



ARDMS Topic:
Ultrasound Physical Principles

Unit 6b:
Echoes

Sononerds Ultrasound Physics
Workbook & Lectures

Unit 6b: Echoes

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Unit 6b: Echoes

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Sononerds
in the classroom

**Unit 6b:
Echoes**



Unit 6b: Echoes

Unit 6a and 6b are going to have the overarching theme of what happens to sound when it travels through a medium.

6a is going to focus on attenuation, or sound weakening as it travels into the body. Understanding attenuation will help the sonographer to understand some of the physical limitations of creating a diagnostic image.

6b is going to focus on the creation of echoes. The whole reason diagnostic medical sonography exists is because sound and the medium, that is a soft tissue body, will interact in a way that returns echoes to the machine for processing and display. Understanding how echoes are created will also help us to better understand some of the physical limitations on creating a diagnostic image.

Remember we're not learning ultrasound physics to build a machine or repair one, we are learning the physics of ultrasound because it will impact the decisions you make as a sonographer for every image you take. From transducer selection to image optimization, physics is there (even when it becomes second nature to you - which it will, I promise!).

Section 6b.1 What Are Echoes?

If you have ever stood in a cave or in a canyon, there is a good chance that you have experienced an echo of your voice. If you yell into the space, the sound wave your voice creates will bounce off of a hard surface and return to your ears.

Although the ultrasound machine isn't "yelling" into the space that is your body, the high frequency sound waves created will interact with tissue. Some of that sound is reflected back to the transducer where it can be processed and turned into an image.

Without echoes, ultrasound imaging would not exist.

But what are the echoes?

As the sound enters the body, it will interact with multiple tissue types and interfaces. An interface is an area in which two different media are in contact. Some interfaces are large and some interfaces are small.

At every interface, the sound can do one or more of these things:

- Absorb
- Reflect
- Scatter
- Refract
- Transmit

The interactions of sound and the body are recorded by the machine and then mapped onto an image. The "color" of brightness of the gray is dependent on the strength of the reflection, strong reflections are white where no reflection is black. The in between strengths are represented as different levels of gray.

We already discussed absorption as a mechanism of attenuation. So we are going to focus more on reflection, scattering, refracting and transmission as they are more related to the redirection of sound and the creation of echoes.

6b.1.1 Reflection

When a sound beam is propagating through the body and interacts with a

- **large interface (those that are larger than a wavelength) a reflection is more likely to occur.**

There are two types of reflections:

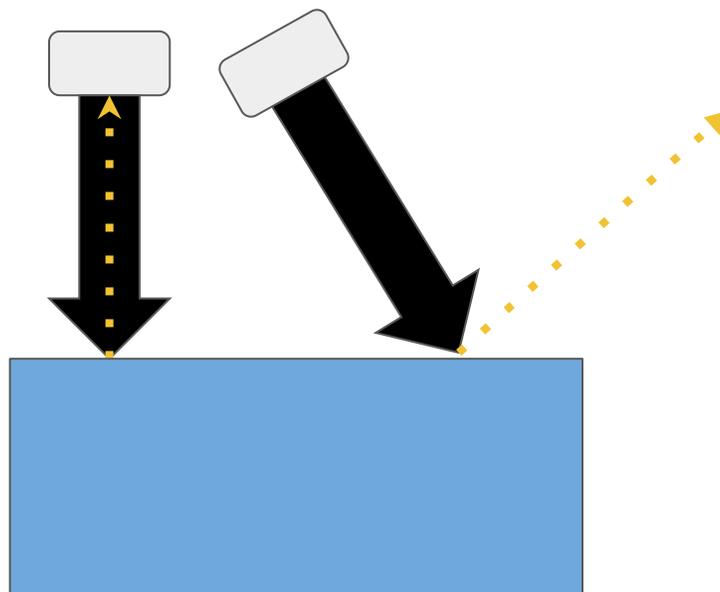
- **Specular (or near specular)**
- **Diffuse**

Specular Reflections

The structures that create specular reflections are more likely to be smooth or nearly smooth and the echoes returned from these interfaces tend to be **stronger**, therefore reflections are displayed as bright white linear echoes.

A true specular reflection occurs when a wave strikes a boundary that is smooth and flat - think of a mirror. In the mirror, you cannot see your reflection unless you are directly in front of it. So, like the mirror, the angle at which the wave strikes the surface matters. (more on this when we talk about the physics of oblique incidence!).

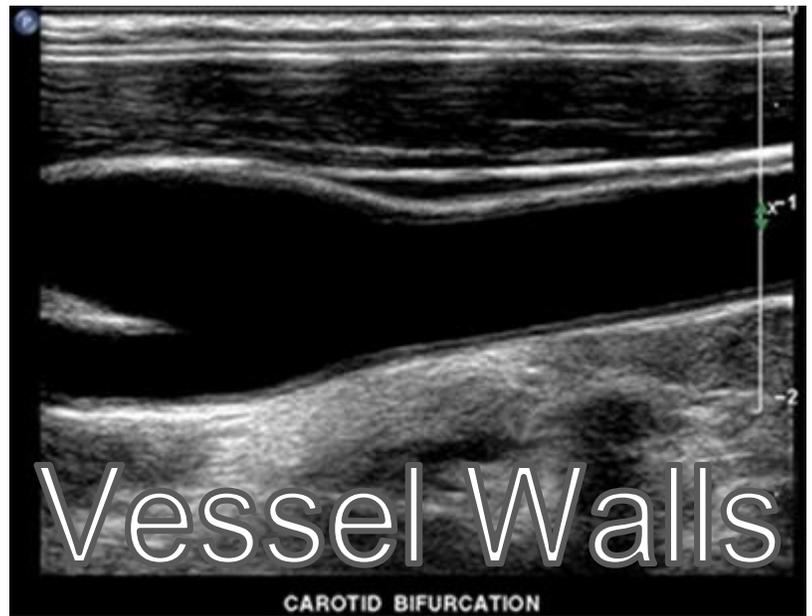
In general through, if the sound strikes a specular reflector perpendicularly or at 90° , the echo will return directly back to the transducer. This creates a really strong bright echo. If the sound comes in at angle, the echo will leave at an angle and won't return to the transducer.



Most surfaces within the body are not true specular surfaces though, so we do have some near specular surfaces that are a little more forgiving on the direction to which sound will be returned. The near specular surfaces are a little more rough. When sound strikes them, they will still send sound back to the transducer, but they are less angle dependent.

However, many of these reflectors still return better echoes at 90 degrees, so we want to attempt perpendicular insonation when we can.

Some examples of specular reflectors in the body include the:

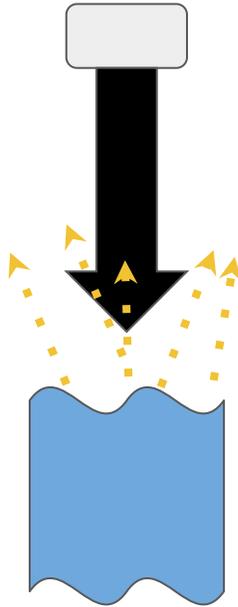


Diffuse Reflectors

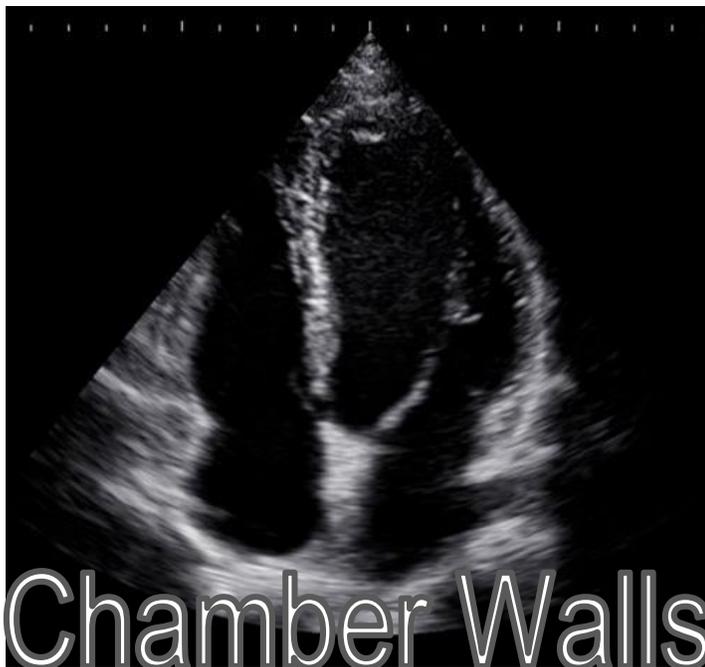
Diffuse reflectors are still large interfaces and have even more uneven surfaces. These surfaces can be found in organs or at interfaces.

Diffuse reflectors send most of their echoes back in the direction of the transducer, but they are **weaker** and a little less predictable as they are not always aimed at the transducer.

Think of looking at tin foil. You can still see your outline and colors of light reflecting, but the details are harder to discern.



Diffuse reflectors are responsible for a lot of the solid tissue we can see within an organ where large interfaces occur. Examples of diffuse reflectors include:



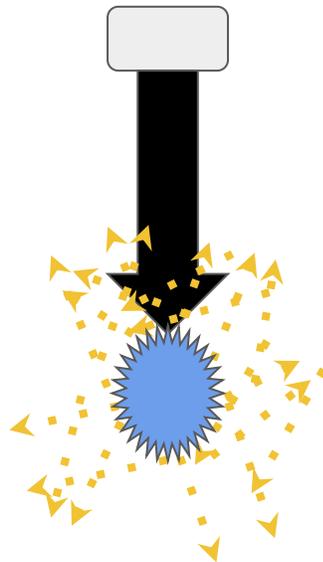
6b.1.2 Scattering

When the sound beam interacts with very small interfaces (less than a wavelength), scattering occurs. The scatter that is seen from larger diffuse reflectors and the scattering from these small, non-specular scattering sources can also be called **backscatter**.

