ray diagrams to calculate the index of refraction of the two glass plates. Students will then use the index of refraction of different hypersonic window materials to calculate how much light is refracted through those materials. Finally, students will explain how light is refracted as it travels from an object, through the atmosphere, through a window on a hypersonic vehicle, and to a sensor.

This lesson is part of a series of high school physics lessons using hypersonics as a context to apply optics content.

NGSS Standards

HS-PS4-1 Use mathematical representations to support a claim regarding relationships among the frequency, wavelength, and speed of waves traveling in various media.

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-PS4-5 Communicate technical information about how some technological devices use the principles of wave behavior and wave interactions with matter to transmit and capture information and energy.

Learning Objectives

By the end of this lesson, students will be able to:

- Trace light as it refracts through a glass material.
- Measure the angles of incidence and refraction on a ray diagram and use the angles to calculate the index of refraction of a material.
- Use the index of refraction to compare how much light is refracted through different materials.
- Explain how light refracts as it travels from an object, through the atmosphere, through a window on a hypersonic vehicle, and to a sensor

Essential/Overarching Question

Is what we see where we see it?

Key Vocabulary

Speed – the rate at which an object is moving. Speed is calculated by dividing the distance travelled by the time it took to travel that distance.

Speed of Sound – the rate at which sound moves through a medium. The speed of sound depends on both the density and the temperature of the medium. The speed of sound through air at 20° C (68° F) at sea level is 343 m/s (767 mph).

Mach – the ratio of the speed of an object to the speed of sound or how many times the speed of sound an object is moving. It is often followed by a number indicating the ratio; for example: Mach 1 is the speed of sound, Mach 2 is twice the speed of sound, Mach 5 is five times the speed of sound.

Sonic – speeds equal to the speed of sound (Mach 1).

Subsonic – speeds smaller than the speed of sound (less than Mach 1).

Transonic – speeds near (Mach 0.8-1.2) the speed of sound where drag is highest (e.g. sound barrier).

Supersonic – speeds greater than the speed of sound (Mach 1 and greater).

Hypersonic – speeds greater than five times the speed of sound (Mach 5 and greater).

Fluid – a substance with no fixed shape; a liquid, gas, or plasma. A substance that flows when an external force is applied to it.

Flow – the motion of a fluid (liquid, gas, or plasma) when it experiences unbalanced forces.

Refraction – the redirection, or bending, of a wave as it passes from one medium to another caused by a change in speed.

Diffraction – the bending of a wave around the corners of an obstacle or the spreading of a wave through an aperture.

Reflection – the change in direction of a wave as it strikes the boundary between two different media so that the wave returns into the medium from which it originated.

Dispersion – the separation of while light into the spectrum of colors when the white light refracts as it passes through a prism.

Index of Refraction – a dimensionless number (n) that measures how much light is bent, or refracted, when entering a material – a measure of how much the material slows down the light wave as it passes through it.

Snell's Law – a formula used to describe the relationship between the angles of incidence and refraction of a wave passing between two mediums – $n_1\sin\theta_1 = n_2\sin\theta_2$.

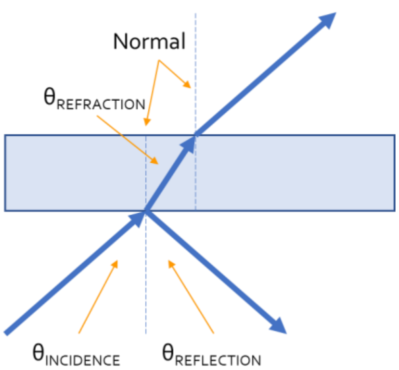
Angle of Incidence – the angle between a ray incident on a surface and the line perpendicular (at a 90-degree angle) to the surface.

Angle of Reflection – the angle between a ray reflected from a surface and the line perpendicular (at a 90-degree angle) to the surface.

Angle of Refraction – the angle between a ray refracted in a medium and the line perpendicular (at a 90-degree angle) to the surface.

Normal – the perpendicular line drawn to the reflecting surface.

