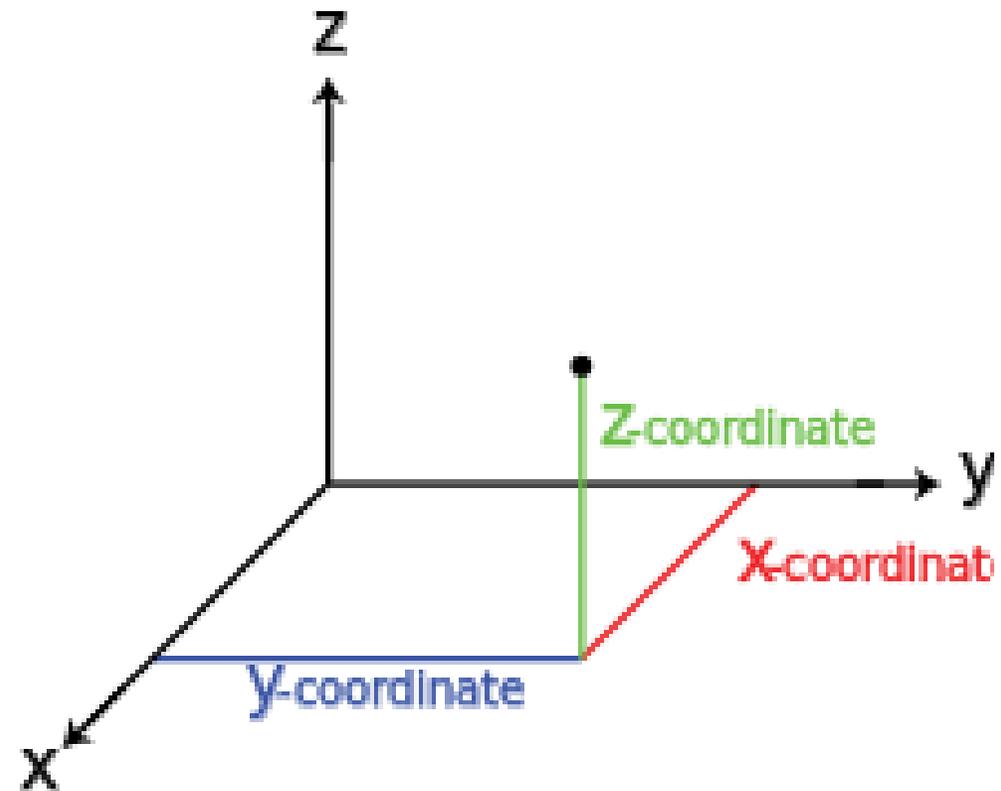


Physical Principles

Chapter 1

Mathy Stuff

- Graphs always have two axes:
 - **Horizontal Axis (X)**
 - **Vertical (Y)**
- Occasionally you will also see:
 - **Vertical (Z)**



Mathy Stuff

- Manipulating formulas to solve for "a," "b," or "c":

$$a = \frac{b}{c} \quad \text{or} \quad a \times c = b \quad \text{or} \quad \frac{b}{a} = c$$

Mathematically it would look like this:

$$10 = \frac{20}{2} \quad \text{or} \quad 10 \times 2 = 20 \quad \text{or} \quad \frac{20}{2} = 10$$

Mathy Stuff

- Knowledge of relationships answers the question “What happens to “a” when “b” changes?”
 1. **Unrelated** - two items have no association
 2. **Related** - two items that are connected, but no specified relation
 - *** 3. **Directly related/Directly Proportional** - two items that are related so that when one increases, the other also increases
 - *** 4. **Inversely related/Inversely Proportional** - two items that are related so that when one increases, the other decreases
 5. **Reciprocal** - special inverse relationship when two factors are multiplied together, they equal one

Mathy Stuff

- Looking at your formulas - connect the relationship:

Rule #1: The factors ('a' and 'b') are directly related to the product ('c')

$a \times b = c$  increasing 'a' or 'b' will cause 'c' to also increase

$a \times b = c$  decreasing 'a' or 'b' will cause 'c' to also decrease

Rule #2: The quotient is directly related to the numerator and inversely related to the denominator

$a = \frac{b}{c}$  increasing "b" will cause "a" to increase
increasing "c" will cause "a" to decrease

Mathy Stuff

- Common units used in ultrasound:

Time: any unit of duration (s, ms, μ s)

Distance: any length measurement (m, mm, km)

Frequency: Hertz (MHz, kHz) or cycles per second

Velocity: any unit of length divided by time (m/s, mm/ μ s)

Area: any distance unit squared (cm², sq. km)

Volume: any distance unit cubed or volume unit (cm³ or mL)

Mathy Stuff

- Some other random things about units:
 - ❖ Percentages are not technically units
 - ❖ Most units used in ultrasound are based off the metric system
 - ❖ If your answer does not have a unit or percentage, it is wrong until you define it
 - ❖ When using units in a formula, like units or complimentary units should be used

Mathy Stuff

- “Increasing by a factor”

Multiply

For example: Intensity has increased by a factor of two means the intensity is two times larger than its original value.

- “Decreasing by a factor”

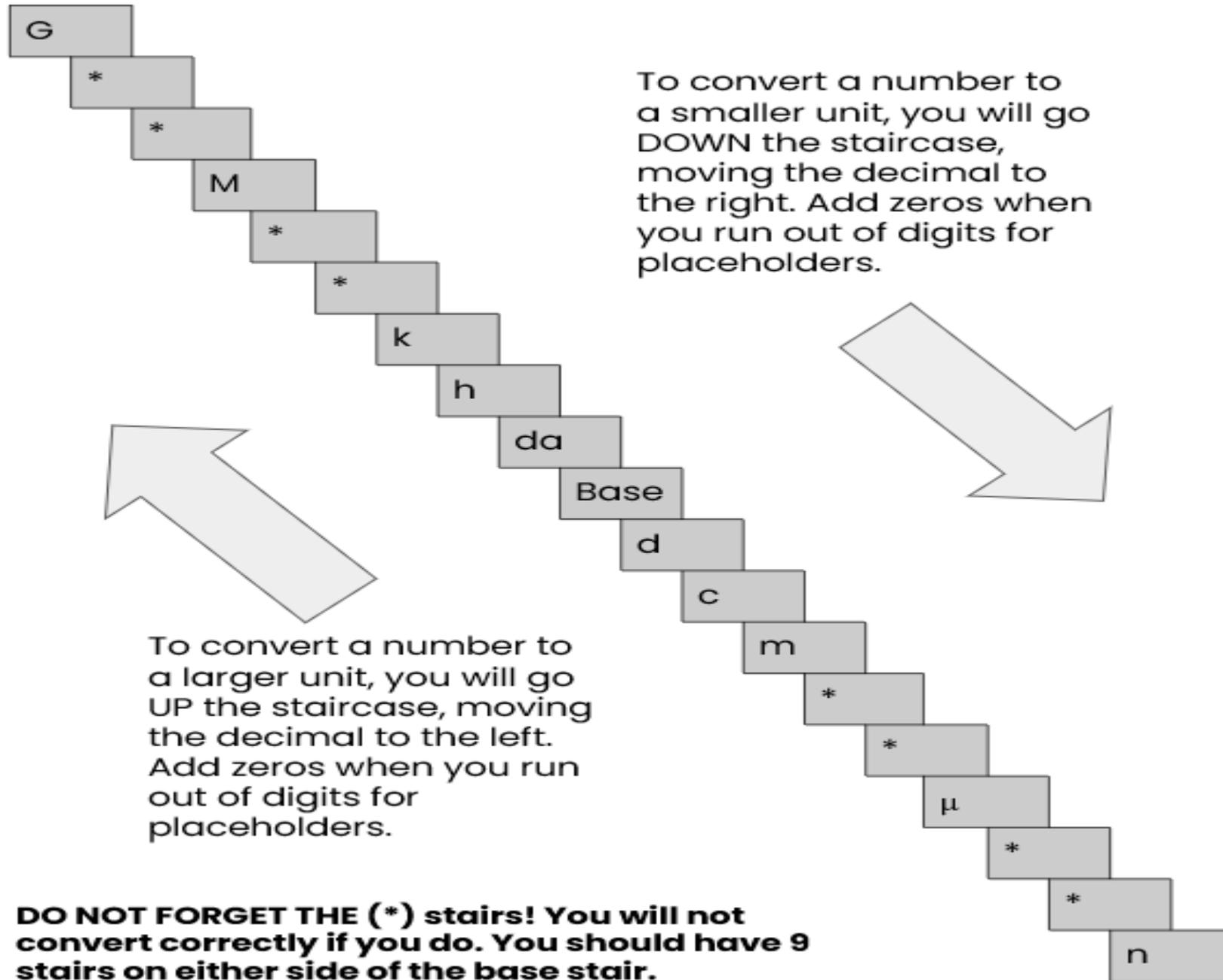
Divide

For example: Intensity has decreased by a factor of four means the intensity is one-quarter of its original value.

Mathy Stuff

Prefix	Value	Symbol	Exponent
Giga	Billion x base (1,000,000,000 x)	G	10^9
Mega	Million x base (1,000,000 x)	M	10^6
Kilo	Thousand x base (1,000 x)	k	10^3
Hecto	Hundred x base (100 x)	h	10^2
Deca	Ten x base (10 x)	da	10^1
Base (Meter = m, Second = s, Liter = L, Hertz = Hz)			10^0
Deci	One tenth of base (0.1 x)	d	10^{-1}
Centi	One hundredth of base (0.01 x)	c	10^{-2}
Milli	One thousandth of base (0.001 x)	m	10^{-3}
Micro	One millionth of base (0.000001 x)	μ	10^{-6}
Nano	One billionth of base (0.000000001 x)	n	10^{-9}

Great **M**an
King **H**enry's
Daughter
Beth **D**rinks
Cold **M**ilk
 μ ntil **N**ine



Mathy Stuff

- Converting units:
 - **When the metric prefix gets larger (ex. mL to L) the number in front of the prefix gets smaller**

To convert to a larger prefix, the decimal point will move to the left
 - **Converting to a smaller metric prefix (ex. km to cm) the number in front of the prefix gets bigger**

To convert to a smaller prefix, the decimal point will move to the right

Example: Convert 1,000.0 mL to L

Convert 55 km to cm

Mathy Stuff

- Scientific notation is a shorthand way to represent very large or very small numbers that can be tricky to write
- Scientific Notation Rules:
 - Positive Exponents have values >10
 - Negative Exponents have values <1
 - Exponent of zero means the value is between 1 & 10

Mathy Stuff

- Shift the decimal point so the resulting number is between 1 & 10, then multiply by the appropriate power of 10:
 - $1,000,000 = 1.0 \times 10^6$
 - $0.000000124 = 1.24 \times 10^{-7}$
 - $1742 = 1.742 \times 10^3$

What is Sound?

- Sound is form of energy
 - It is a **pressure wave** that relies on **mechanical action** and therefore it is referred to as a mechanical wave
- Sound requires a medium to propagate
 - Medium is any form of matter: solid, liquid, or gas (think biological tissues)
 - Sound cannot travel through a vacuum

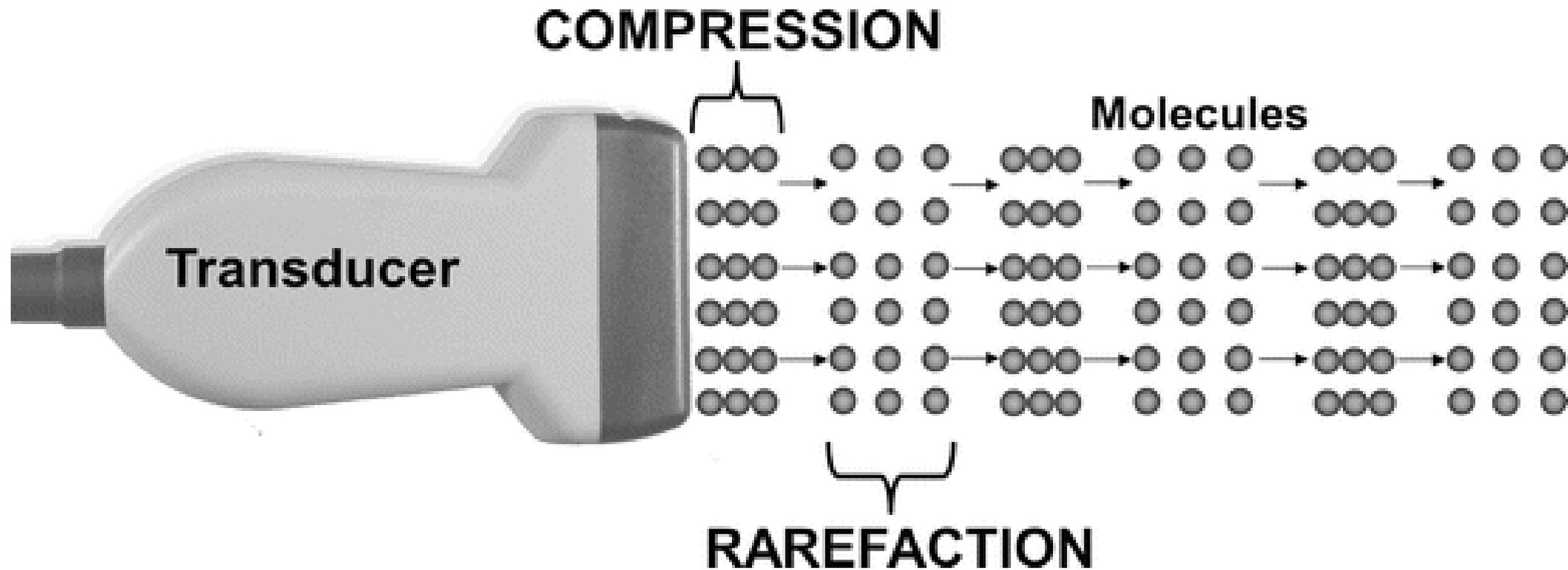
What is Sound?