Scattering is really the backbone of ultrasound - echoes produced from non-angle dependent reflectors make up the majority of the image and are going to express different patterns of interference.

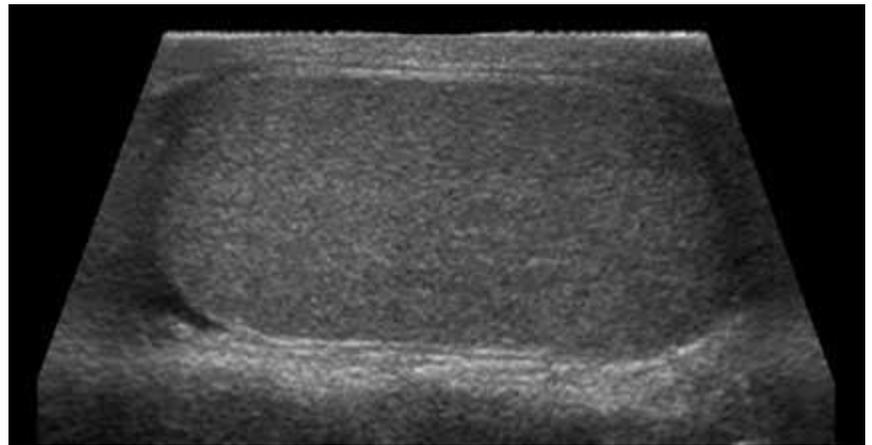
The pattern of interference is called **acoustic speckle** and gives rise to being able to see the tissue or parenchyma of the organs, muscles, fat and other connective tissue in the body.

When the sound beam propagates through the body, it will interact with A LOT of small scatter reflectors. Each of those reflectors will send multiple echoes in multiple random directions (some towards and some away from the transducer). These are the **weakest** echoes produced, but the echo waves that are created will interfere with one another, causing constructive and destructive interference. The resulting pattern is often unique to the type of tissue / pathology and is displayed as tiny, grainy dots.



→ **Higher frequency waves scatter more than low frequency waves.**

Some examples of scattering reflections include:



Testicle Tissue

These are not images of the reflectors or individual cells, but rather the acoustic pattern the interference of the waves creates.

Rayleigh Scattering

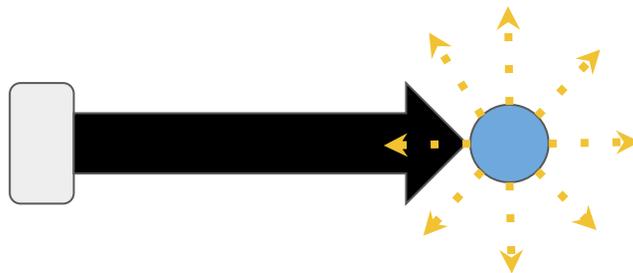
A special type of scattering occurs when the sound interacts with a VERY small reflector like **red blood cells**. Normal backscatter is unorganized and can send sound in multiple, unpredictable directions.

→ **Rayleigh scatter is organized and sends sound equally in all directions.**

Rayleigh Scattering is directly proportional to the frequency. If frequency increases, Rayleigh scattering increases by an exponent of 4.

$$\text{Rayleigh Scattering} \propto \text{frequency}^4$$

If frequency triples the scattering effect increases by 81 times. This is why **low frequency transducers** should be used for Doppler imaging.

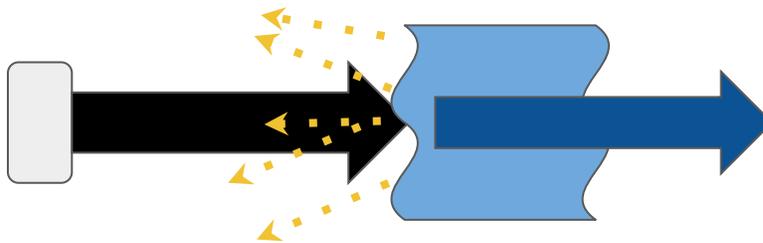


6b.1.3 Transmission

Reflection and scattering are responsible for returning echoes from an interface, but not all the sound energy is sent back. In fact a very small fraction of energy is sent back to the transducer where most of the energy will continue to move forward.

→ **The transmit wave is the sound energy that continues beyond the interface**

Without a transmit wave, ultrasound wouldn't be very useful. If the first reflector sent all the sound back, we wouldn't be able to see into the body. The transmitted wave will weaken over distance traveled because of attenuation.



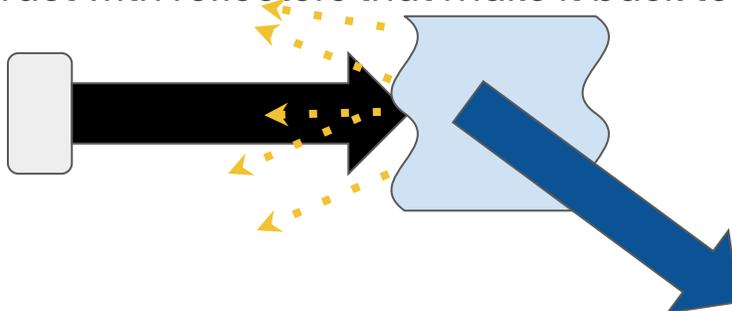
6b.1.4 Refraction

As sound moves from one type of tissue into another, it has the potential to refract.

→ **Refraction is a change in direction of transmission as sound travels into a new medium.**

Refraction won't always occur as it depends on the tissue that sound is traveling from and into. If the propagation speeds are different and the wave comes in at an angle to the surface, then refraction will occur.

Refraction can cause artifacts where anatomy is duplicated, as the redirected sound can still interact with reflectors that make it back to the transducer.



Section 6b.2 Rules of the Road

Now that you know that echoes are created and sound is transmitted at interfaces, we're going to learn about the physics behind Reflection & Transmission (Section 6b.3 & 4), but first, we need to define a few vocab words and lay out some ground rules.

6b.2.1 Helpful Concepts & Vocabulary

→ Impedance

Impedance is the resistance to the propagation of sound in a medium.

Acoustic impedance is a determining factor of an interface. When two media are adjacent to one another, and they have different impedances, sound may change its behavior due to those impedance changes at a boundary.

$$Z \text{ (rayls)} = \text{density} \left(\frac{\text{kg}}{\text{m}^3} \right) \times \text{propagation speed} \left(\frac{\text{m}}{\text{s}} \right)$$

The letter Z represents impedance and it is measured in units of Rayls.

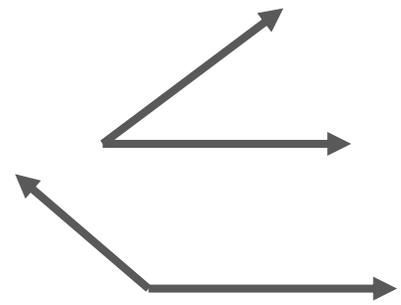
If a medium has increased density, it is harder for sound to travel through (more resistance is present)

If a medium has increased propagation speeds, it is also going to be harder for sound to travel through (again more resistance).

Impedance is determined by the physical characteristics of the medium.

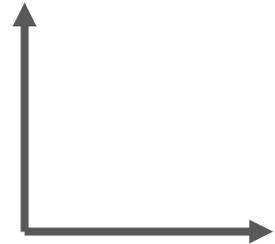
→ **Oblique Angles**

Any angle that not a 90° angle. Acute angles are less than 90° and obtuse angles are more than 90° .



→ **Right Angle**

An angle that measures *exactly* 90° . This is created between two lines that are perpendicular.

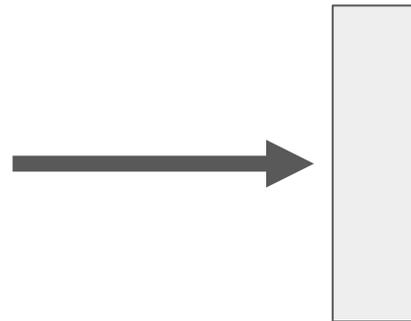


→ **Incidence**

The angle at which sound strikes a boundary.

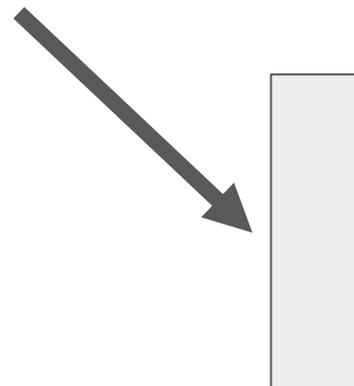
→ **Normal Incidence**

Sound beams strikes boundary at a right angle. Also known as perpendicular incidence, orthogonal incidence, and 90° incidence.



→ **Oblique Incidence**

Sound beams striking a boundary at anything other than a right angle.



→ **Incidence Angle**

The angle that the beam strikes the boundary- related to an imaginary perpendicular line.

→ **Reflection Angle**

The angle that the beam leaves the boundary- related to an imaginary perpendicular line.

→ **Transmission Angle**

The angle that the sound beam propagates -related to an imaginary perpendicular line.