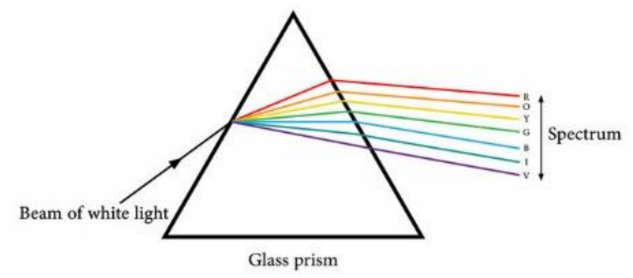
Science Concepts Overview

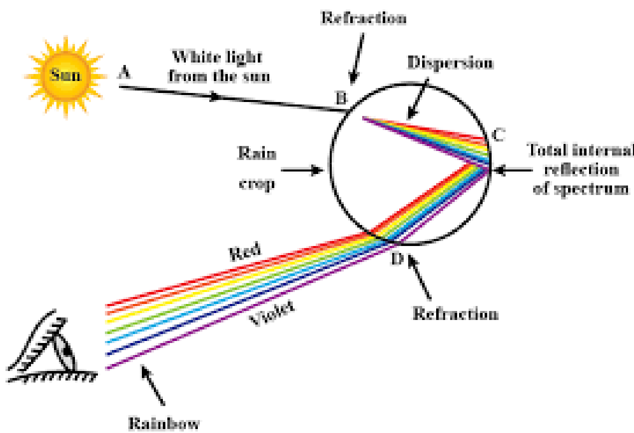


For you to see an object, light from the object must reach your eye. As light travels through different mediums, it changes speeds based on the mediums optical density. To account for the change in speed, the wave bends towards or away from the normal. When the light wave speeds up, it bends away from the normal. When the light wave slows down, it bends towards the normal.

Snell's Law give us a formula that describes the relationship between the angles of incidence and the angles of refraction of a wave as it passes between two mediums → $n_1\sin\theta_1 = n_2\sin\theta_2$ where n_1 and n_2 are the indices of refraction for the two materials and θ_1 and θ_2 are the angles of incidence and angle of refraction. The angles of incident and refraction are measured from the normal, or perpendicular, to the surface.

Rainbows and prisms are a great example of refraction plus dispersion. When white light hits a prism, it is refracted. But, the different wavelengths of light (or colors) are refracted at slightly different angles. This disperses, or separates, the while light into its different colors. When the light is refracted again at the other side of the prism, the colors remain separated and you are able to see the full color spectrum. Rainbows are created in a similar fashion as while light is refracted, reflected, and refracted again in a water droplet.





Materials List

- ☐ Three glass containers
- ☐ Three pencils or straws to place in glass container
- ☐ Water to fill one glass container
- ☐ Vegetable oil to fill one glass container
- ☐ Rectangular glass refracting plate (one per student – but they can share)
- ☐ Triangular glass plate (prism) (one per student – but they can share)
- ☐ Rulers (one per student)
- ☐ Protractors (one per student)
- ☐ Cardboard in 8.5 x 11 sheets (one per student)
- ☐ Straight pins (six per student)
- ☐ Tape
- ☐ Calculators (one per student)
- ☐ Hypersonics – Moving at a Snell's Pace handout (one per student)
- ☐ Hypersonics – Moving at a Snell's Pace Exit Ticket handout (one per student)

Lesson Preparation

Prior to the lesson, the instructor should gather materials and make copies of the copies of the Hypersonics – Moving at a Snell's Pace handout and the Hypersonics – Moving at a Snell's Pace Exit Ticket handout.

Safety

Due to the nature of this lesson, it is recommended that the class take the following safety precautions:

- Participants should be reminded to be careful to not break the refraction blocks.
- Participants should be told the protocol in the case that a refraction block breaks.
- Participants should be reminded to use the straight pins appropriately.

Procedure

Engage (5 minutes)

1. At the front of the room, place three glass containers (one empty, one filled with water, and one filled with vegetable oil), each with a straw or pencil in it.
2. Pose the following questions to your students:
   - What observations do you have about the three containers?
   - What do you think is happening?
3. Individually, or as a class, have students read the Introduction to the Hypersonics – Moving at a Snell's Pace handout.