- Sound is a mechanical, longitudinal wave
- Sound travels in a straight line
- Waves carry energy, not matter, from one location to another
- Categorized as infrasonic, audible, or ultrasonic based on its frequency
 - Diagnostic medical sonography utilizes ultrasound, which ranges in megahertz (MHz) to image the body

Acoustic Variables

- Acoustic variables are changes that occur within a medium as a result of sound traveling through the medium
 - Molecules become squeezed together and stretched apart creating areas of compressions and rarefactions
 - **Compressions** - areas of increased pressure or density (molecules are squeezed together)
 - **Rarefactions** - areas of decreased pressure or density (molecules are spaced further apart)

Acoustic Variables



Acoustic Variables

- Three primary acoustic variables:

- 1. Pressure**

- Concentration of force within an area; units are pascals (Pa)

- 2. Density**

- Concentration of mass within a volume; units are kg/cm^3

- 3. Distance (particle motion)**

- Measurement of particle motion; may have any unit of length (cm, feet, miles, etc)

Acoustic Variables

- As sound travels through a medium and creates areas of compressions and rarefactions, the molecules become squeezed together and separated

This creates **pressure** and **density** variations

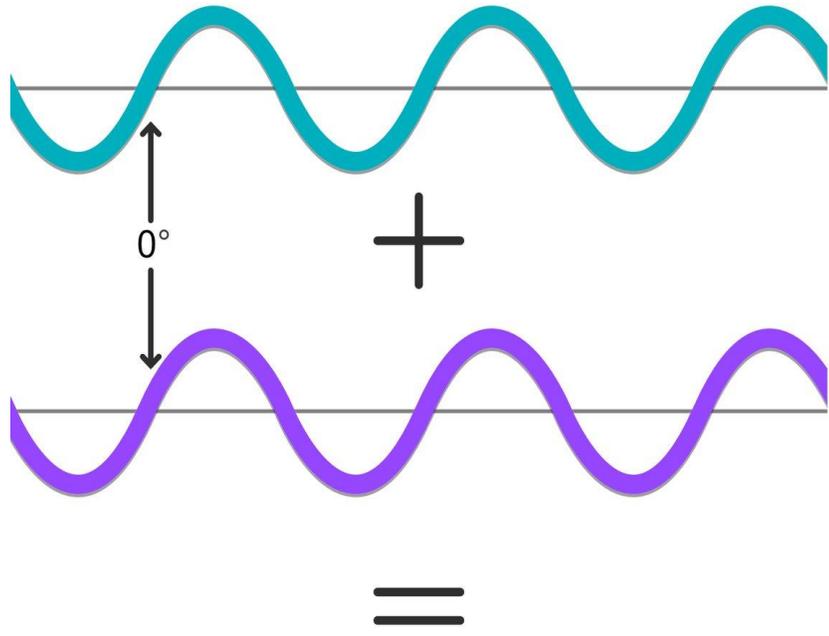
- The movement of these molecules, or **particle motion**, is due to the propagation of sound energy

Sound Waves

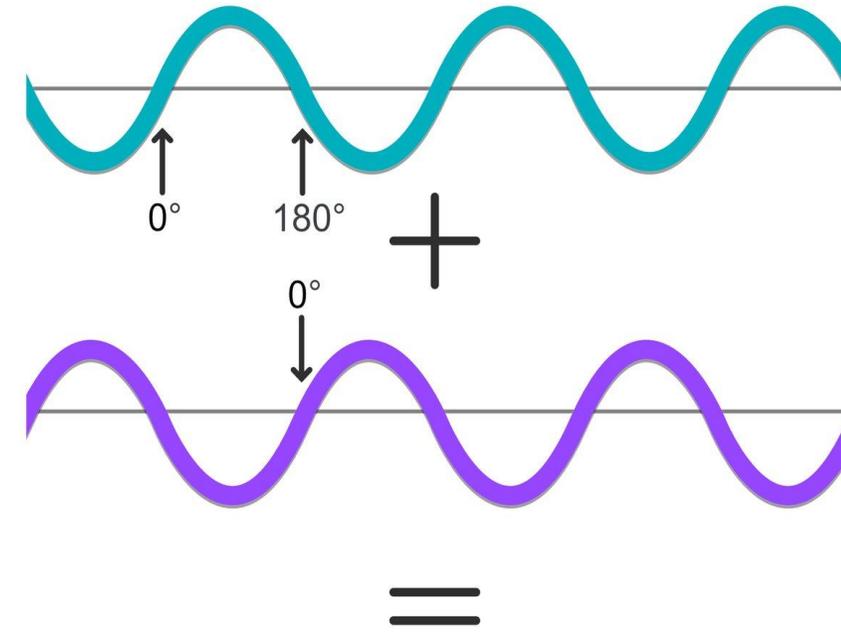
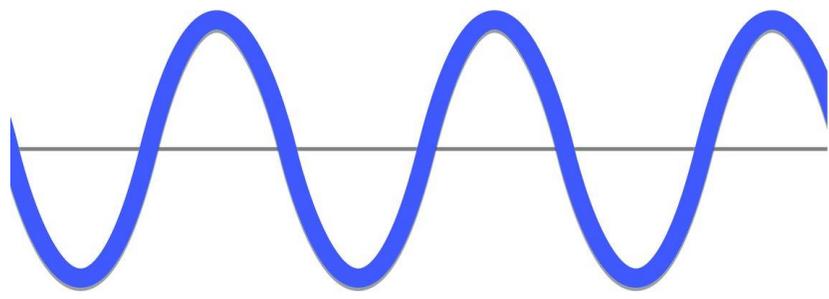
- Interesting things happen when waves meet:
 - They can be described as “in-phase” or “out-of-phase”
 - In-phase waves means the peaks and troughs overlap each other in both waves
 - When **in-phase waves** meet, they create **constructive interference** where they create one larger wave
 - Out-of-phase means the peaks and troughs of two waves occur at different times
 - When **out-of-phase waves** meet, they create **destructive interference** where they cancel each other out

Sound Waves

In-Phase Waves



Constructive Interference



Out-of-Phase Waves

Destructive Interference



Parameters of Sound

- Parameters are measurable
- There are seven acoustic parameters:
 - 1. Period**
 - 2. Frequency**
 - 3. Amplitude**
 - 4. Power**
 - 5. Intensity**
 - 6. Propagation Speed**
 - 7. Wavelength**

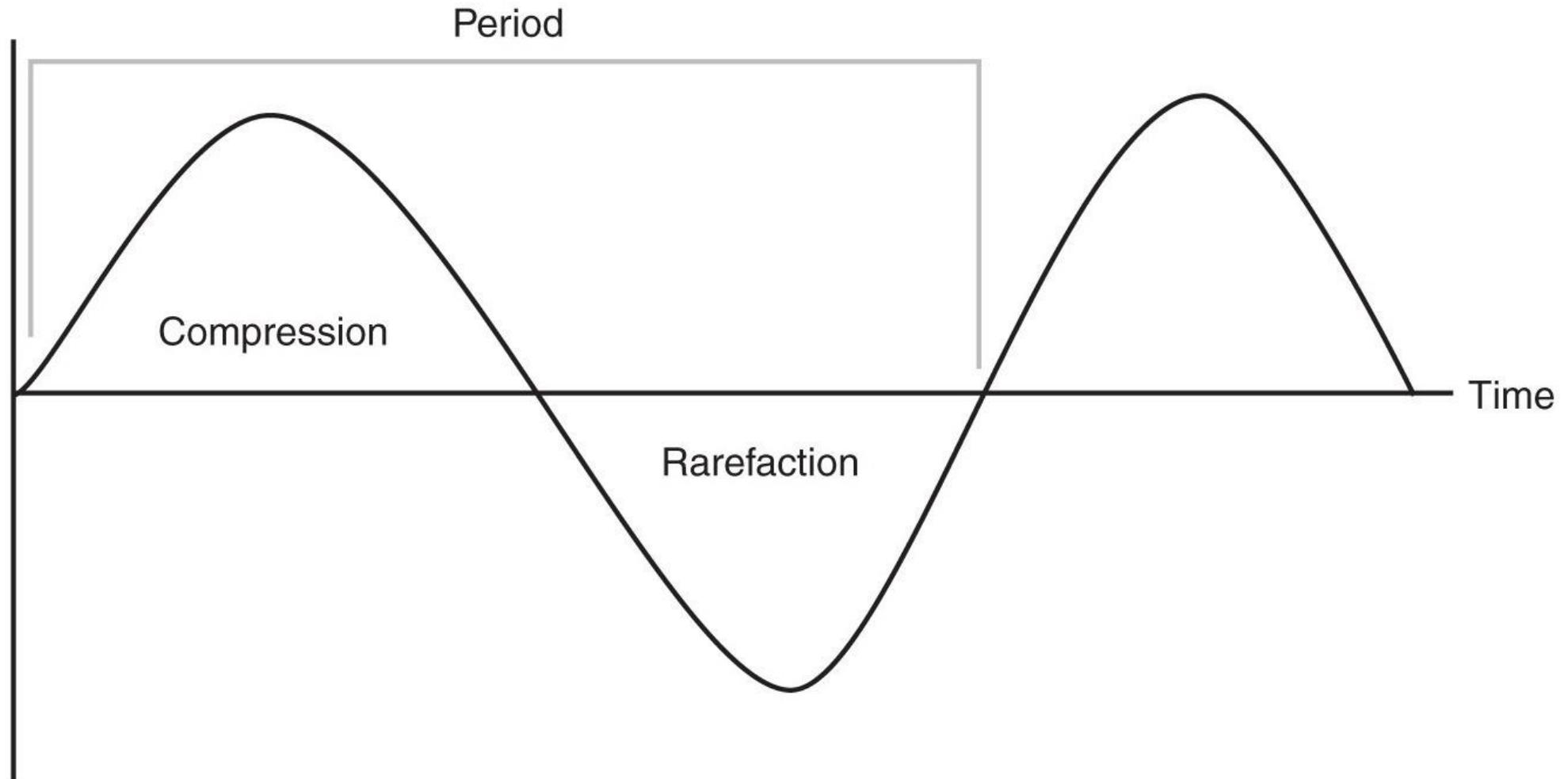
Parameters of Sound

- Different components of the ultrasound system and/or human body will have different effects on the sound wave:
 - **Some parameters are determined by the ultrasound system and cannot be adjusted**
 - **Some parameters are determined by the sonographer**
 - **Other parameters are determined by the tissue/medium in which the sound beam is traveling**

Period and Frequency

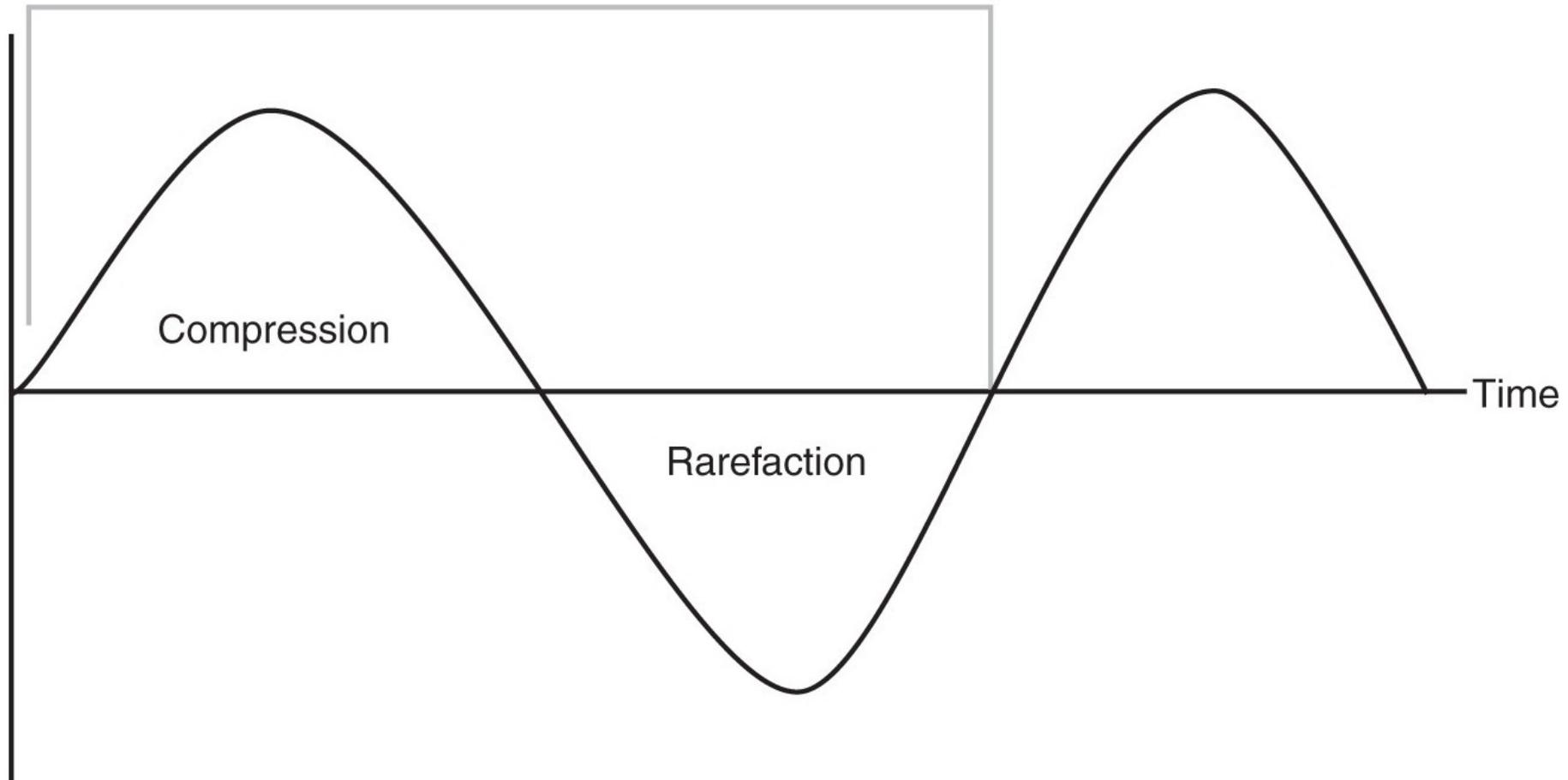
- Period (T) – Time it takes a wave to vibrate a single cycle or the time from the start of a cycle to the start of the next cycle
 - **Units are measurement of time, typically microseconds (μs)**
 - **Determined by the ultrasound machine and is not adjustable**
- Frequency (f) – Number of cycles per second
 - **Units are defined in hertz (Hz), kilohertz (kHz), or megahertz (MHz)**
 - **Determined by the ultrasound machine and is not adjustable**