→ **Medium 1 or Z_1 or Speed 1**

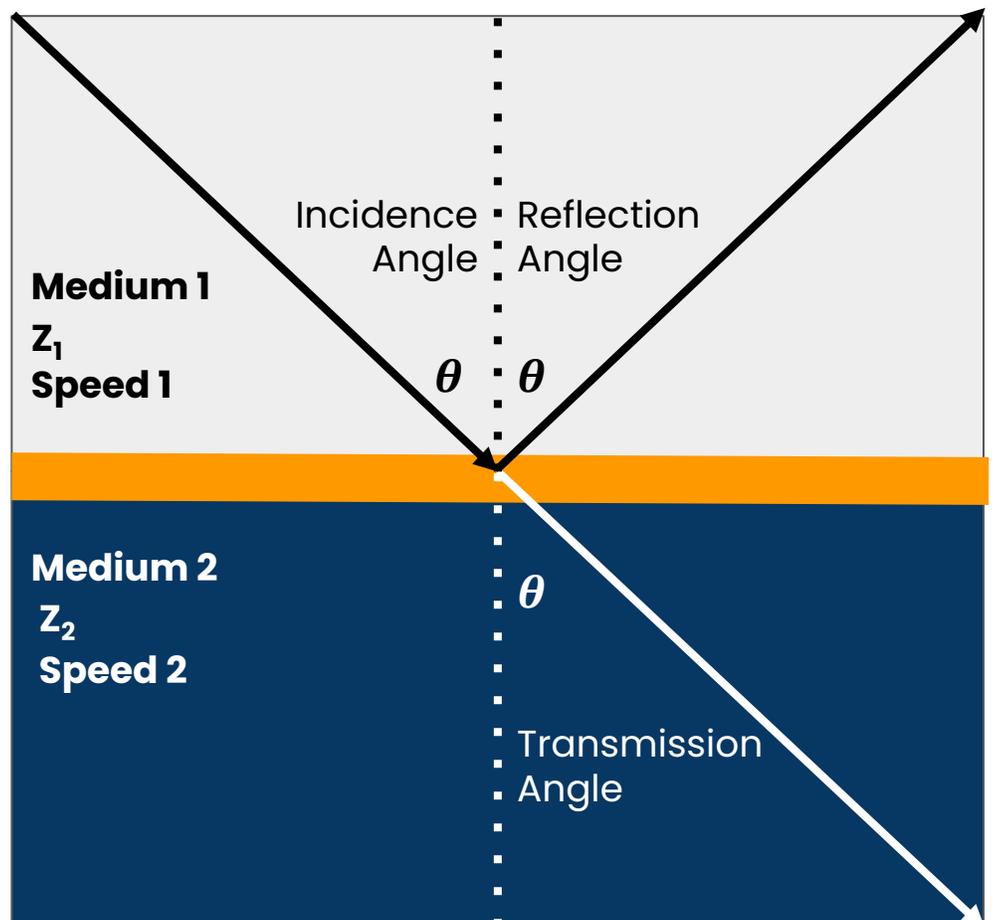
Describes the medium from which the sound is traveling from.

→ **Medium 2 or Z_2 or Speed 2**

Describes the medium to which the sound is entering into.

→ **Boundary**

The interface between two different media.



θ This symbol is used to denote angles. It is the greek letter theta.

→ **Incident Intensity (W/cm^2)**

The intensity of the beam before it gets to a boundary.

→ **Reflected Intensity (W/cm^2)**

The intensity of the part of the incident beam that is reflected (the echo) after interacting with the boundary.

→ **Transmitted Intensity (W/cm^2)**

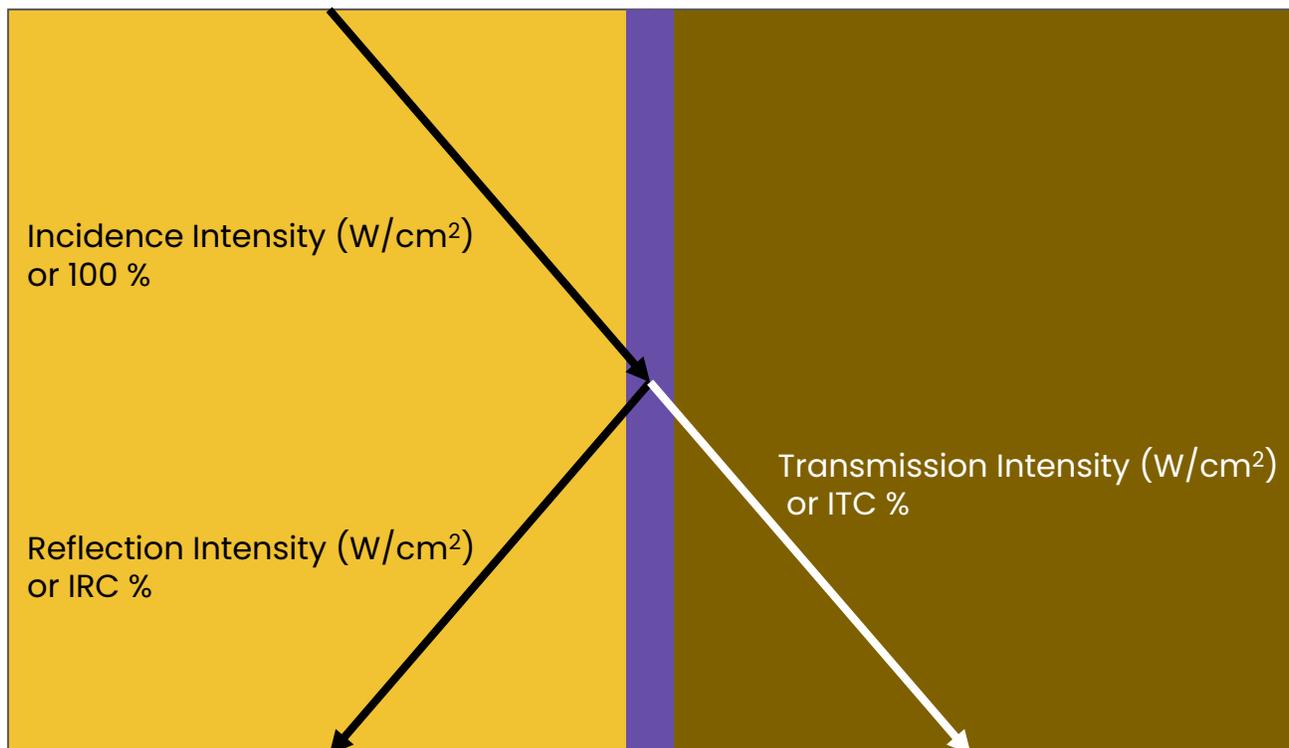
The intensity of the part of the incident beam that continues forward after interacting with the boundary.

→ **Intensity Reflection Coefficient (%)**

Percentage of the original beam that is reflected (the echo) after interacting with the boundary. In clinical imaging this is $< 1\%$.

→ **Intensity Transmission Coefficient (%)**

Percentage of the original beam that is transmitted after interacting with the boundary. In clinical imaging this is $>99\%$.



6b.2.2 Rules

All of these “rules” will be discussed in the next sections, but I wanted to compile them in one spot for easier reference.

Rule #1

Energy cannot be created or destroyed.

You may have heard something similar in your previous classes. This is the basic conservation of energy law and applies to intensities and coefficients. It is true for both normal and oblique incidence.

- **Incident Intensity = Reflected Intensity + Transmitted Intensity**
- **100% = IRC % + ITC %**

Rule #2

With normal incidence, reflection will not occur if $Z_1 = Z_2$.

There must be a difference in impedances when the incidence angle is 90°.

Small mismatched impedances create small reflections.

Huge mismatched impedances create huge reflections.

Rule #3

With normal incidence, 100% transmission will occur if $Z_1 = Z_2$

This is basically another way to restate Rule #2. Since there is no reflection, then all of the sound must keep traveling and that is because of Rule #1!

Rule #4

Reflection & Transmission with oblique incidence cannot be predicted

At any given interface with oblique incidence, there is no predicting if sound will reflect or transmit or both.

Rule #5

With oblique incidence, reflection angle = incident angle

No matter how the sound beam comes into the boundary, the reflection will leave at the same angle.

Rule #6

For refraction to occur:

- **Incidence must be oblique**
- **There must be two different propagation speeds**