Explore (30 minutes)

4. Students will trace light as it passes through a glass refraction plate and use their ray diagram to calculate the index of refraction of the blocks. They will do so following directions in the Using Angles to Calculate Index of Refraction section:
   - Gather: a protractor, a ruler, a piece of cardboard, tape, 6 straight pins, a rectangular glass plate, and a triangular glass plate.
   - Tape a piece of cardboard to the bottom of the Rectangular Glass Plate Diagram sheet (end of this packet).
   - Place the rectangular glass plate in the center of the Rectangular Glass Plate Diagram sheet. Trace the outline of the glass plate.
   - Remove the glass plate and construct a normal near the top left of the outline. Be sure your normal extends into the square of the glass plate (see refraction tracing examples – above for the rectangle and below for the triangle).
   - Using a ruler and a protractor, draw a heavy line at an angle of 40° with the normal. Draw the line so it is on the side of the normal closest to the corner. This line is the incident ray and corresponds to the line AB in the figure.
   - Place three straight pins along line AB.
   - Place the glass plate back in the outline on the paper. With your eyes on the same level as the edge of the glass plate, look through the opposite edge of the glass plate and look for the pins on line AB. Place another row of three pins on the same side of the glass plate as your eye so that all six of the pins appear to be aligned. The new pins represent line CD on the drawing above. Use your ruler to draw in line segment CD.
   - Remove the glass plate and draw in line segment BC. At point C, construct the normal to that face.
   - Each face of the glass plate is an air-glass interface where we can apply Snell's Law. Therefore, label the incident and refracted angle at each face.

Remember, segment AB is the original ray. This boundary is an air to glass interface. Segment CD is the final refracted ray and corresponds to a glass to air interface.

- Use a protractor to measure the angle θi and θr for each interface.
- Use Snell's Law to determine the index of refraction of the glass for each interface (2 calculations). Show all your calculations on your diagram.
- Repeat for the triangular glass plate.

Explain (20 minutes)

5. Students will apply their knowledge of Snell's law to calculate the angle of refraction for a variety of hypersonic vehicle window materials to compare how much the light is bent given an angle of incidence of 40°. They will fill in their answers in the table on the Using Index of Refraction to Calculate Angles section of the handout.
6. Students will explain their understanding of refraction by answering the following questions in the Using Index of Refraction to Calculate Angles section of the handout:
    - If ni < nr, the angle of refraction should be ____________ than the angle of incidence.
    - If ni > nr, the angle of refraction should be ____________ than the angle of incidence.
    - How different were the angles of refraction for those materials.
    - Why is it important to understand how much a sensor window refracts light?

Elaborate (10 minutes)

7. In the Refracting Light & Hypersonics section of the handout, students will be asked to apply Snell's law to light that travels from an object, through the atmosphere, through a window on a hypersonic vehicle, and to a sensor. They will answer the following questions:
    - The diagram below shows the nose of a hypersonic vehicle with a sensor and sensor window on the bottom of the nose. On the diagram below, trace the light as it comes from the object (tree), refracts through the different media, and reaches the sensor.
    - Use a ruler to extend your final light ray to the sensor so it crosses the ground. Based on the diagram you drew, would you perceive the object to be at its actual location, in front of its location, or behind its location? What makes you say that?
    - How would the different window materials you explored earlier change how you perceive the object?
    - The index of refraction for the atmosphere changes gradually, rather than in chunks as the diagram suggests, how does this change how you perceive images?

Evaluate (5 minutes)

8. Students will complete the Hypersonics – Moving at a Snell's Pace Exit Ticket where they are asked to share three big ideas that they are taking away from this lesson.

STEM Career Connections

- Hypersonics engineering
- Aerospace engineering
- Aeronautical engineering
- Test engineering
- Systems engineering
- Physics
- Optics
- Machinists
- Manufacturing
- Metrology

Extensions

Students could *expand* their understanding of Snell's Law by finding other transparent materials that they could use to calculate the index of refraction using the procedure from the Hypersonics – Moving at a Snell's Pace handout. It is ideal that these materials are rectangular blocks.