Period and Frequency



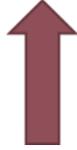
Period and Frequency

Frequency is the number of cycles per second



Period and Frequency

- Inversely related:

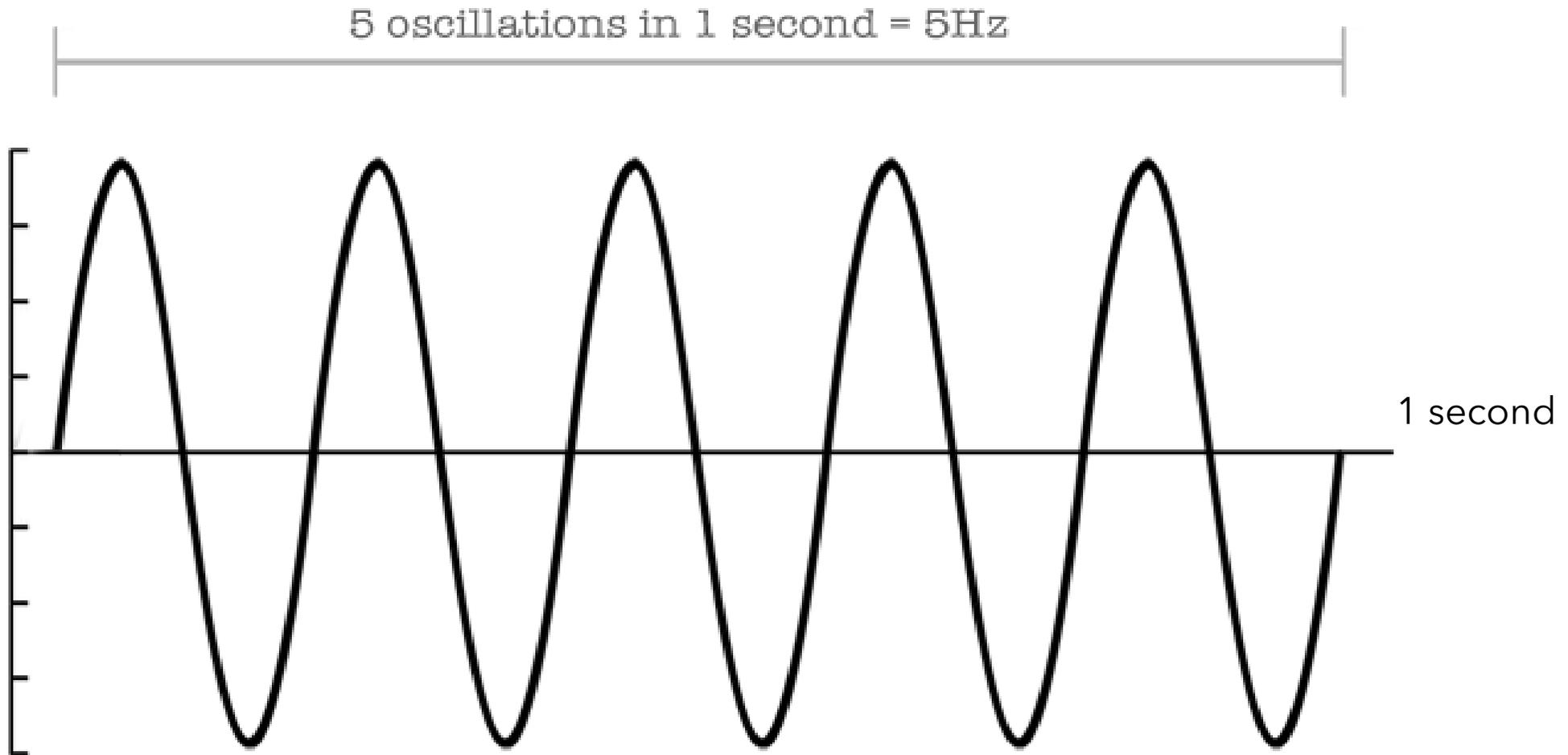
As frequency  period 
As frequency  period 

- Period and frequency are also reciprocals:

$$\text{Period} \times \text{frequency} = 1$$

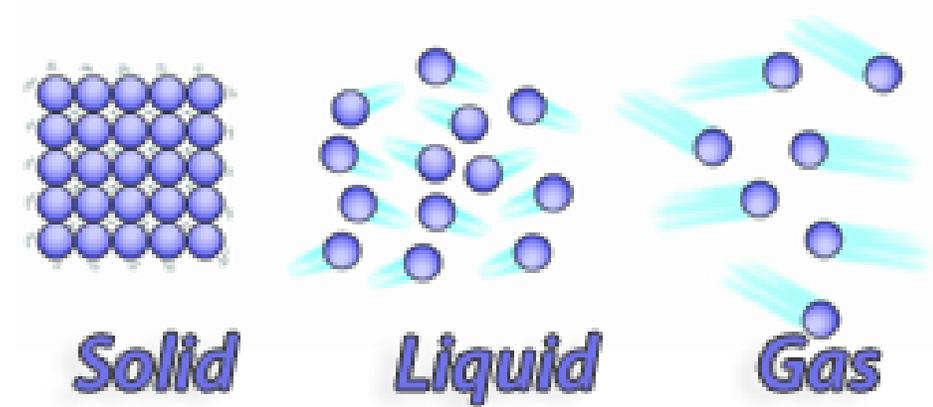
If the frequency of a wave is 12 Hz, what is the period?

Period and Frequency



Propagation Speed

- Propagation speed (c) is the speed at which a sound wave travels through a medium
 - **All sound, regardless of its frequency, travels at the same speed through any particular medium**
 - A 20 Hz wave and a 20 MHz wave travel at the same speed in the same tissue



Sound travels fastest through solids where molecules are packed tightly together.

Sound can't travel through empty space where there are no molecules to vibrate.

Propagation Speed

- Speeds will vary as sound travels through various organs and tissues
 - **Units for propagation speed are m/s or mm/μs**
 - **Determined by the medium and is not adjustable by the sonographer**
- Speed of sound in soft tissue:

1540 m/s or **1.54 mm/μs**

***Approximately 1 mile per second

Propagation Speed

TISSUE TYPE	SPEED (m/s)
LUNG	660
FAT	1,450
SOFT TISSUE (AVERAGE)	1,540
LIVER	1,555
BLOOD	1,560
MUSCLE	1,600
TENDON	1,700
BONE	4,080
OTHER MATERIAL	SPEED (m/s)
AIR	330
WATER	1,480
METALS	2,000 – 7,000

Propagation Speed

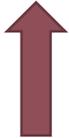
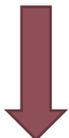
SPEED (m/s) = FREQUENCY (Hz) X WAVELENGTH (m)

$$C = f \lambda$$

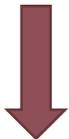
- Two properties of the medium determine the speed of sound:
 1. Stiffness (describes the tissues elasticity)
 - **Bulk modulus (tissue is stiff)**
 - **Elastic or compressible (tissue is not stiff)**
 2. Density
 - **Refers to the mass and inertia of the medium**

Propagation Speed

- Stiffness/Speed are directly related:

As Stiffness  Speed 
As Stiffness  Speed 

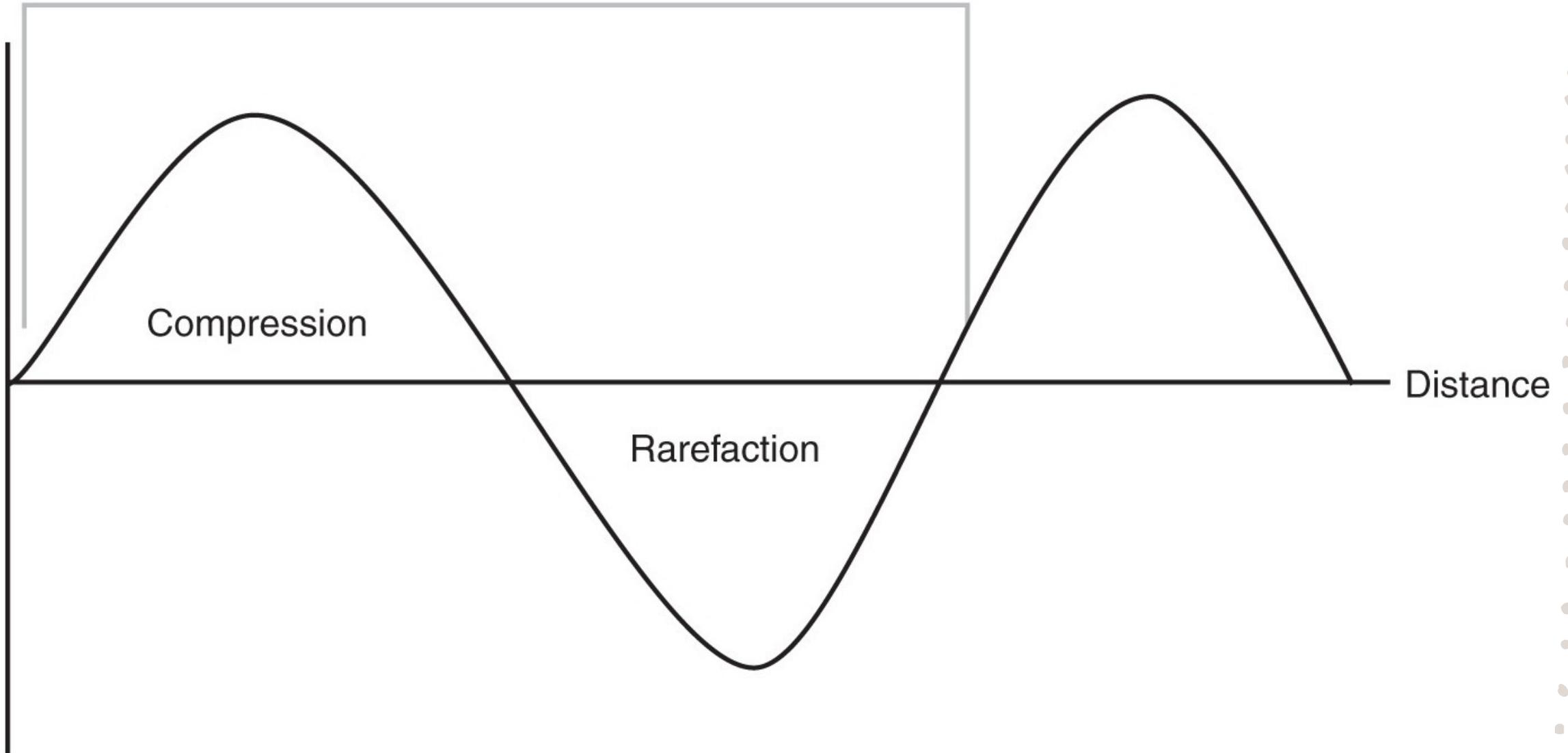
- Density/Speed are inversely related:

As Density  Speed 
As Density  Speed 

Wavelength

- The length of a single cycle of sound (λ)
 - **Distance from the beginning of a cycle to the end of that cycle**
 - **Units are any unit of length (mm)**
 - **Determined by the ultrasound system and the medium**
 - Only acoustic parameter determined by both
 - **Not adjustable by the sonographer**

Wavelength



Wavelength

- Wavelength and frequency are inversely related:

As Frequency  Wavelength 
As Frequency  Wavelength 

- The higher the frequency, the shorter the wavelength
 - **Shorter wavelengths have superior image detail, produces higher quality images**
- The lower the frequency, the longer the wavelength

Wavelength

- **WAVELENGTH (mm) = $\frac{\text{PROPAGATION SPEED (m/s)}}{\text{FREQUENCY (MHz)}}$**

$$\lambda = \frac{c}{f}$$

What is the wavelength of a 1 MHz transducer?