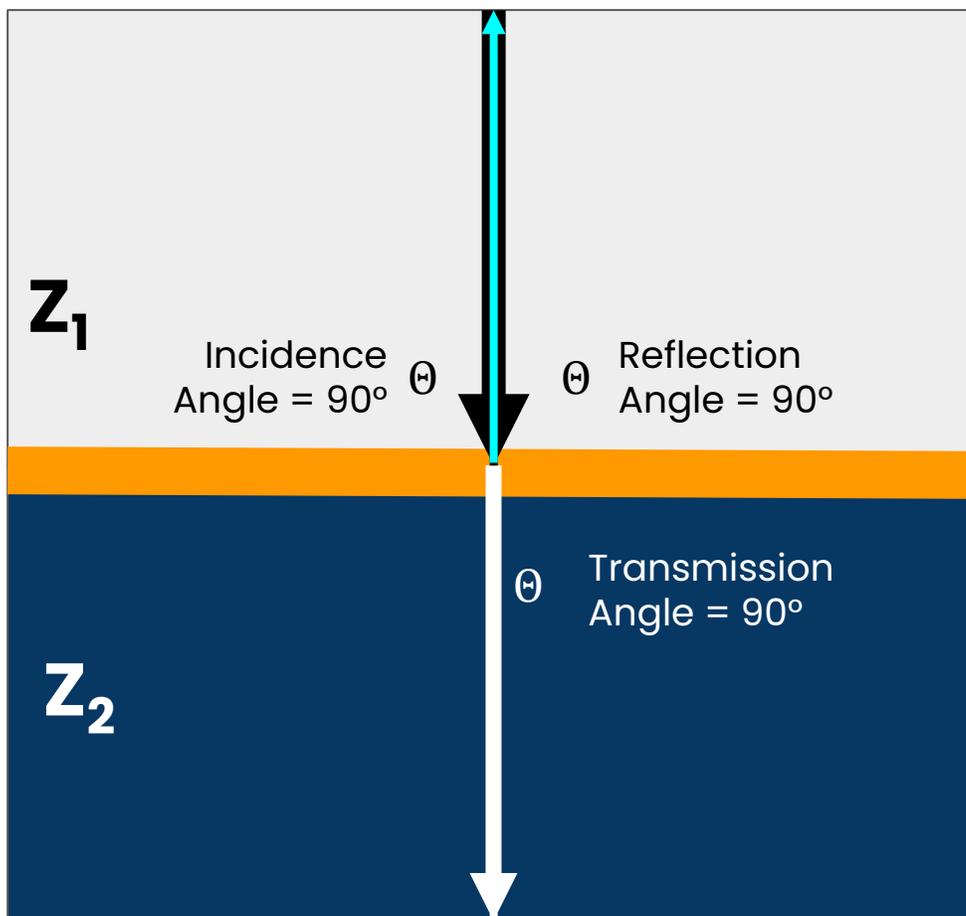
If these two criteria are met and transmission occurs (remember we won't know if will or not will oblique incidence) the transmission wave will not travel in the same direction as the incidence wave.

Section 6b.3 Physics of Normal Incidence

When a sound beam comes to an interface at a normal incidence, it is perpendicular or 90 degrees to the boundary. For a reflection to occur, the impedance of medium 1 **must be different** from the impedance of medium 2.

The amount of energy that is reflected versus the amount that is transmitted is based on the impedances of the media.

- **Same impedance = no reflection**
- **Small mismatch = small reflection**
- **Large mismatch = large reflection**



The ultrasound beam heading towards the boundary has an intensity. When it hits the interface, some of the energy will transfer to the echo and some will be transmitted forward. The intensity of the echo and the intensity of the transmission, when added together, will equal that of the original intensity because of the law of conservation.

$$\textit{incident intensity} = \textit{reflection intensity} + \textit{transmitted intensity}$$

We can also express the amount of energy transfer as fractions or percentages. The incident beam holds 100% of the energy. The percent that is transferred to the reflection is the Intensity Reflection Coefficient (IRC) and the percent that is transferred to the transmission is the Intensity Transmission Coefficient (ITC). The IRC and ITC should still add up to 100%.

$$100\% = IRC \% + ITC \%$$

Calculating the IRC and ITC is simple when given the intensities:

$$IRC \% = \frac{\text{Reflection Intensity} \left(\frac{W}{cm^2} \right)}{\text{Incidence Intensity} \left(\frac{W}{cm^2} \right)} \times 100 \quad ITC \% = \frac{\text{Transmission Intensity} \left(\frac{W}{cm^2} \right)}{\text{Incidence Intensity} \left(\frac{W}{cm^2} \right)} \times 100$$

Or once you calculate IRC or ITC...

$$IRC \% = 100\% - ITC \%$$

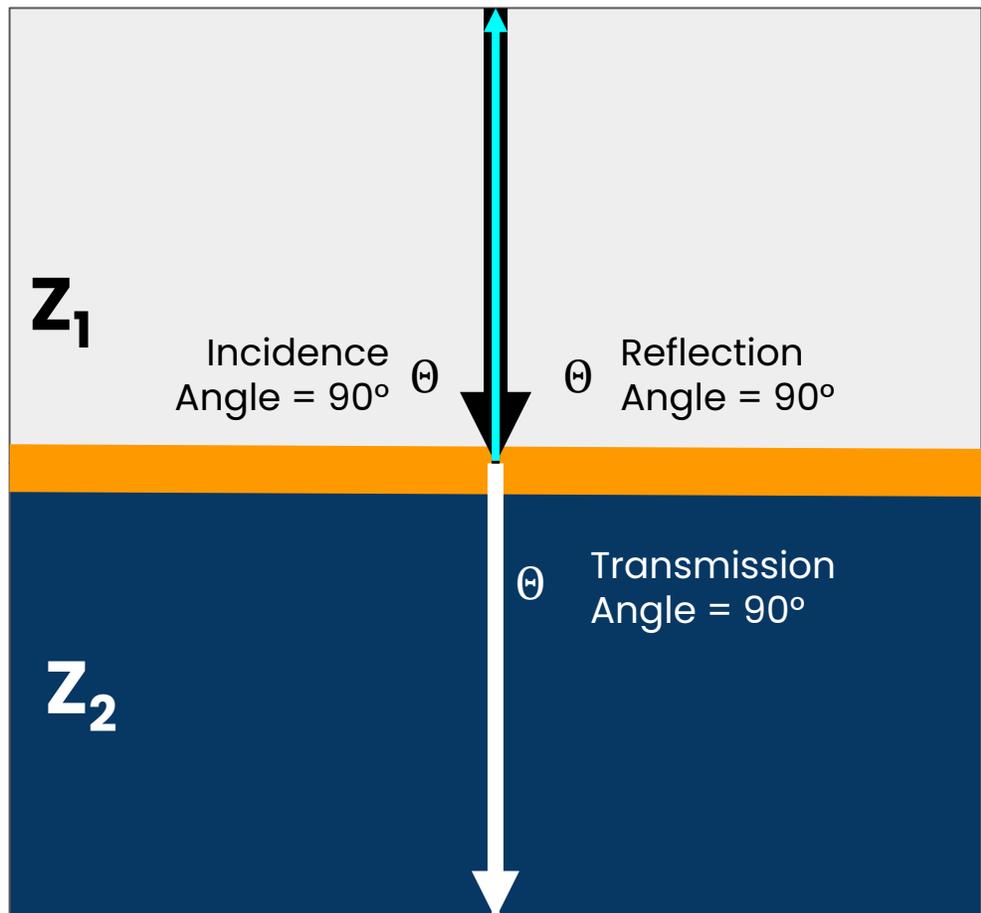
$$ITC \% = 100\% - IRC \%$$

Incident intensity =
60 mW/cm²

Reflected Intensity =
2 mW/cm²

Transmission intensity =
58 mW/cm²

100% = 3% + 97%



Calculating the IRC % when only given impedances gets a little more....exciting.

Remember this only works for **perpendicular incidence...**

$$IRC \% = \left[\frac{z_2 - z_1}{z_2 + z_1} \right]^2 \times 100$$

Once you calculate the IRC % the ITC % can be calculated by subtracting the IRC % from 100%.

Let's look at some clinically relevant examples:

Sound is traveling from liver tissue into kidney tissue at perpendicular incidence. The Liver Tissue Impedance = 1.64 MRayls and Kidney Tissue Impedance = 1.62 MRayls.

STOP! Will reflection even occur?? Yes - the incidence is 90 degrees and the impedances are different.

Okay then...let's plug in some numbers:

$$IRC \% = \left[\frac{1.62 - 1.64}{1.62 + 1.64} \right]^2 \times 100$$

$$IRC \% = \left[\frac{-0.02}{3.26} \right]^2 \times 100$$

$$IRC \% = \frac{1}{26569} \times 100$$

$$IRC \% = 0.0037\%$$

$$ITC \% = 99.9963\%$$

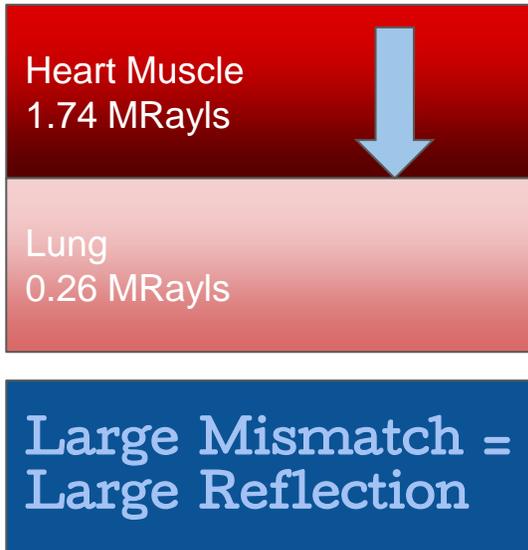


**Small Mismatch =
Small Reflection**

Sound is traveling from heart muscle into the lung at normal incidence. The heart muscle impedance = 1.74 MRayls and lung impedance = 0.26 MRayls.

STOP! Will reflection even occur?? Yes - the incidence is 90 degrees and the impedances are different.

Okay then...let's plug in some numbers:



$$IRC \% = \left[\frac{0.26 - 1.74}{0.26 + 1.74} \right]^2 \times 100$$

$$IRC \% = \left[\frac{-1.74}{2} \right]^2 \times 100$$

$$IRC \% = 0.7569 \times 100$$

$$IRC \% = 75.69 \%$$

$$ITC \% = 24.31\%$$

Sound is traveling from smooth muscle of the spleen into the spleen at orthogonal incidence. The muscle impedance is 1.65 MRayls and the spleen tissue impedance is 1.65 MRayls.

STOP! Will reflection even occur?? NO - the incidence is 90 degrees BUT the impedances are the same.

Of course we're still going to prove this.



$$IRC \% = \left[\frac{1.65 - 1.65}{1.65 + 1.65} \right]^2 \times 100$$

$$IRC \% = \left[\frac{0}{3.3} \right]^2 \times 100$$

$$IRC \% = 0 \times 100$$

$$IRC \% = 0 \%$$

$$ITC \% = 100 \%$$

Section 6b.4 Physics of Oblique Incidence

When sound arrives at an interface at an oblique angle, it behaves very differently than at a perpendicular angle.