References & Resources

ABC Education. (2014, February 24). *ABC Zoom – Refraction: Why glass prisms bend and separate light* [Video]. YouTube. https://www.youtube.com/watch?v=Aggi0g67uXM

Joo, K. R. (1985). *Effects of variation of index of refraction of atmosphere on Cerenkov radiation* [Masters thesis, Naval Postgraduate School]. https://apps.dtic.mil/sti/tr/pdf/ADA164358.pdf

Science Sauce. (2019, October 29). *Refraction explained* [Video]. YouTube. https://www.youtube.com/watch?v=zarxpu43-ls-

SciShow. (2019, July 8). *A surprisingly simple secret to supersonic flight* [Video]. YouTube. https://www.youtube.com/watch?v=kGefMLHJBKA

SciShow. (2014, May 14). *How do rainbows form?* [Video]. YouTube. https://www.youtube.com/watch?v=5cVX3eq6NUQ

Talented Tuber. (2017, April 11). *Difference between subsonic, supersonic and hypersonic speed* [Video]. YouTube. https://www.youtube.com/watch?v=LBJ3tXCjzN0

TED-Ed. (2013, September 19). *Light waves, visible and invisible - Lucianne Walkowicz* [Video]. YouTube. https://www.youtube.com/watch?v=O0PawPSdk28

TestTube 101. (2015, November 11). *Flying at hypersonic speeds* [Video]. YouTube https://www.youtube.com/watch?v=vL1qAfS0gic

Dr. Lori M. Stiglitz
JHTO Workforce Development Lead

Dr. Stephanie Stehle
Curriculum Specialist

Name: ____ Date: ____________________

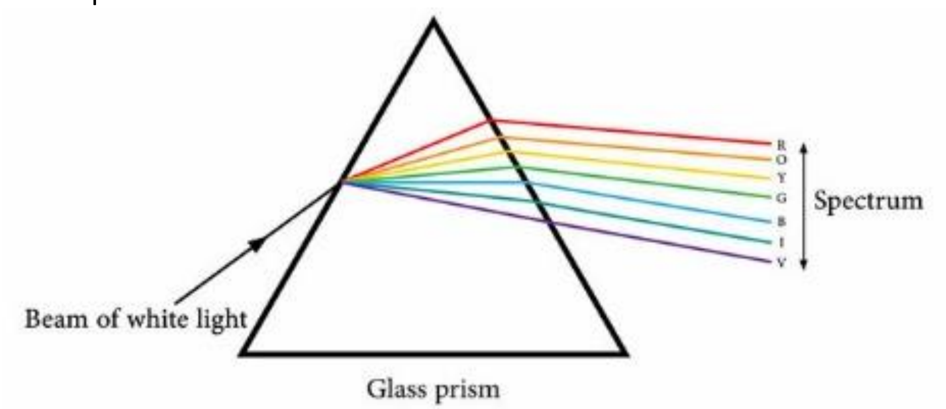
Hypersonics – Moving at a Snell's Pace

✈Introduction

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

Snell's Law gives us a formula to describe the relationship between the ***angle of incidence*** and the ***angle of refraction*** of a wave as it passes between two mediums. How much the light bends depends on the ***index of refraction*** of the two mediums. In the equation, n_1 and n_2 are the indices of refraction for the two materials and θ_1 and θ_2 are the angles of incidence and angle of refraction.

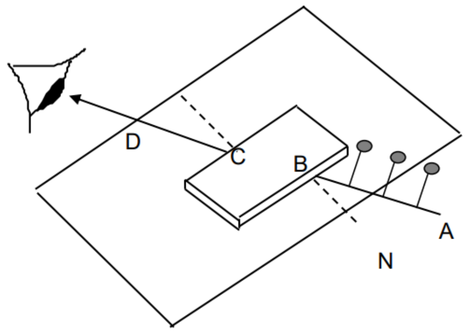
Prisms are a great example of ***refraction*** plus ***dispersion***. When while light hits a prism, it is refracted. But, the different wavelengths of light (or colors) are refracted at slightly different angles. This disperses, or separates, the while light into its different colors. When the light is refracted again at the other side of the prism, the colors remain separated and you are able to see the full color spectrum.