What is the wavelength of a 2 MHz transducer?

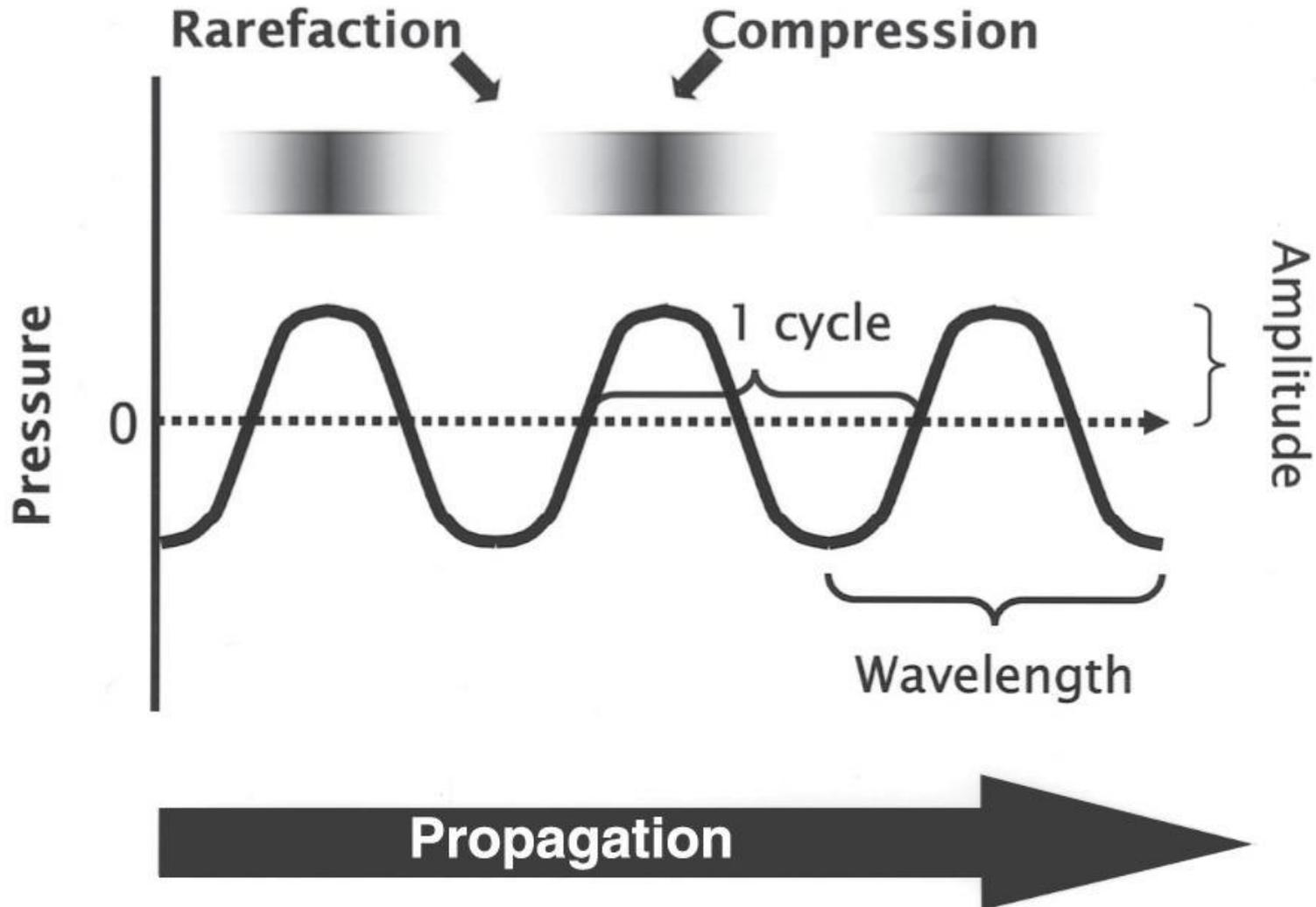
Amplitude, Power, Intensity

- All three parameters relate to the size or strength of the sound wave
- Amplitude, Power, and Intensity decrease as sound travels through a medium

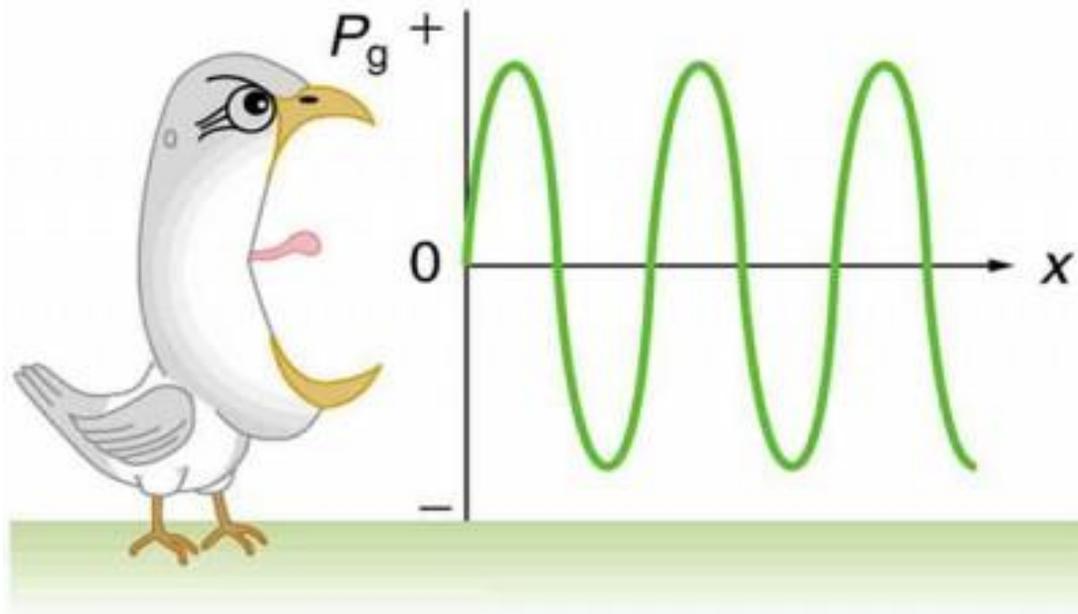
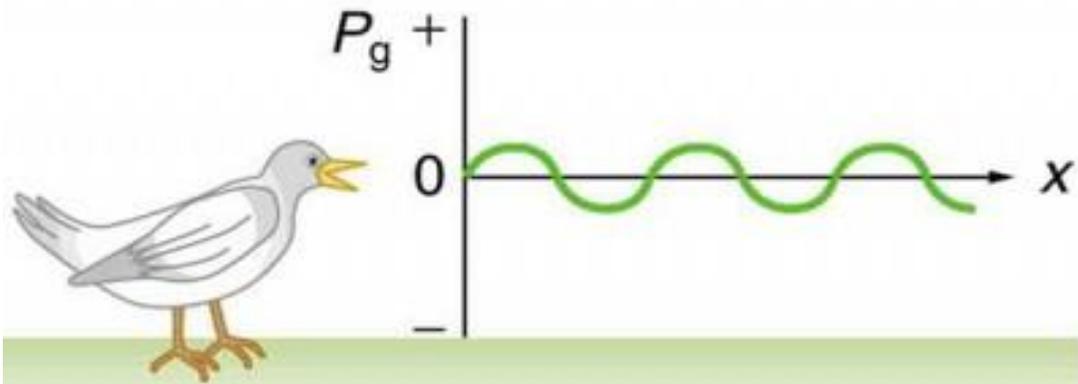
Amplitude

- Amplitude is defined as the maximum or minimum deviation of an acoustic variable from the average value of that variable
 - **Variables include pressure, density, and distance (particle motion)**
 - **The amplitude of these changes can be measured and have units of Pascals (Pa), kg/cm^3 , mm, or decibels (dB)**
 - **Determined by the ultrasound machine initially and decreases as it encounters different tissues/sound wave interactions**
 - **This is adjustable by the sonographer by changing the output power**

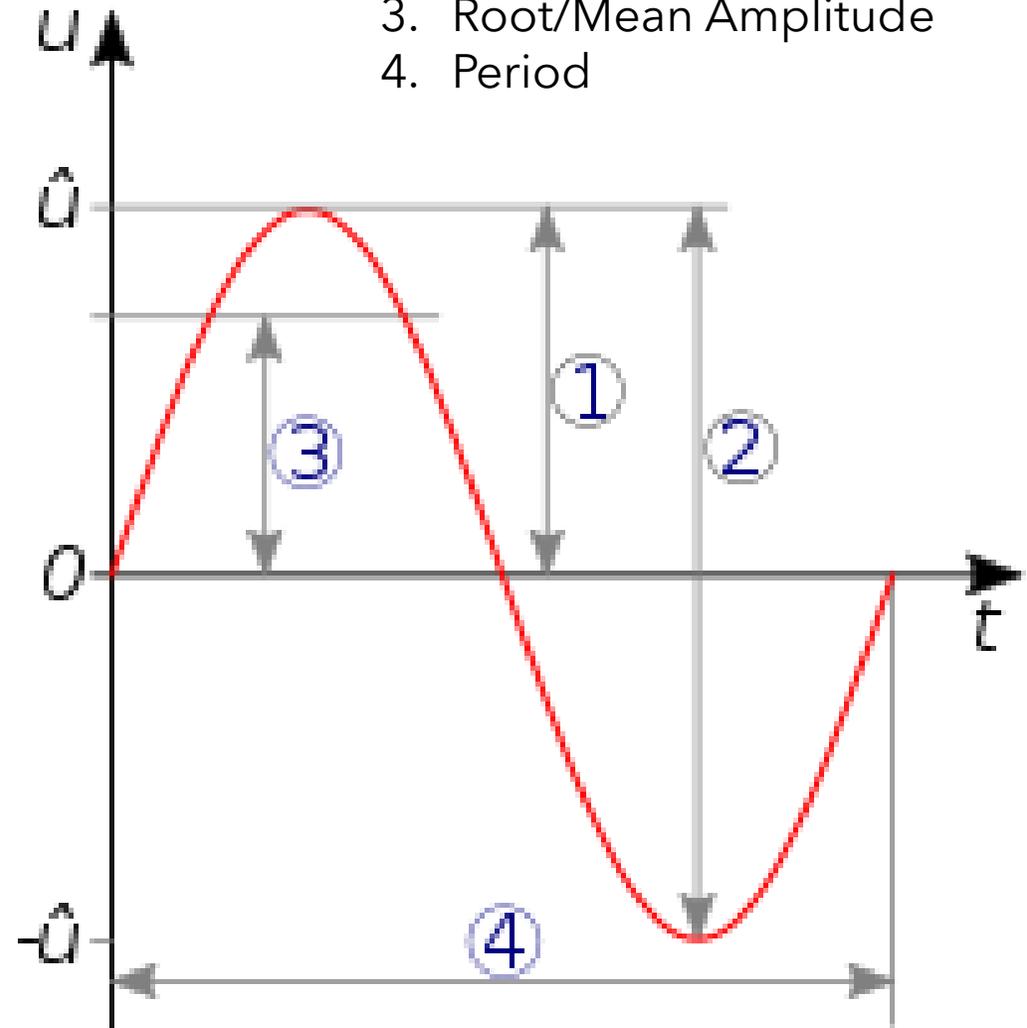
Amplitude



Amplitude



1. Amplitude
2. Peak-to-Peak Amplitude
3. Root/Mean Amplitude
4. Period

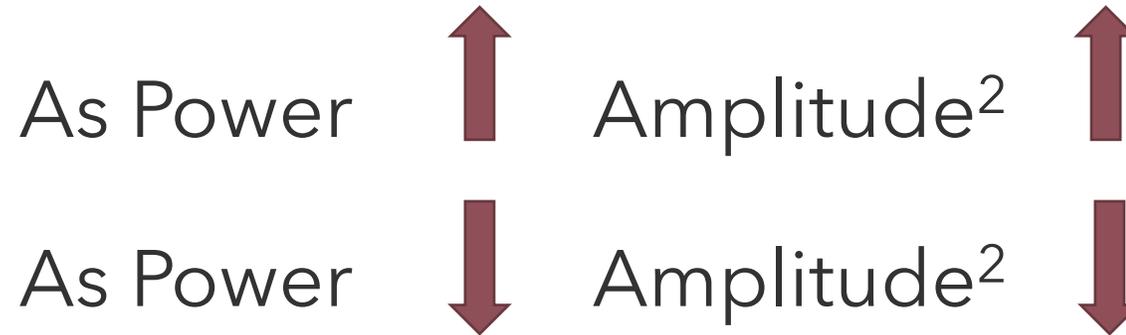


Power

- Power (P) is defined as the rate at which work is performed or energy is transmitted
 - **Units are in watts (W) or milliwatts (mW)**
 - **Determined by the ultrasound machine initially and decreases as it encounters different tissues/sound wave interactions**
 - **This is adjustable by the sonographer by changing the output power**
- Power – think of a light bulb!!!!