Perpendicular incidence required a difference of impedances...

Oblique incidence doesn't care about impedances!!

Perpendicular reflection and transmission could be calculated...

Oblique incidence reflections might occur or might not... transmission might occur or might not... or some combo of both might occur. Oblique incidence does what it wants.

Knowing that oblique incidence behaves differently than perpendicular incidence we need to think of it as its own entity that follows its own rules.

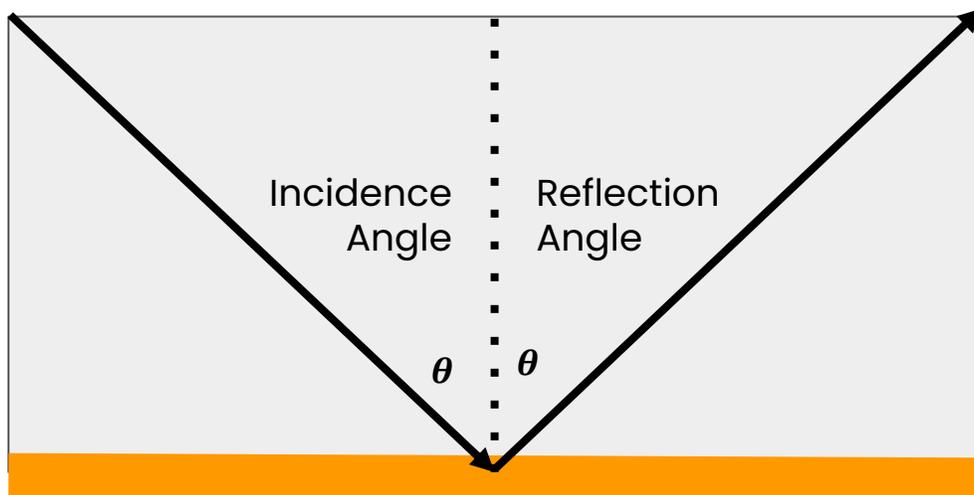
IF reflection occurs (remember it might not), it will still follow the law of conservation where :

$$\textit{incident intensity} = \textit{reflection intensity} + \textit{transmitted intensity}$$

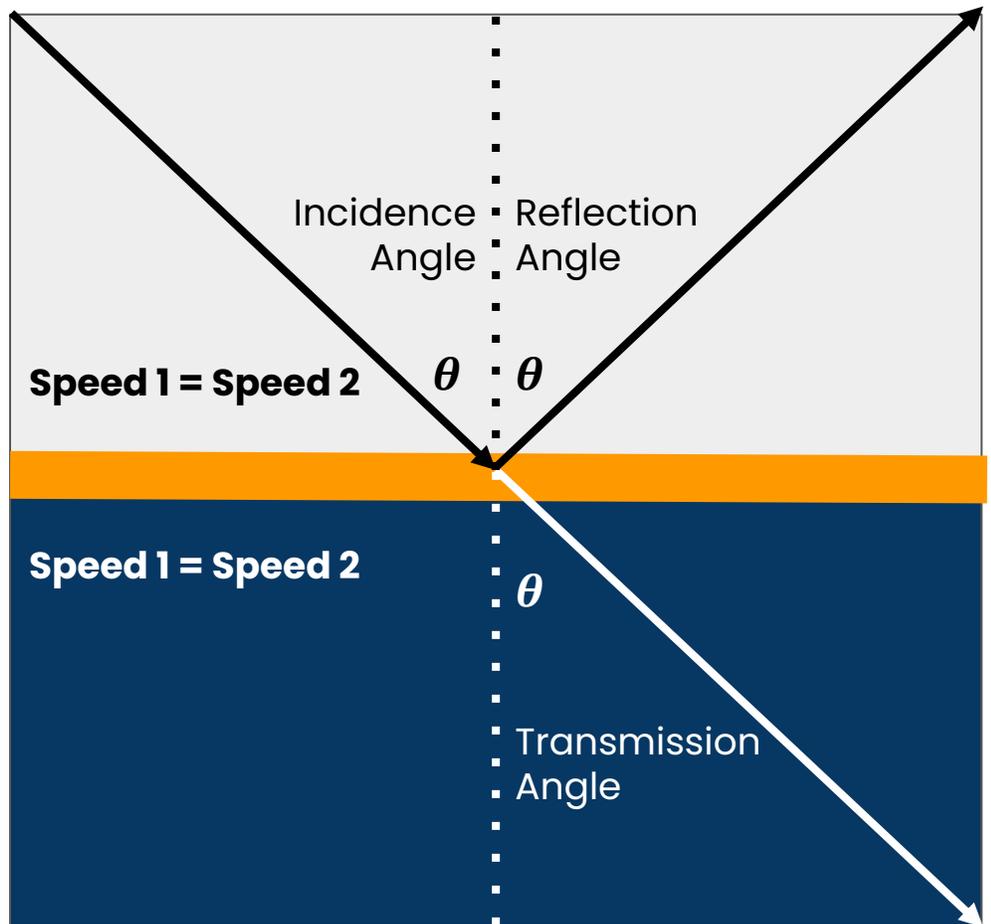
But we cannot calculate the IRC % using impedances because it doesn't matter with oblique incidence.

The reflection will also leave the boundary at the same angle the incidence beam came in at:

$$\textit{incidence } \theta = \textit{reflection } \theta$$

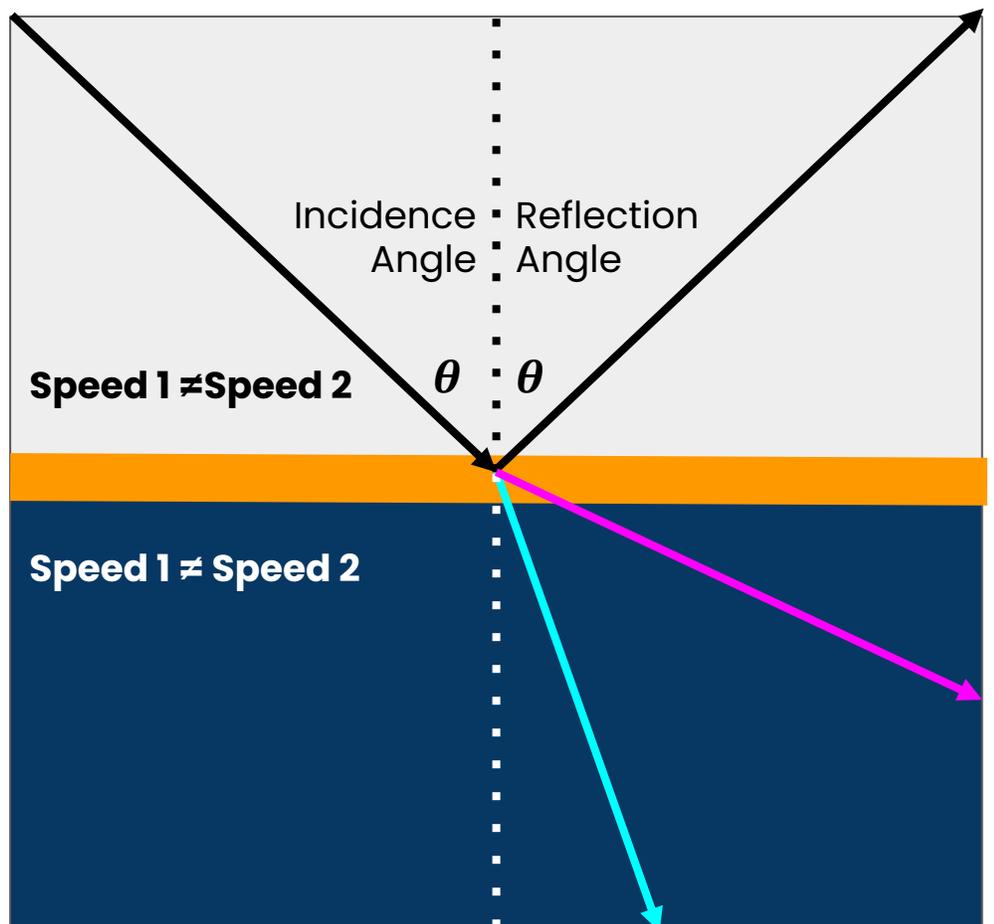


IF transmission occurs with an oblique incidence (remember it might not), it will continue in the same direction if the **propagation speeds** of the media on either side of the boundary are the same.



If the propagation speeds are different, the transmission wave will "bend" and head in a different direction.