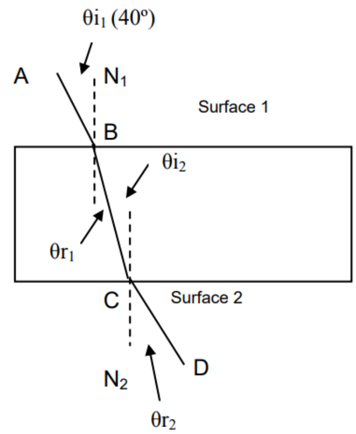


We are going to use two different glass plates to trace the path of light as it bends in and out of a medium and use our ray diagrams to calculate the index of refraction for those materials.

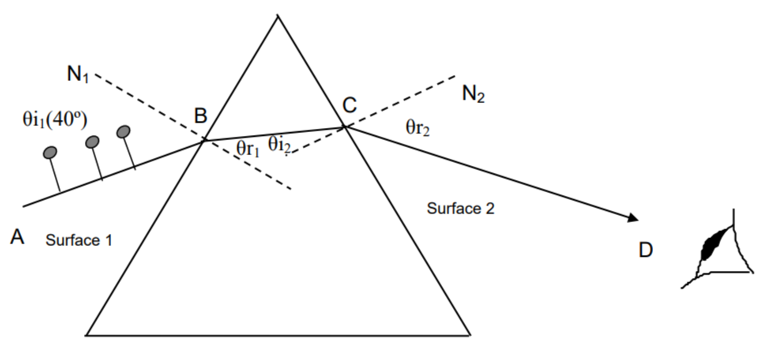
Using Angles to Calculate Index of Refraction

1. Gather: a protractor, a ruler, a piece of cardboard, tape, 6 straight pins, a rectangular glass plate, and a triangular glass plate.
2. Tape a piece of cardboard to the bottom of the Rectangular Glass Plate Diagram sheet (end of packet).
3. Place the rectangular glass plate in the center of the Rectangular Glass Plate Diagram sheet. Trace the outline of the glass plate.
4. Remove the glass plate and use a ruler to construct a normal near the top left of the outline. Be sure your normal extends into the square of the glass plate (see refraction tracing examples – above for the rectangle and below for the triangle).





5. Using a ruler and a protractor, draw a heavy line at an angle of 40° with the normal. Draw the line so it is on the side of the normal closest to the corner. This line is the incident ray and corresponds to the line AB in the figure.
6. Place three straight pins along line AB.
7. Place the glass plate back in the outline on the paper. With your eyes on the same level as the edge of the glass plate, look through the opposite edge of the glass plate and look for the pins on line AB. Place another row of three pins on the same side of the glass plate as your eye so that all six of the pins appear to be aligned. The new pins represent line CD on the drawing above. Use a ruler to draw in line segment CD.
8. Remove the glass plate and use a ruler draw in line segment BC. At point C, use a ruler to construct the normal to that face.
9. Each face of the glass plate is an air-glass interface where we can apply Snell's Law. Therefore, label the incident and refracted angle at each face. Remember, segment AB is the original ray. This boundary is an air to glass interface. Segment CD is the final refracted ray and corresponds to a glass to air interface.
10. Use a protractor to measure the angle θ_i and θ_r for each interface.
11. Use Snell's Law to determine the index of refraction of the glass for each interface (2 calculations). Show all your calculations on your diagram.
12. Repeat for the triangular glass plate.



Using Index of Refraction to Calculate Angles

Hypersonic vehicles use different materials for their sensor windows such as diamond, sapphire, and garnet. Calculate the angle of refraction for those materials, plus that of glass and plastic to compare how much the different window materials bend light incident at a 40°. Fill in the table and show all work below. Assume the light is coming from air (n = 1.0)

Properties of Possible Hypersonic Vehicle Window Materials			
Material	**Index of Refraction**	**Angle of Incidence**	**Angle of Refraction**
Plastic	1.3	40°	
Glass	1.47	40°	
Diamond	2.42	40°	
Sapphire	1.77	40°	
Garnet	1.89	40°	

Calculations:

1. If $n_i < n_r$, the angle of refraction should be ____________ than the angle of incidence.

2. If $n_i > n_r$, the angle of refraction should be ____________ than the angle of incidence.

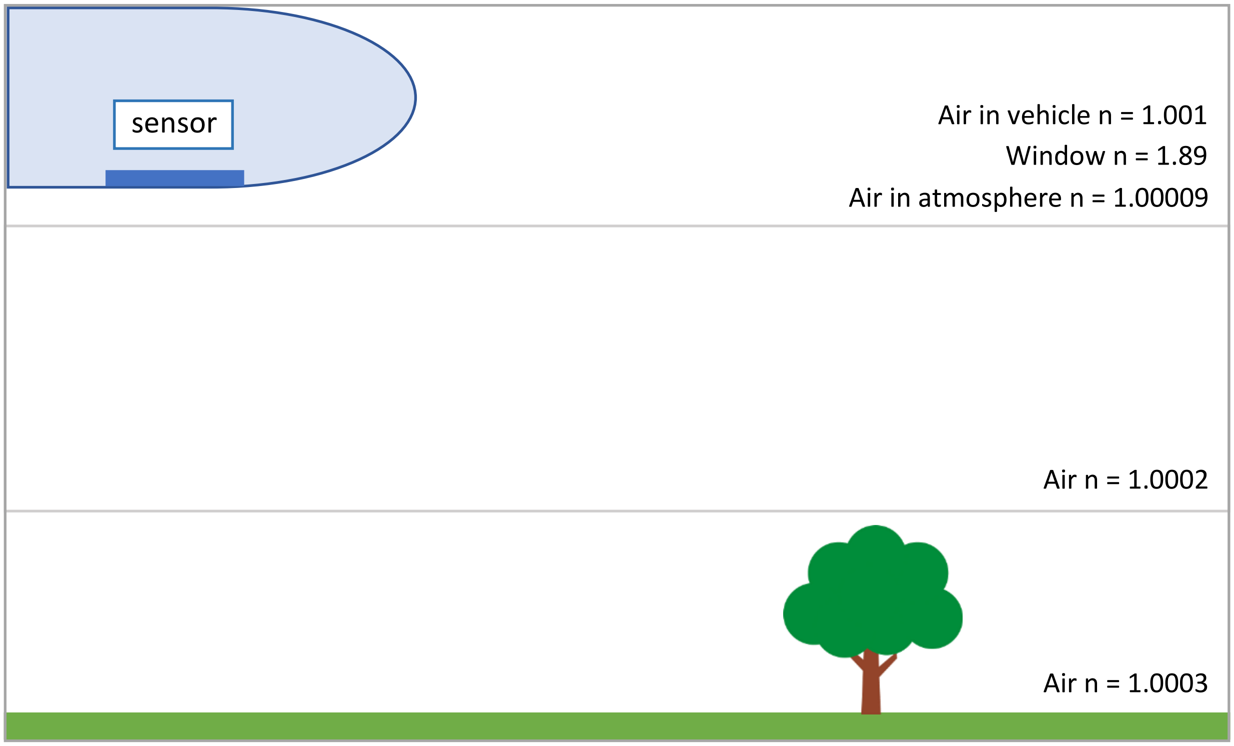
3. How different were the angles of refraction for those materials?

4. Why is it important to understand how much a sensor window refracts light?

✈Refracting Light & Hypersonics

Hypersonic vehicles use sensors to detect different types of electromagnetic waves. As light travels to and from the sensor to an object, the light ray will refract many times – from the inside of the hypersonic vehicle to the window, from the window to the outside of the vehicle, many times as the air density changes throughout the atmosphere and finally to the object and vice versa.

5. The diagram below shows the nose of a hypersonic vehicle with a sensor and sensor window on the bottom of the nose. On the diagram below, trace the light as it comes from the object (tree), refracts through the different media, and reaches the sensor.



6. Use a ruler to extend your final light ray to the sensor so it crosses the ground. Based on the diagram you drew, would you perceive the object to be at its actual location, in front of its location, or behind its location? What makes you say that?

7. How would the different window materials you explored earlier change how you perceive the object?

8. The index of refraction for the atmosphere changes gradually, rather than in chunks as the diagram suggests. How does this change how you perceive images?

Rectangular Glass Plate Diagram

✈ Triangular Glass Plate Diagram

Name: ____ Date: ____________________

Hypersonics – Moving at a Snell's Pace

In the lightbulbs below, share three big ideas that you are taking away from this lesson.



Name: ____ Date: ____________________

Hypersonics – Moving at a Snell's Pace

In the lightbulbs below, share three big ideas that you are taking away from this lesson.