Amplitude & Power

- Amplitude and Power are directly related:

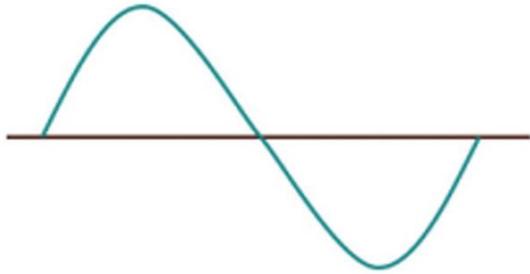


- Power proportional to amplitude²

It is not a one-to-one relationship!!!!

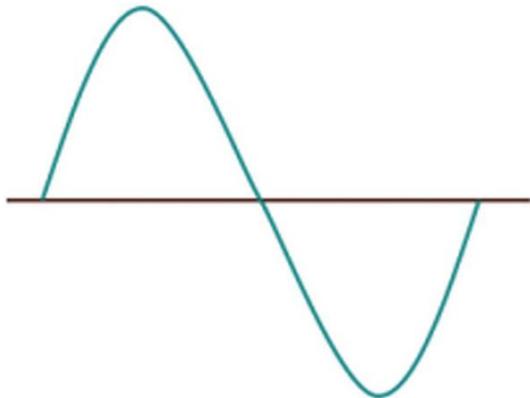
Power and Amplitude

What happens to the power if the amplitude doubles?



Ampl = 1.2 MPa

Power = 25 mW



Ampl = 2.4 MPa

Power = 100 mW



Amplitude & Power

- What happens to the Power if the Amplitude is tripled?
- What happens to the Power if the Amplitude is halved?

Intensity

- Intensity (I) of a sound wave is defined as the power of a wave divided by the area (a) over which it is spread

$$I = \frac{\text{Power (W)}}{\text{Area (cm}^2\text{)}}$$

- **Units are in watts per area (W/cm²)**
- **Determined by the ultrasound machine initially and decreases as it encounters different tissues/sound wave interactions**
- **This is adjustable by the sonographer by changing the output power**

Intensity

- Intensity is proportional to Power
 - **Power is doubled, Intensity is doubled**
 - **Power is quartered, Intensity is quartered**
- Intensity is proportional to Amplitude²
 - **Amplitude² is doubled, Intensity is quadrupled**
 - **Amplitude² is halved, Intensity is quartered**

Amplitude, Power, & Intensity

- The word “squared” always follows the word amplitude
 - **Power is related to amplitude squared**
 - **Intensity is related to amplitude squared**
 - **Power is related to intensity**

Amplitude	I or P
2x	4x
3x	9x
4x	16x

PARAMETER	ADJUSTABLE	UNITS	DETERMINED BY	TYPICAL VALUE
PERIOD	NO	seconds, μ s, time	SOURCE	0.06 – 0.5 μ s
FREQUENCY	NO	per second, Hz	SOURCE	2 – 15 MHz
AMPLITUDE	YES	pascals, cm, g/cm^3 , dB	SOURCE	1MPa – 3 MPa
POWER	YES	watts	SOURCE	4 – 90 mW
INTENSITY	YES	watts/cm ²	SOURCE	0.01 – 300 w/cm ²
WAVELENGTH	NO	mm, distance	BOTH	0.1 – 0.8 mm
SPEED	NO	m/s	MEDIUM	1,500 – 1,600m/s



Questions??

A wave with a frequency of 15,000 MHz is ultrasonic.

- True
- False

Propagation speed increases as frequency increases.

- **True**
- **False**

Which of the following are considered acoustic variables?

1. Frequency
2. Density
3. Particle Motion
4. Temperature
5. Period
6. Pressure

Which of the following are considered acoustic parameters?

1. Frequency
2. Density
3. Distance
4. Pressure
5. Period

Which of the following cannot be changed by the operator?

1. Wavelength
2. Frequency
3. Intensity
4. Propagation speed
5. Period
6. Power
7. Amplitude (initial)

If the pressure amplitude is increased by a factor of 2, then the intensity is increased by a factor of:

A. 1

B. 2

C. 3

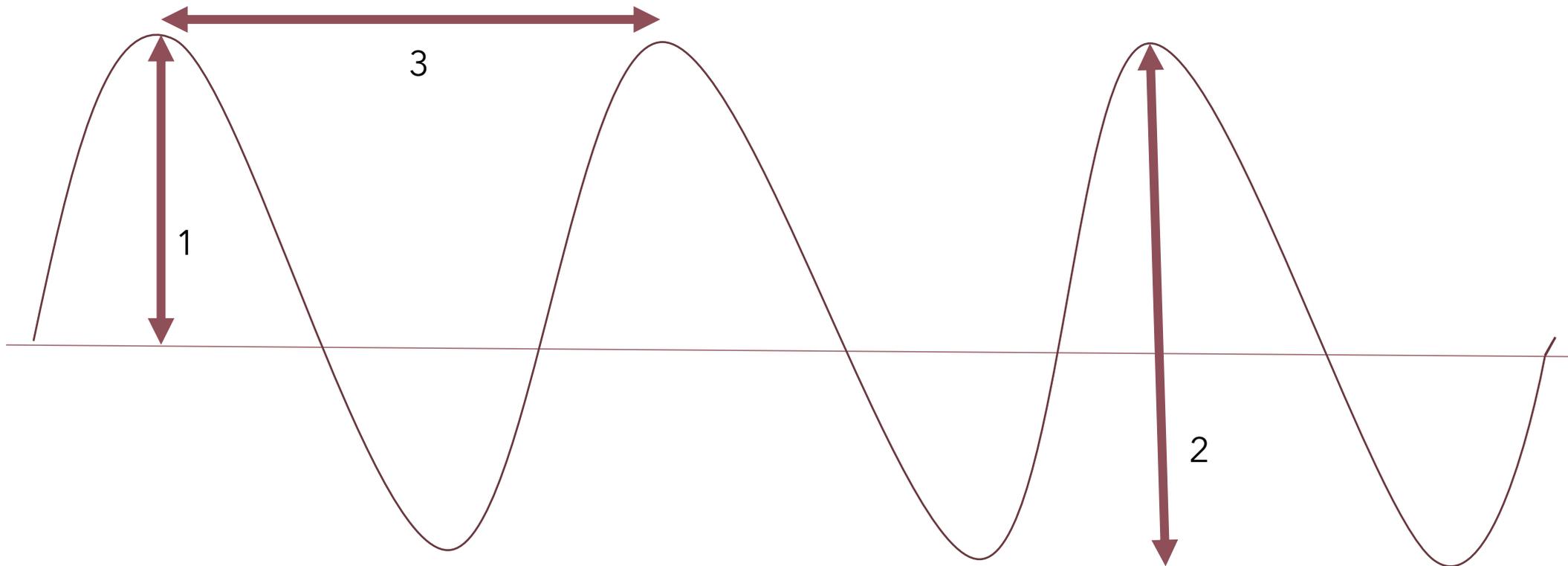
D. 4

E. 6

Calculate the wavelength for a 3 MHz transducer.

- A. 3 mm
- B. 3 m
- C. 0.5 mm
- D. 0.05 km

Identify the components of a sound wave



Impedance

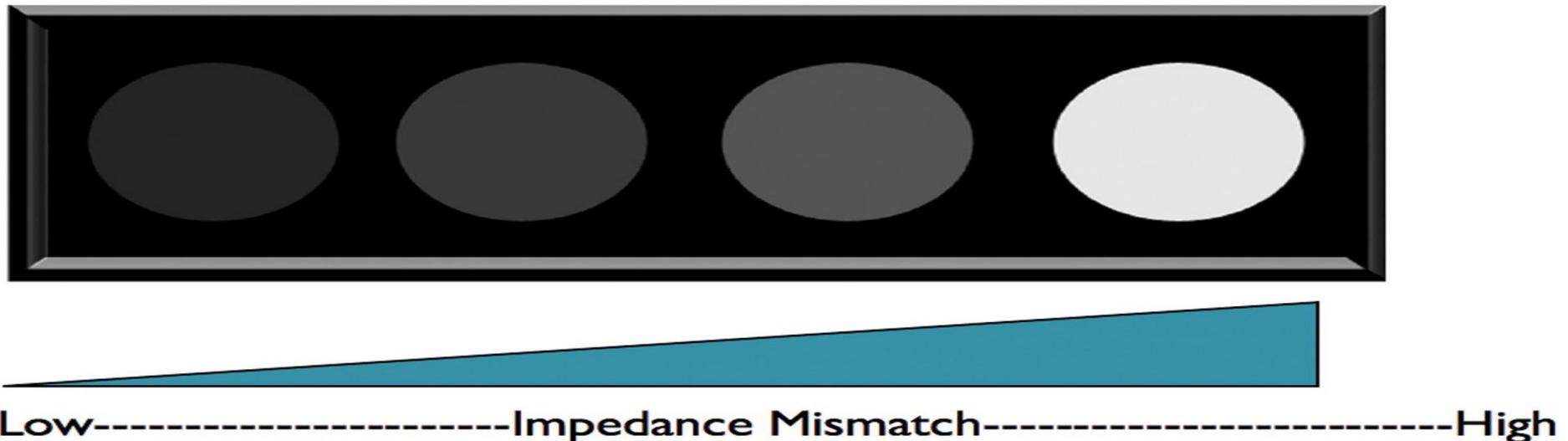
- Any medium through which sound is traveling will offer some amount of resistance to the sound. This is called **impedance** (Z).
- The amount of impedance is dependent upon the density (ρ) and propagation speed (c) of the medium

$$\text{Impedance} = \text{density} \times \text{propagation speed}$$

- **Units of impedance are Rayls**
- **Entirely dependent on the characteristics of the medium**

Impedance

- Biological tissue has slight variations in their densities and propagation speeds, these differences help to create reflections at the interface between tissues.



Impedance

- If the beam strikes the interface at 90 angle and there is a large impedance difference between two tissues, there will be a strong reflection and well-defined boundary on the imaging screen
- If the impedance difference between two media is more subtle, there will be a weaker reflection

Question....

- **Two media have different propagation speeds and densities. Is it possible that they end up with the same impedance?**

Continuous Wave Ultrasound

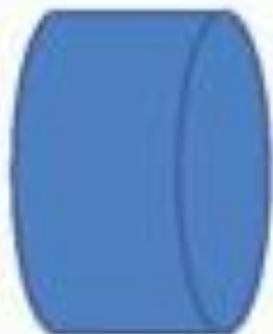
- Continuous wave (CW) ultrasound is non-imaging
- Sound waves are constantly being sent into the body without any pause
- Tiny transducer face that only houses two crystals:
 - **One crystal is constantly sending sound into the body**
 - **One crystal is constantly receiving sound coming from the body**
- More to come in future chapters.....

Pulse-Echo Technique

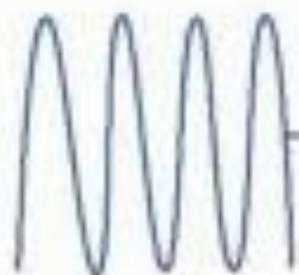
- Pulse-wave (PW) ultrasound is used in most diagnostic ultrasound cases
 - Short pulses of ultrasound produce the image
- Only one crystal is needed to both transmit and receive sound
 - If a PW transducer has 200+ crystals, then all 200+ crystals can transmit and receive sound

Pulse-Echo Technique

- For an image to be created using sound, the sound waves must not only be sent into the body, but the sound returning from the body must be timed to determine the reflector's distance from the transducer; this describes the pulse-echo technique
 - Once the pulse is sent, the machine listens for the sound to return and calculates how long it took for that pulse to travel in the body
 - This calculation allow the machine to plot the location of the reflectors on the display

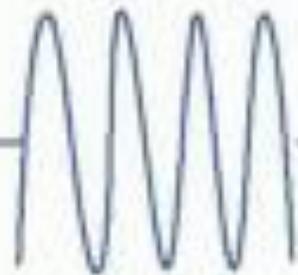


PW



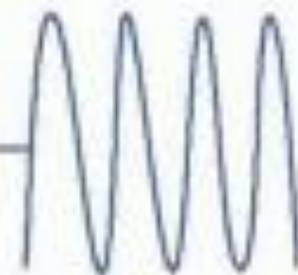
Transmit

Listen



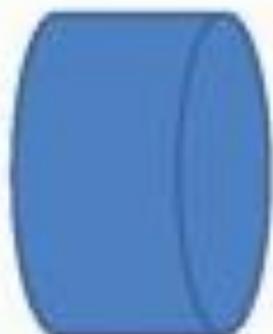
Transmit

Listen

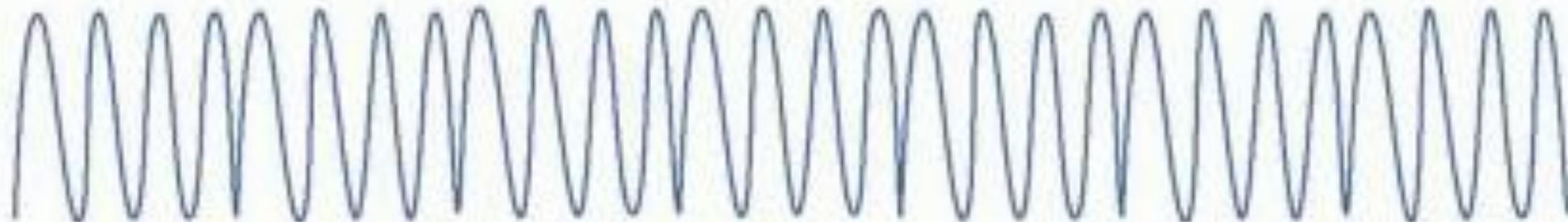


Transmit

(Range specificity)



CW



Transmit and listen continuously
(Range ambiguity)

Pulse-Echo Technique

- A transducer is any device that can convert one form of energy into another
 - Performs two functions:
 1. Transmission - electrical energy converted into sound
 2. Reception - reflected sound converted into electricity
 - Other examples of transducers:
 - Car engines
 - Light bulb
 - Muscle

Pulse-Echo Technique

- Transducers have material within them that, when electronically stimulated, produces ultrasound waves. These are referred to as **piezoelectric materials** (PZT) and most often consist of some form of lead zirconate titanate
 - **Materials which convert sound into electricity are called piezoelectric or ferroelectric**
 - **PZT in the ultrasound transducer is usually called the ceramic, active element or crystal**
- Quartz and tourmaline are two elements found in nature that have PZT properties
 - **Our crystals are usually lead zirconate titanate (PZT) and are man-made**

Pulse-Echo Technique

- The piezoelectric effect describes the property of certain materials to create a voltage when they are mechanically deformed or when pressure is applied to them
 - *Piezo* literally means to squeeze or press
- Within the transducer, the element is electronically stimulated or stressed, which results in a pressure wave (sound) as a result of the vibration of the material

Pulse-Echo Technique

- Keep in mind that while PZT is the predominant transducer material used today, newer technology and materials are being developed, such as **capacitive micromachined ultrasound transducers (CMUT's)** and the thermoplastic fluoropolymer synthetic resin referred to as **polyvinylidene fluoride**.