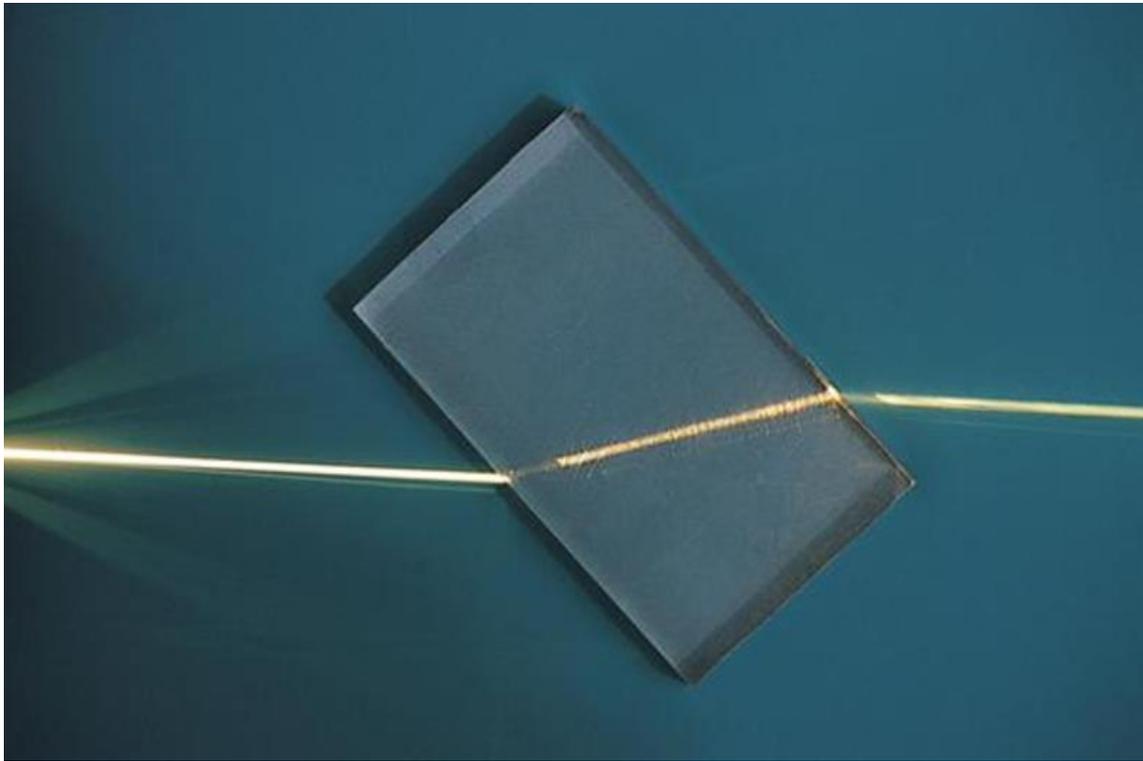
This is called refraction.



6b.4.1 Refraction

For refraction to occur, two things must be true:

- **Oblique incidence**
- **Different propagation speeds on either side of the boundary**



Snell's Law

The way in which the sound beam will change directions can be calculated by Snell's Law. Snell's Law takes into account the ratio of the propagation speeds of the two media and their angles to determine their relationship.

$$\frac{\sin(\text{transmission } \theta)}{\sin(\text{incident } \theta)} = \frac{c (\text{Medium 2})}{c (\text{Medium 1})}$$

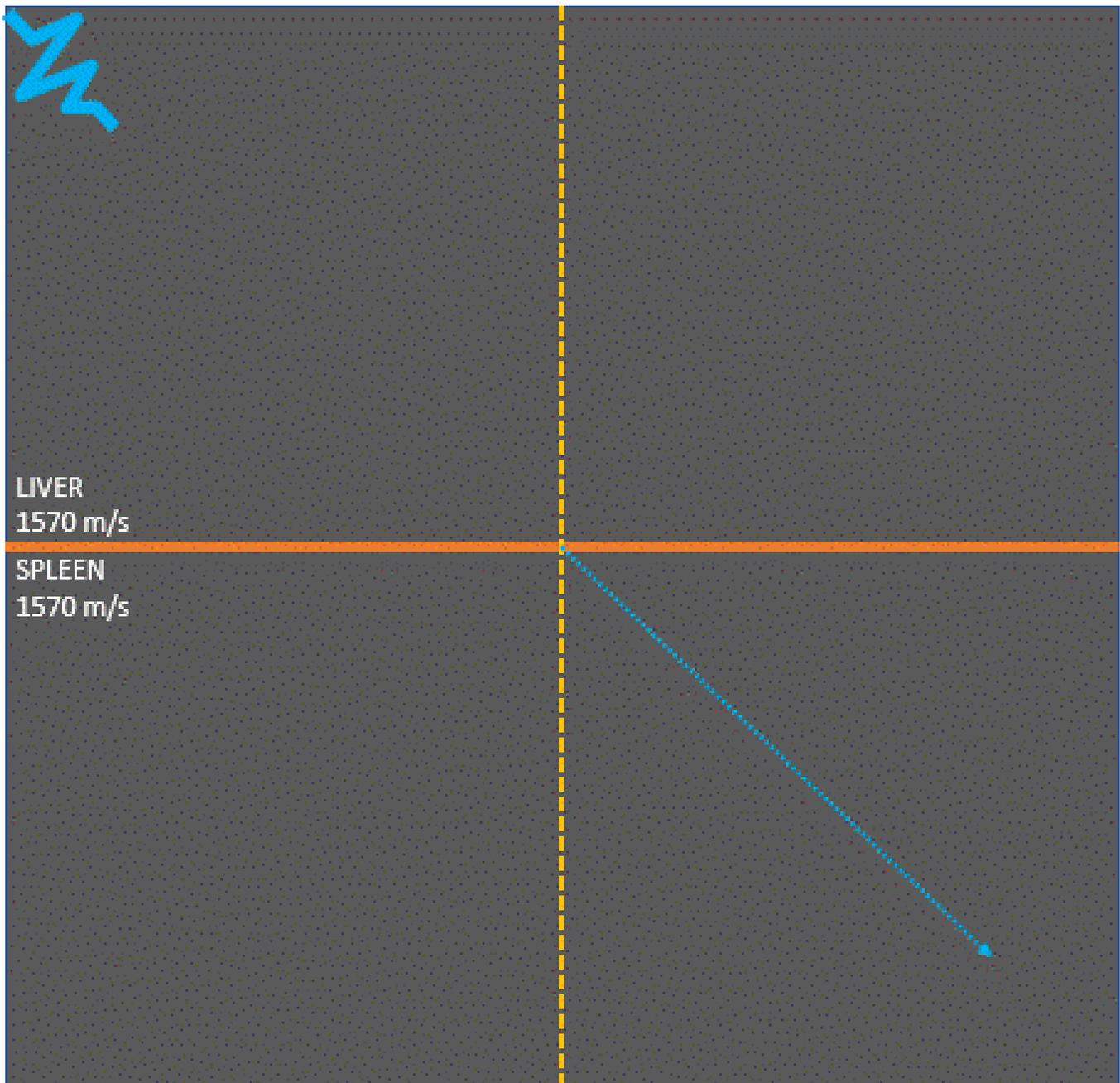
$$\sin(\text{transmission } \theta) = \sin(\text{incident } \theta) \times \frac{c_2}{c_1}$$

These are the same formulas, but the second one will help us to see the relationships clearer of how the propagation speed in medium 2 and the angle of transmission.

The “sin” of the equation is a trigonometry derived value that includes right angles and hypotenuses and...HEY WAKE UP! Ok - no, you don't need to know what the sine of the angle is per se, just know it gives us a functional value of an angle so we can calculate the change of the angle.

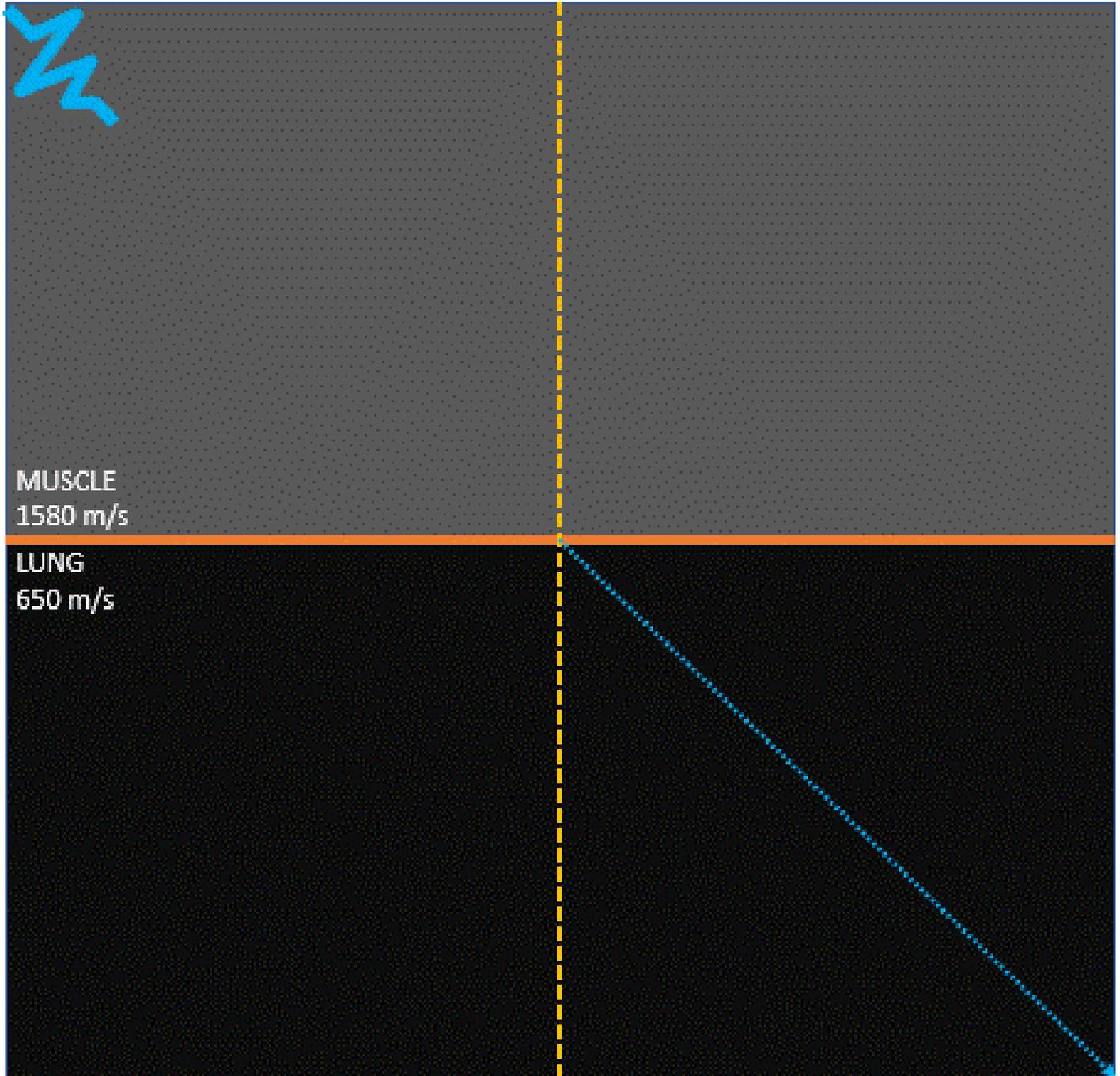
From the formula, here is what we really need to know about refraction:

- **Speed of medium 1 = Speed of medium 2**
- **Incident θ = Transmission θ**



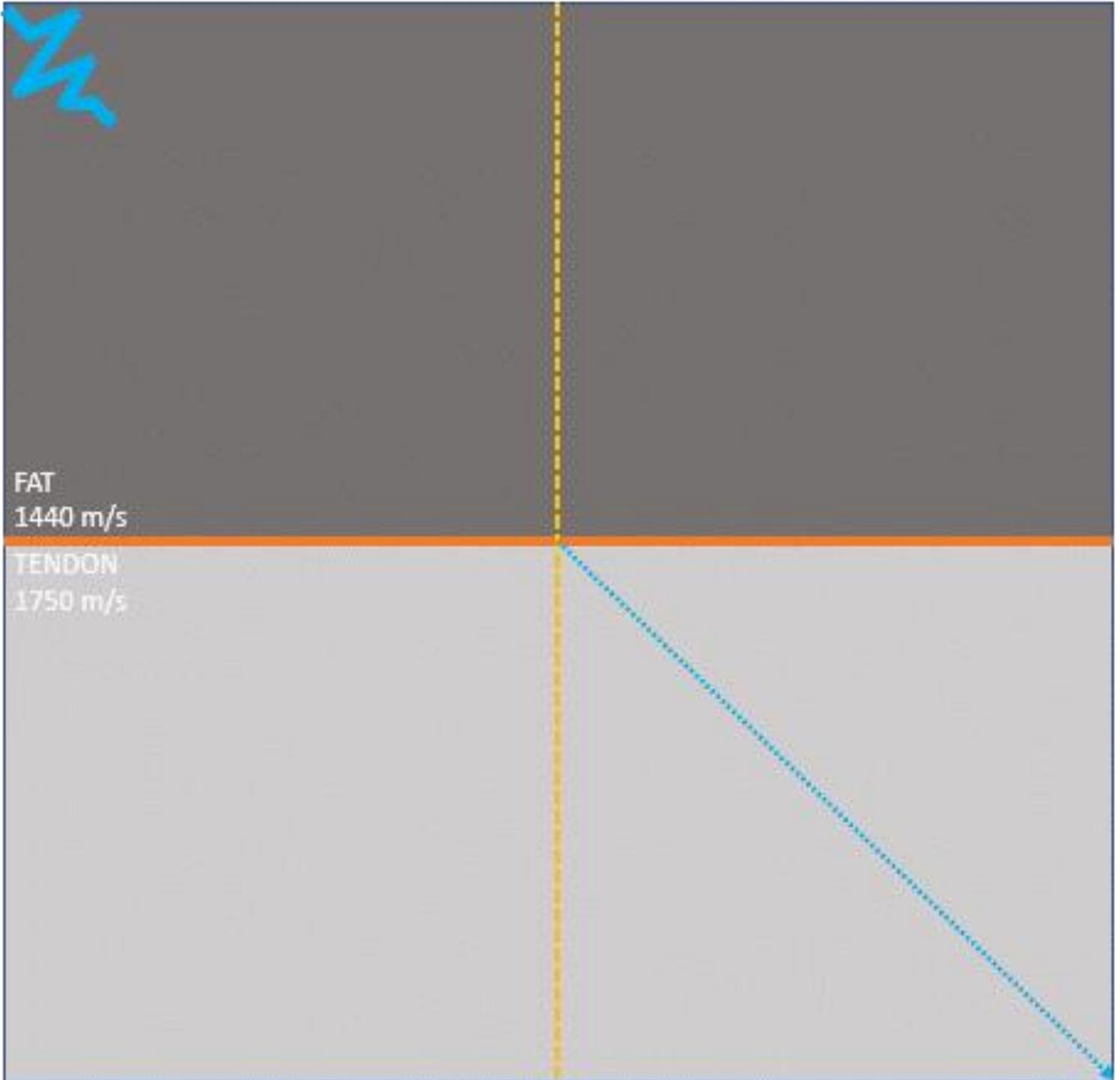
→ Speed of medium 1 > Speed of medium 2

→ Incident θ > Transmission θ



→ Speed of medium 1 < Speed of medium 2

→ Incident θ < Transmission θ



Section 6b.5 Activities ← Link to Answers

1. Complete the charts***

Incident Intensity	IRC	ITC	Reflected Intensity	Transmitted Intensity
50 W/cm ²	100%			
60 W/cm ²	50%			
50 W/cm ²	2%			

Incident Intensity	IRC	ITC	Reflected Intensity	Transmitted Intensity
100 W/cm ²			35 W/cm ²	
200 W/cm ²		36%		
80 W/cm ²				20 W/cm ²

*** Given basic numbers, like the ones found in the top chart, you should be able to do these types of questions for your boards. The bottom chart is presented more as a challenge.

2. Fill in this chart *** Calculate the IRC & Impedance, based on the information given, assuming normal incidence & soft tissue propagation speed. (Round to whole numbers for Rayls)

Media 1 Impedance	Media 2 Impedance	Media 2 Density	IRC %	ITC %
10 Z		.0065 kg/m ³		
10 Z		.0198 kg/m ³		
10 Z		0.01 kg/m ³		
10 Z		.0019 kg/m ³		

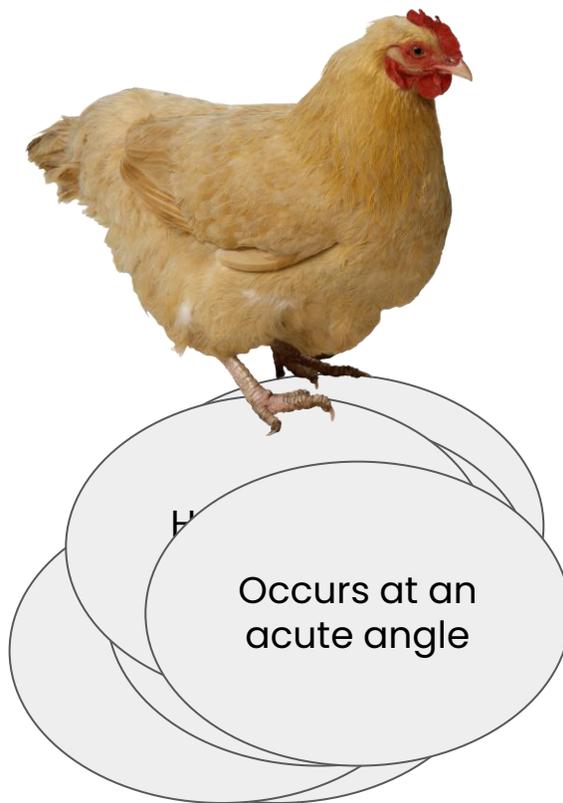
*** This chart is definitely more of a challenge, but you should be able to answer these questions: In perpendicular incidence...

What happens to the reflection when media 1 impedance = media 2 impedance?	
What happens to the reflection when the impedances are very similar?	
What happens to the reflection when the impedances are very dissimilar?	
What happens to the transmission when media 1 impedance = media 2 impedance?	
What happens to the transmission when the impedances are very similar?	
What happens to the transmission when the impedances are very dissimilar?	