Pulse-Echo Technique

- Pulsed-wave (PW) has several specific parameters:
 - **Pulse Repetition Frequency (PRF)**
 - **Pulse Repetition Period (PRP)**
 - **Pulse Duration (PD)**
 - **Duty Factor (DF)**
 - **Spatial Pulse Length (SPL)**

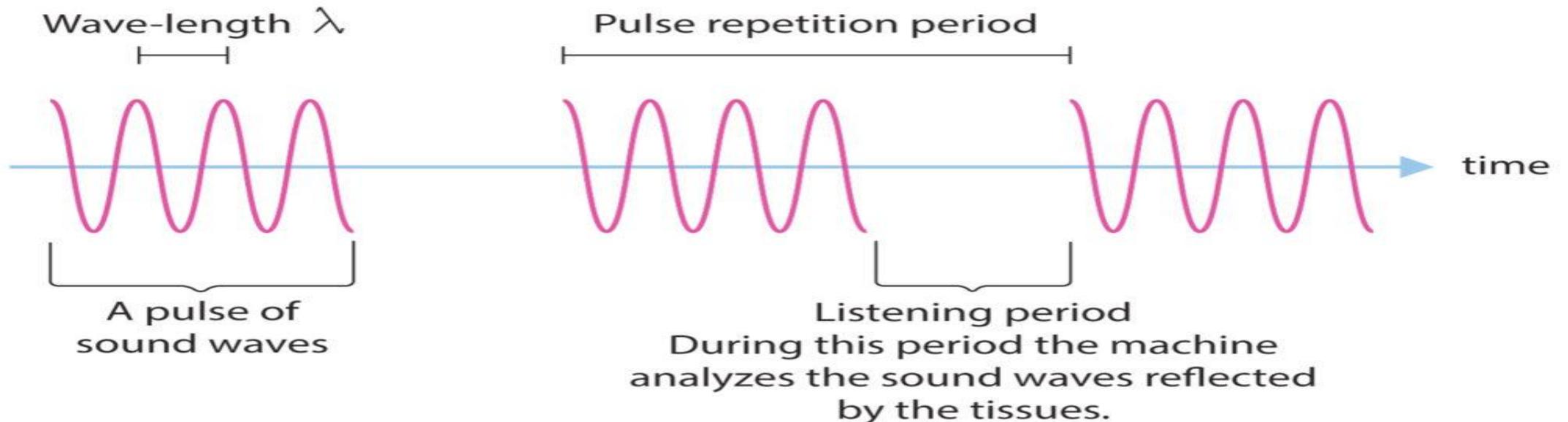
Just to Recap....

- In diagnostic imaging, we used Pulsed Wave (PW) sound
 - **Short bursts or pulses of acoustic energy are used to create anatomic images**
- Continuous Wave (CW) sound cannot create anatomic images
 - **Used for certain types of Doppler**

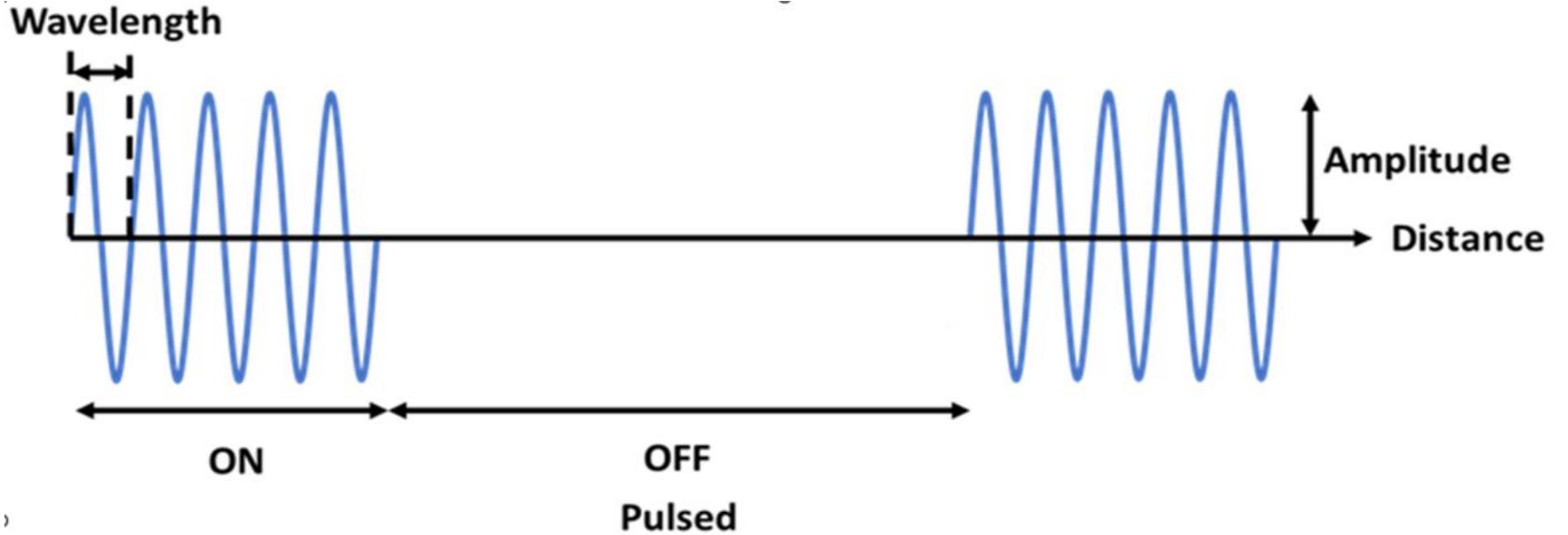
Just to Recap....

- Pulsed sound has two components
 - **Transmit (talking - ON)**
 - **Receive (listening - OFF)**

Ultrasound pulses

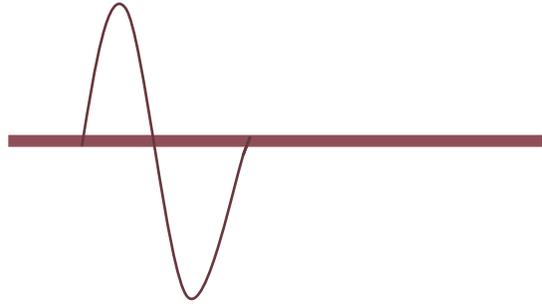


Pulsed Sound



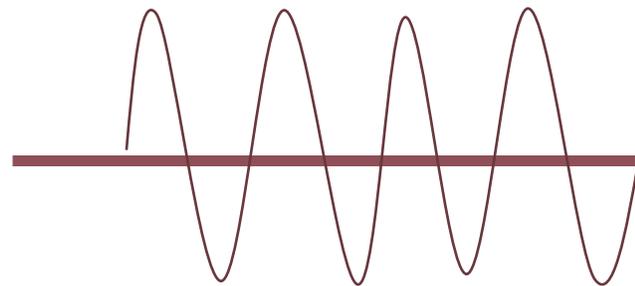
Parameters of Pulsed Sound

- Remember that frequency is defined as the number of cycles of sound produced in 1 second



One single cycle

- The number of pulses of sound produced in 1 second is called the Pulse Repetition Frequency (PRF)



One Single Pulse
(comprised of multiple cycles)

Pulse Repetition Frequency

- Frequency and PRF are not the same.
- It is critical that the pulse term "PRF" is not confused with the cycle term "operating frequency" or just "frequency."
 - **These two terms have no relation to each other, and PRF is completely independent of operating/transducer frequency.**
- In diagnostic imaging, the PRF has typical values between 1000 and 10,000 Hz (1 to 10 KHz).

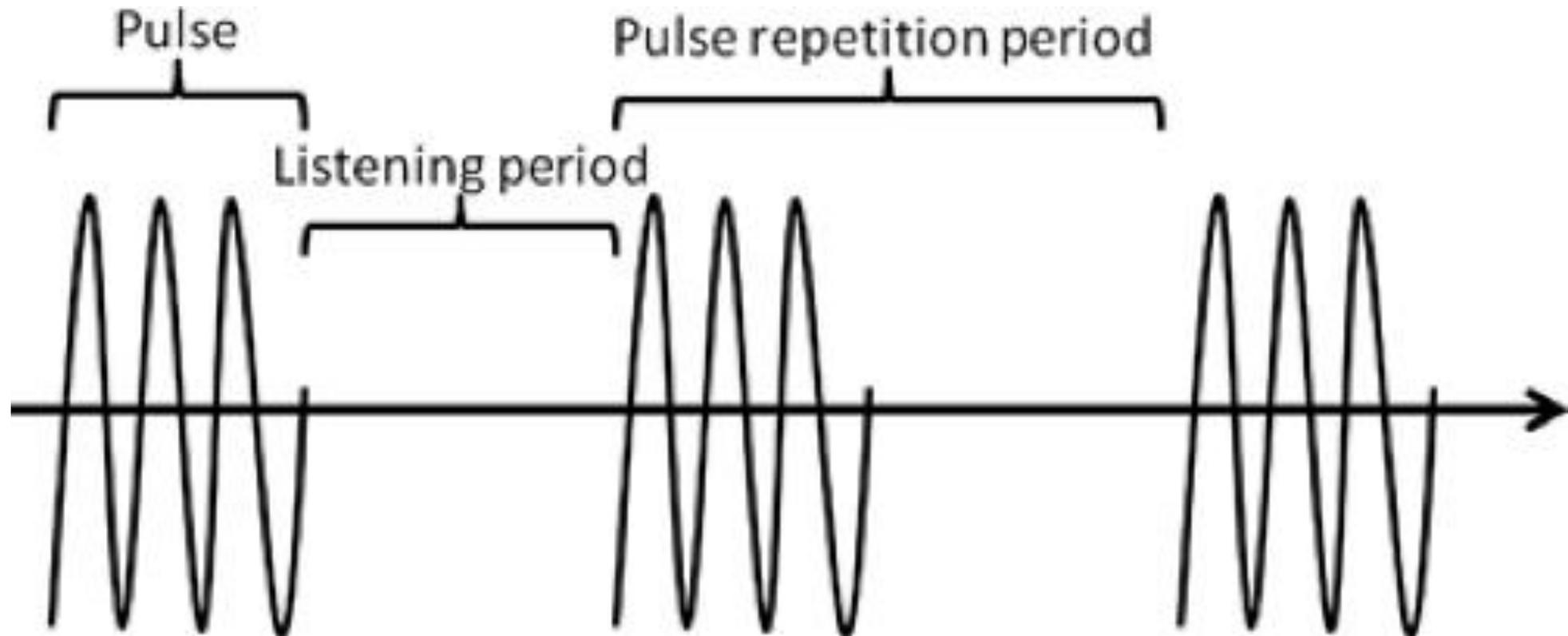
Pulse Repetition Frequency

- The PRF changes whenever the sonographer adjusts the depth control on the ultrasound machine
 - **If the imaging depth is shallow, the echoes return quickly. If the area of interest is deep, it will take a longer time for the echoes to get back to the transducer**
- Therefore, the deeper the area of interest, the slower the PRF. As the imaging depth increases, the PRF decreases, and as the depth decreases, the PRF increases

Pulse Repetition Period

- The time taken for a pulse to occur is called the pulse repetition period (PRP)
- The PRP is the time from the start of one pulse to the start of the next pulse, and therefore, it includes the "on" (or transmit) and "off" (or listening) times.

Pulse Repetition Period

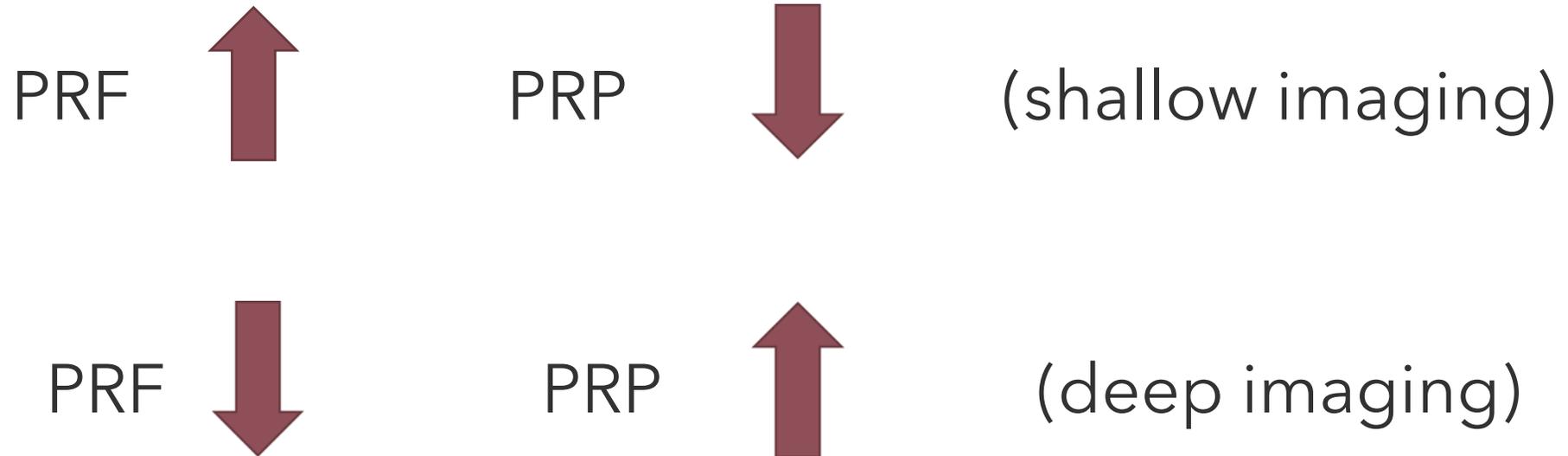


Pulse Repetition Period

- When imaging of superficial structures is performed, the echoes from each pulse return to the transducer quickly, so the time between pulses (PRP) is short.
 - **Since the machine is receiving the echoes quickly, it can emit pulses at a faster rate (PRF).**
- Imaging deeper in the body takes a longer time for the echoes to return to the transducer, so the time between pulses, the PRP, increases.
 - **Consequently, the transducer is unable to emit pulses as often, so the PRF decreases.**

PRP/PRF Relationship

- Inversely related:



PRP/PRF Relationship

- Reciprocals:

- **When the PRF and PRP are multiplied together, the result is "1"**

$$\mathbf{PRF = \frac{1}{PRP} \quad \text{or} \quad PRP = \frac{1}{PRF}}$$

- Use complimentary units:

- **PRP/PRF - seconds/Hertz (s/Hz)**
milliseconds/kilohertz (ms/kHz)



Questions??

Four pulses have PRP as listed below. Which of the following waves has the highest PRF?

A. 8 s

B. 80 ms

C. 5 ms

D. 400 ks

The pulse with the shortest PRP will have the highest PRF

Which of these four pulses with the PRF's listed below has the shortest PRP?

A. 12 kHz

B. 6,000 Hz

C. 20 kHz

D. 1 kHz

Highest PRF has the shortest PRP

*PRF and PRP are determined only by the
imaging depth*

TRUE

FALSE

Two waves can have identical PRF's, even if their frequencies are different.

TRUE

FALSE

Pulse Duration

- Pulse Duration (PD) relates to the time during which the sound is being transmitted, the “on” or “talking” time
- The duration of the “on” time depends on how many cycles there are in the pulse, and the period of each cycle

$$\text{Pulse Duration} = \text{number of cycles } (n) \times \text{period } (T)$$

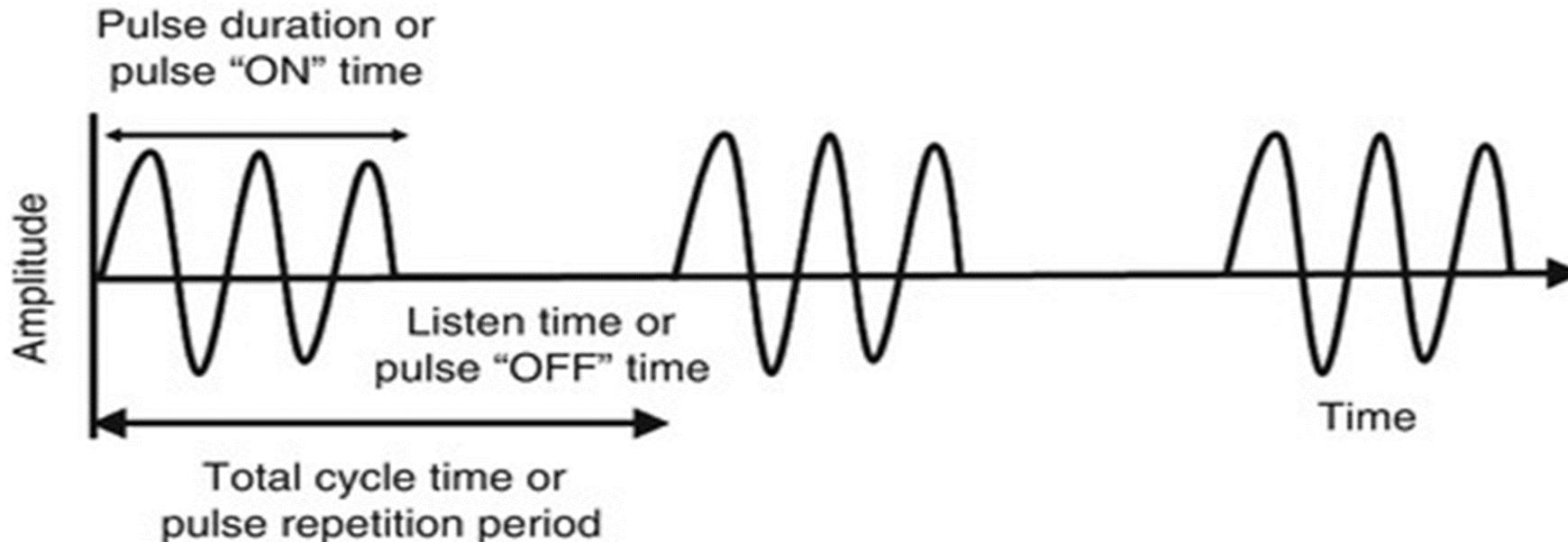
- Determined by manufacturer and cannot be adjusted by the sonographer

PRP vs. PD

- PRP includes the listening ("off") time, PD does not
- Both have units of time
- PRP can be changed by the operator, PD cannot

PRP vs. PD

- Hint:
 - **“Pulse Repetition Period” is a long word, and “Pulse Duration” is a short word**
 - **Notice how PRP is longer than PD in the graphic!!!!**

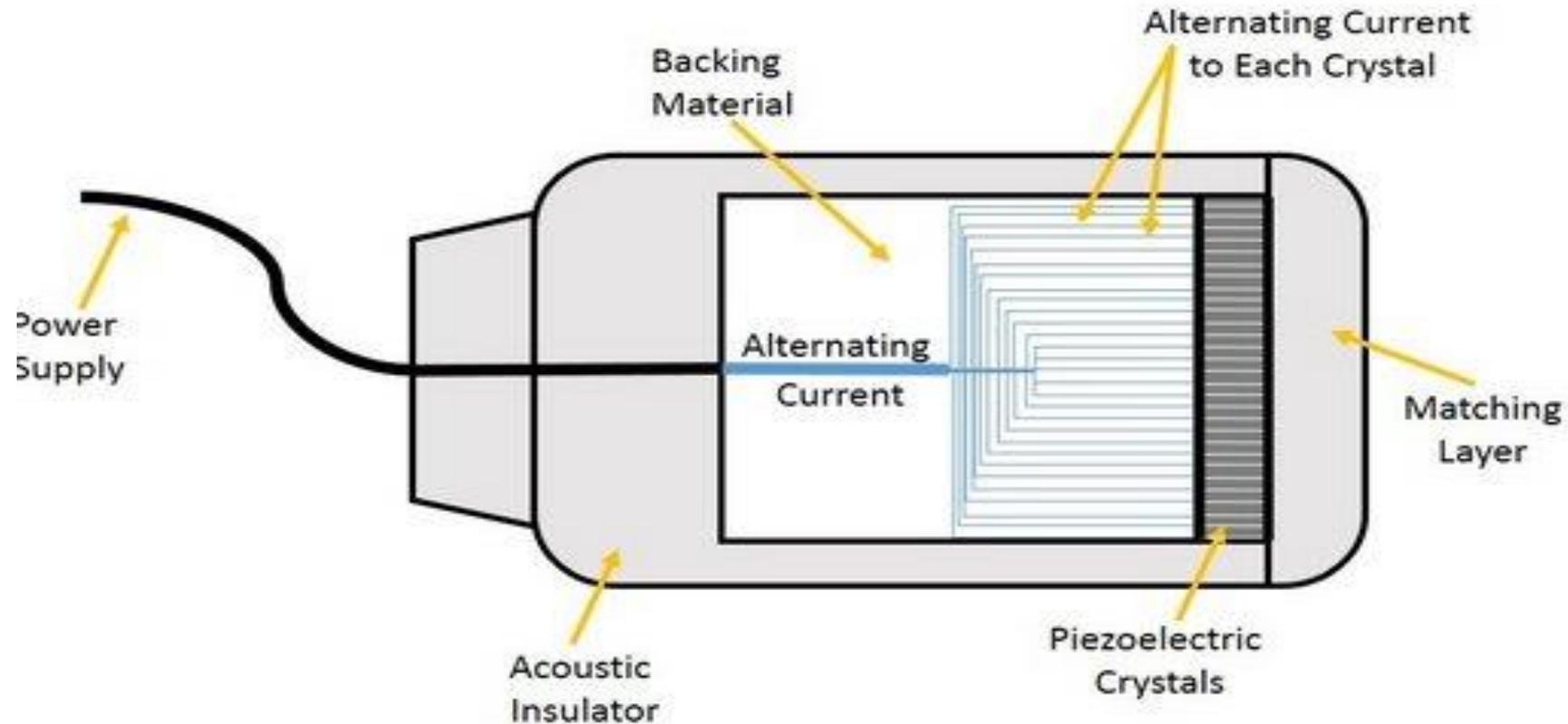


Pulse Duration

- When the crystal in a transducer vibrates or “rings,” it produces long pulses with several cycles in each pulse, that is, a long PD.
- For imaging purposes, a short PD is preferable. To do this, the vibrations of the crystal are damped by a special backing material inside the transducer.
- The backing or **damping** layer reduces the long “ring” of a vibrating crystal to two or three cycles per pulse. This helps to improve the image by enhancing the **axial resolution**.

Transducer Construction

Transducer Basics



Duty Factor

- Duty Factor (DF) is the percentage or fraction of time that the system is transmitting a pulse

$$\text{Duty Factor} = \frac{\text{Pulse Duration}}{\text{Pulse Repetition Period}} \times 100$$

- If the PRP is short, then the DF will be higher
- If an ultrasound system has a DF of 100%, it must be a CW ultrasound system.....why?

Duty Factor

- Pulsed ultrasound will always have DF less than 100%
 - **In clinical imaging, the DF is 1% or less**
 - **System spends very little time transmitting sound, most of the time is spent receiving sound (aka "listening")**
- It is a percentage.....technically *unitless*
- Adjustable by the sonographer when changing the depth
 - **DF is higher with shallow imaging**
 - **DF is lower with deeper imaging**

**DF is inversely related
to imaging depth**

Duty Factor

- Maximum value is only seen using CW
 - **DF would have a value of 1 or 100%**
 - **System is ALWAYS producing sound**
- PW or imaging systems
 - **DF must always be <100%**
 - **Typical value 0.2 % - system is listening approximately 500 times longer than it is transmitting**

When would the DF be 0?

Duty Factor

- When you change the depth

As depth increases (deeper)

- Transmit time remains the same but the listening time is longer (DF decreases)

As depth decreases (shallow)

- Transmit time remains the same but the listening time is shorter (DF increases)



Questions??

Which of the following terms does not belong with the others?

A. High Duty Factor

B. Shallow Imaging

C. Low PRF

D. Short PRP

If all other factors remain unchanged, what happens to the duty factor when the imaging depth increases?

A. Increases

B. Decreases

C. Remains the same

If all other factors remain unchanged, what happens to the duty factor when the sonographer uses a new transducer with a longer pulse duration?

A. Increases

B. Decreases

C. Remains the same

Spatial Pulse Length

- Spatial Pulse Length (SPL) is defined as the length of a pulse
- The length of the pulse depends on the wavelength of each cycle and the number of cycles in each pulse

$$\text{SPL} = \text{number of cycles } (n) \times \text{wavelength } (\lambda)$$

- If the wavelength increases, the SPL increases!!!!
- If the number of cycles in a pulse increases, then the SPL also increases!!!