3. Sort these statements.

Normal Incidence

Oblique Incidence



4. Match the requirements with the event:

Reflection with
normal incidence

Reflection with
oblique incidence

Intensity
Transmission
Coefficient

Refraction

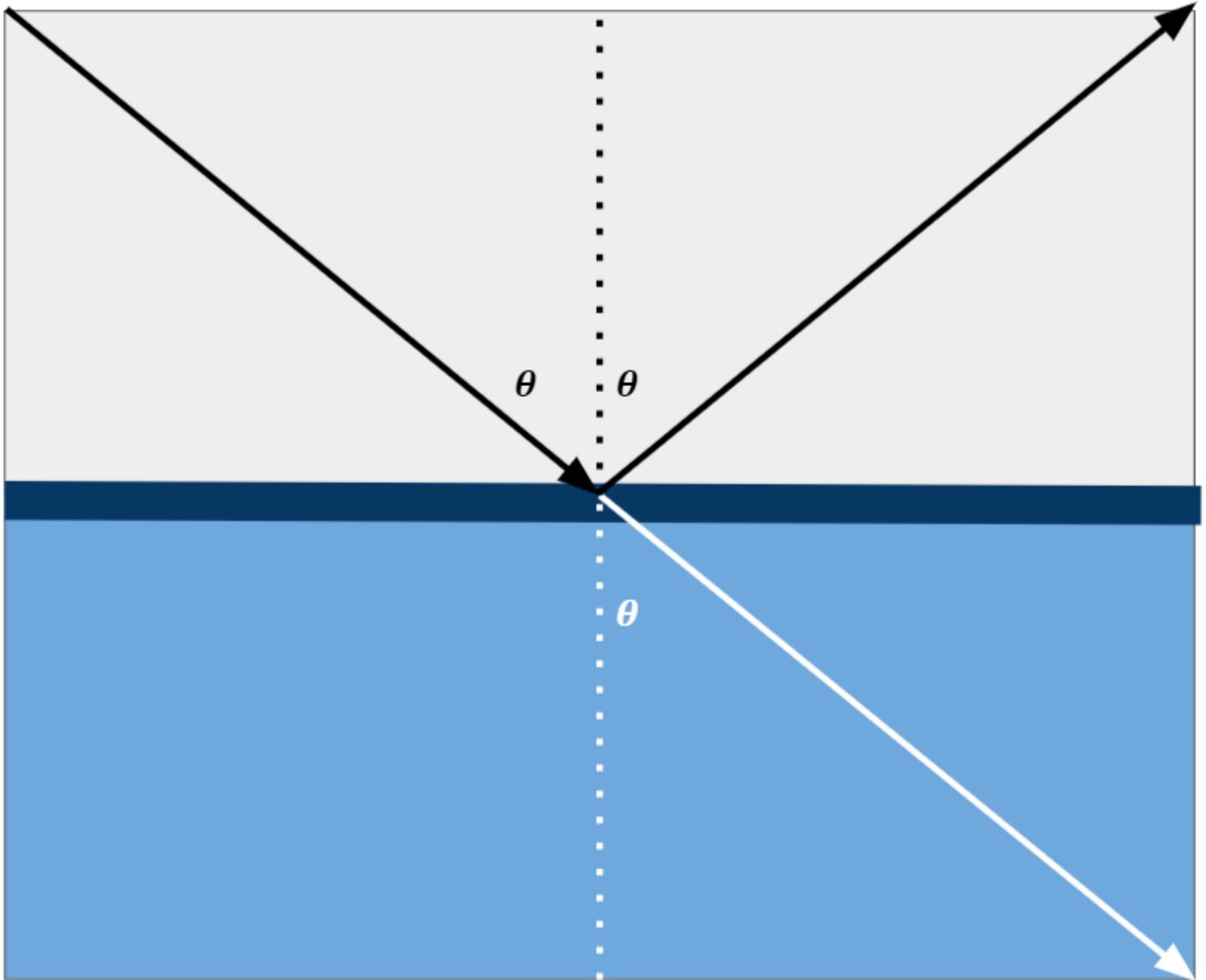
Different impedances
required

Calculated from the IRC,
must abide by the law of
conservation of energy

Cannot predict - too
complex!

Oblique incidence and
different propagation
speeds

5. Drag the labels to the correct spot on the diagram.



Incidence
Wave

Incidence
Angle

Reflection
Wave

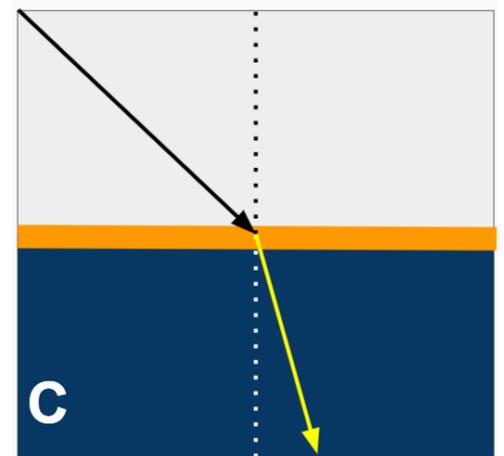
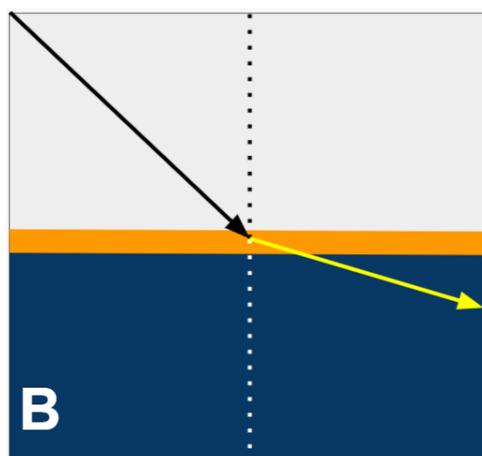
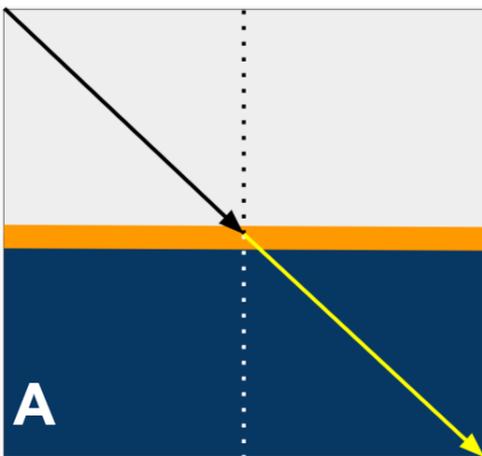
Reflection
Angle

Transmission
Wave

Transmission
Angle

6. Place an = , < or > in the blue box to make the row true, assuming oblique incidence. Then, indicate which diagram corresponds with the statement the best. Row 1 is done as an example.

Medium 1 Speed		Medium 2 Speed	Incident θ		Transmission θ	Diagram
1540 m/s	=	1540 m/s	θ	=	θ	A
speed		speed	45°		45°	
Soft Tissue		Air	θ		θ	
650 m/s		1230 m/s	θ		θ	
speed		speed	20°		80°	
Bone		Soft Tissue	θ		θ	
780 m/s		330 m/s	θ		θ	



Section 6b.6 Nerd Check!

1. What can happen at each interface a sound wave encounters?
2. What determines the brightness of an echo?
3. Describe the interface that will make a reflection.
4. What are the two types of reflection that can occur?
5. What is a specular reflector similar to?
6. How does angle affect the reflection from a specular transducer?
7. What do specular reflections look like on ultrasound?
8. Why are they more likely to be white?
9. What are some examples of specular reflectors from the body?
10. What is the best angle to insonate specular and near specular reflectors?
11. Describe a diffuse reflector.
12. How do the echoes return from a diffuse reflector?
13. Are diffuse reflections strong or weak?
14. Are diffuse reflections all sent back to the transducer?
15. What are some examples of diffuse reflectors?
16. What is back scatter?
17. Describe a scattering reflector.
18. Why is backscatter good?
19. What does backscatter represent in the image?
20. What is acoustic speckle?
21. What are the echoes that represent the solid part of the organ actually showing?
22. Are scatter echoes strong or weak?
23. How do scatter echoes leave the the reflector?
24. What frequencies are more likely to scatter?
25. What is Rayleigh scattering?
26. What body tissue is most likely to cause Rayleigh scattering?
27. How is frequency related to Rayleigh scattering?
28. If frequency doubles, by what factor does Rayleigh scattering increase?
29. What is unique about the way echoes leave a Rayleigh scatterer?
30. What is a transmission wave?
31. What would happen if we didn't have transmission waves?
32. What happens to the transmission wave as it travels deeper in the body?
33. What is refraction?
34. When does refraction occur?
35. Can echoes still be returned from a refracted wave?
36. What is impedance?
37. How is impedance calculated?
38. What is the symbol for impedance?
39. What unit is impedance reported in?
40. If density increases, what happens to that medium's impedance?
41. If the propagation speed increases, what happens to that medium's impedance?

42. What types of angles are oblique angles?
43. Give some examples of an acute angle. Give some example of an obtuse angle.
44. How many degrees is a right angle?
45. When two line make a right angle, they are _____ to each other.
46. What is incidence?
47. What is normal incidence?
48. What is perpendicular incidence?
49. What is 90 degree incidence?
50. What is orthogonal incidence?
51. What is oblique incidence?
52. Describe the incidence angle.
53. Describe the reflection angle.
54. Describe the transmission angle.
55. How do we determine Medium 1 from medium 2?
56. What is a boundary?
57. Describe incident, reflected and transmitted intensity.
58. What unit do intensities get reported in?
59. What is the intensity reflection coefficient and what is the transmission coefficient?
60. What is normal IRC and ITC for clinical imaging?
61. Why do we care about energy not being created or destroyed?
62. What two formula are base on the law of conservation?
63. Under what circumstances will ZERO reflection occur?
64. Under what circumstances will 100% transmission occur?
65. How do we know if reflection or transmission will occur with oblique incidence?
66. With oblique incidence, the angle is 35 degrees, what is the reflection angle? Why?
67. What are the two criteria for refraction?
68. In perpendicular incidence, describe the reflection if the impedances of the media at the interface are the same, similar, very different.
69. What is the formula for incident intensity?
70. What do IRC % and ITC% always add up to?
71. If you have IRC OR ITC, how would you calculate the other?
72. How can you calculate IRC or ITC with intensity values?
73. How can the IRC at a perpendicular incidence be calculated only using the impedances of the two media?

73. What is oblique incidence?
74. How is oblique incidence affected by impedance?
75. How is reflection and transmission calculated with oblique incidence?
76. If reflection and transmission occur in oblique incidence how are they related to the incident intensity?
77. If the incidence beam is at an angle, how does that affect the reflection angle?
78. If oblique incidence is present and transmission occurs what path will the transmission wave take if:
 - a. The propagation speeds are the same?
 - b. If medium 1 is faster than medium 2?
 - c. If medium 1 is slower than medium 2?
79. What law helps us to calculate refraction?