Spatial Pulse Length

- Like PD, SPL can be controlled with damping or backing material in the transducer
 - **Damping reduces the SPL by reducing the number of cycles in each pulse**
 - **Reducing the number of cycles improves axial resolution (BETTER IMAGE QUALITY!!!)**
- Units are lengths (typically mm)
- Determined by both the sound source and the medium
 - **Remember: $SPL = n \times \lambda$**
- Not adjustable by the sonographer

Parameter	Adjustable	Units	Determined By	Typical Values
Pulse Duration	No	μs	Source	0.5-3.0μs
PRP	Yes	ms	Source	0.1-1.0ms
PRF	Yes	1/sec Hz	Source	1-10kHz
Spatial Pulse Length	No	mm, cm	Both	0.1-1.0mm
DF	Yes	None	Source	0.2%-0.5%



Questions??

_____ is the time from the start of a pulse to the start of the next pulse.

A. PRF

B. PRP

C. DF

D. PD

is the time from the start of a pulse to the end of that pulse.

- A. PRF
- B. PRP
- C. DF
- D. PD

Which of the following describes line A?

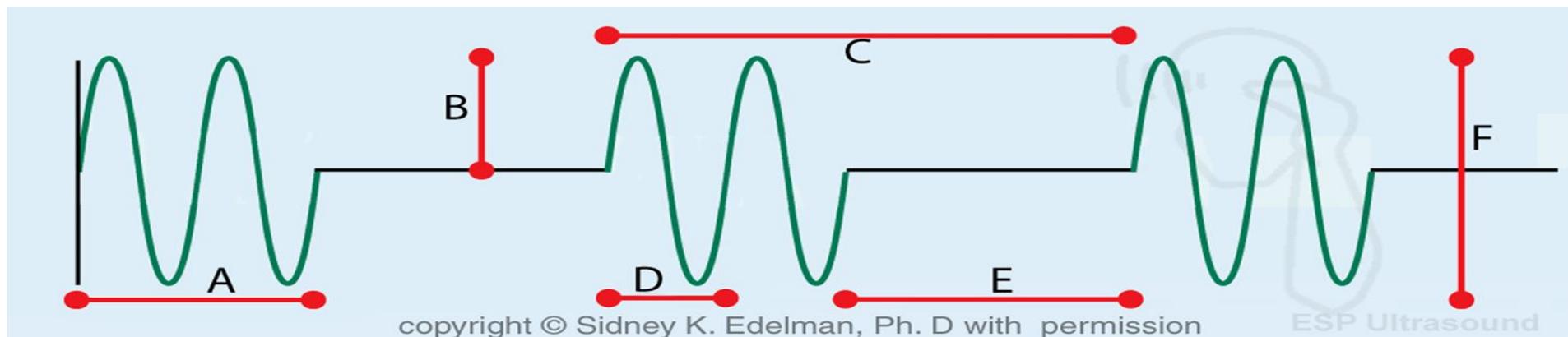
A. Frequency

B. Period

C. Duty Factor

D. Pulse Duration

E. Amplitude



Which of the following describes line F?

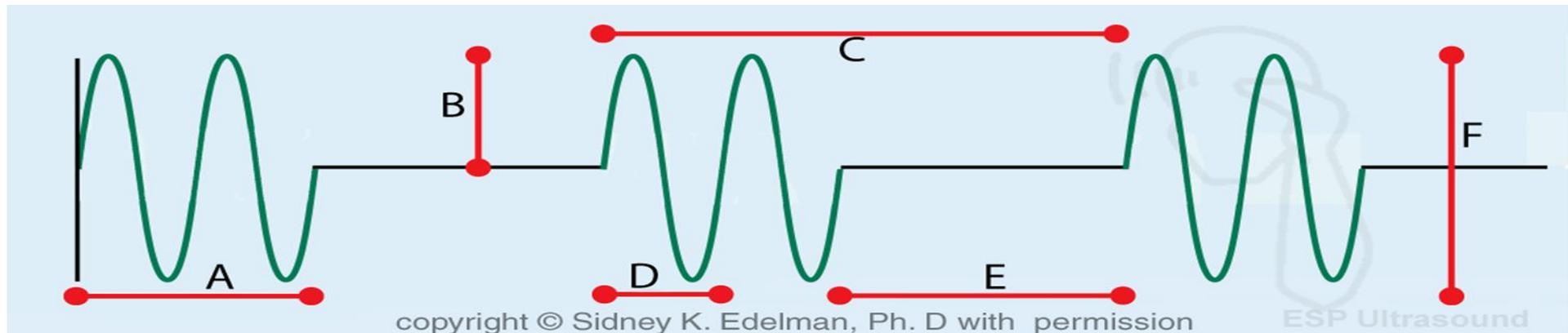
A. Frequency

B. Period

C. Peak-to-Peak Amplitude

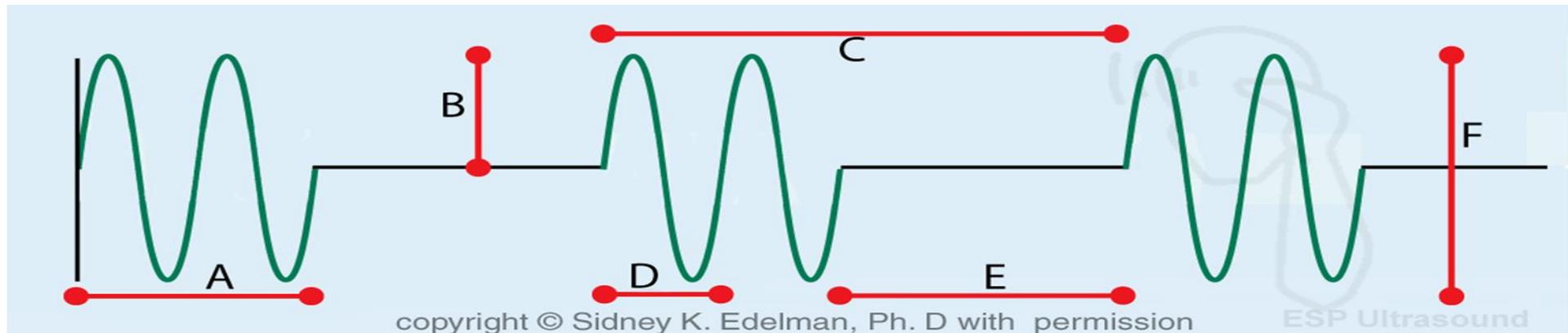
D. Pulse Duration

E. Pulse Repetition Period



Which of the following describes line C?

- A. Frequency
- B. Pulse Repetition Period
- C. Duty Factor
- D. Pulse Duration
- E. Amplitude



Which of the following describes line B?

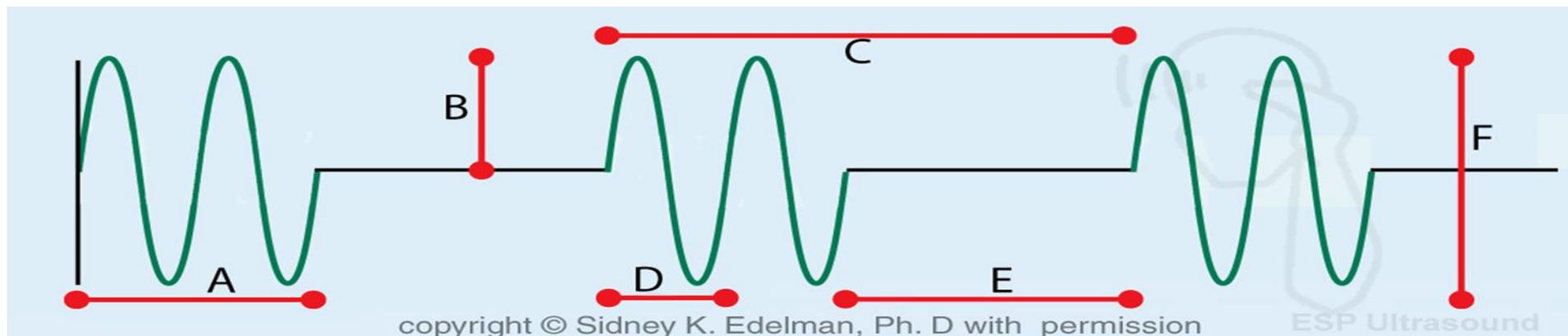
A. Frequency

B. Period

C. Duty Factor

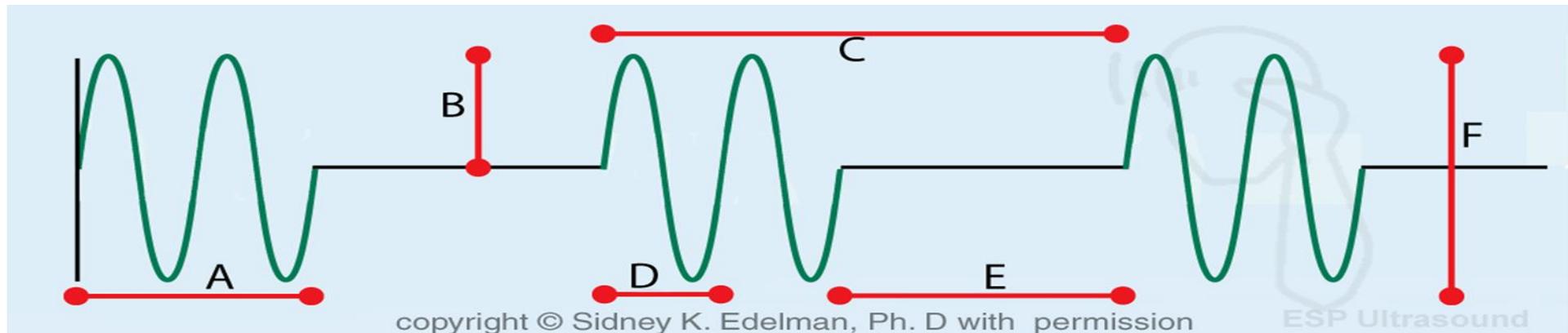
D. Pulse Duration

E. Amplitude



Which of the following describes line D?

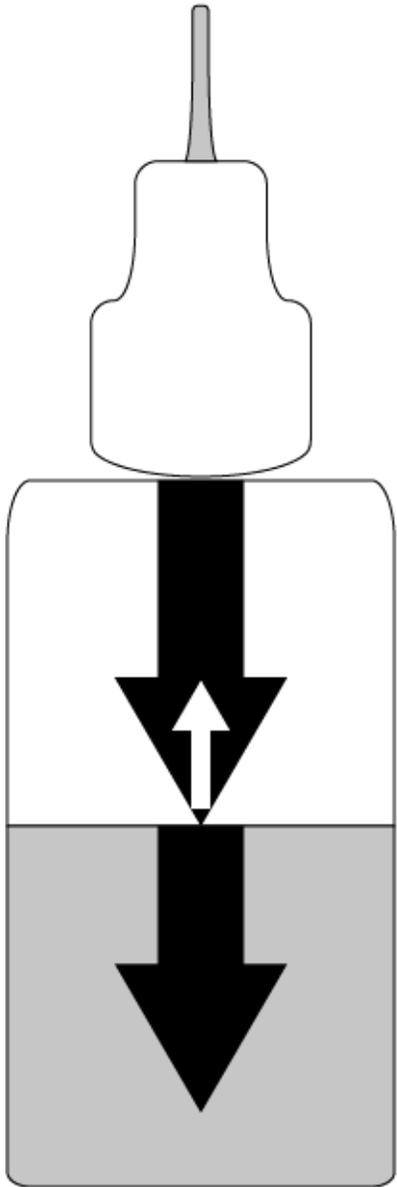
- A. Pulse Duration
- B. Pulse Repetition Period
- C. Duty Factor
- D. Wavelength
- E. Amplitude



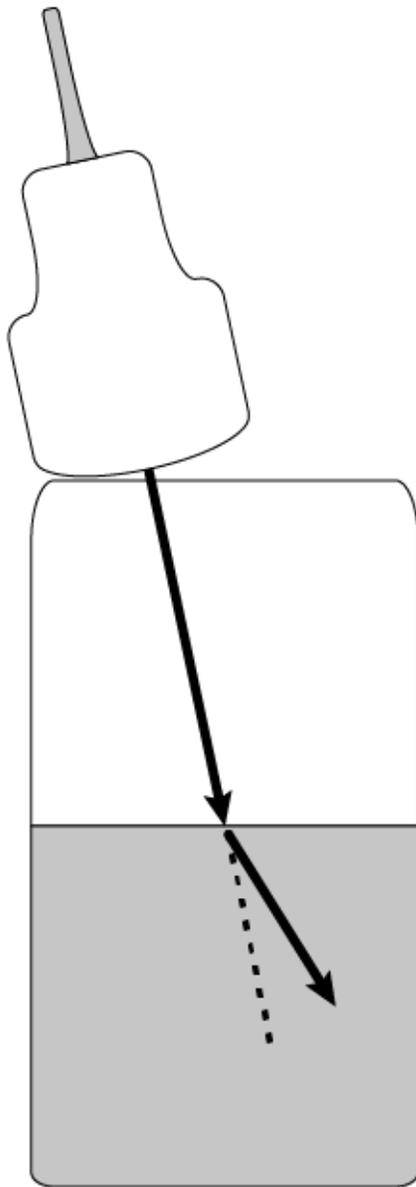
Attenuation and Absorption

- **Attenuation** is a decrease in the amplitude, power, and intensity of the sound beam as sound travels through tissue
 - **Three mechanisms of attenuation:**
 1. Absorption
 2. Scattering
 3. Reflection
- Units for attenuation are decibels (dB)

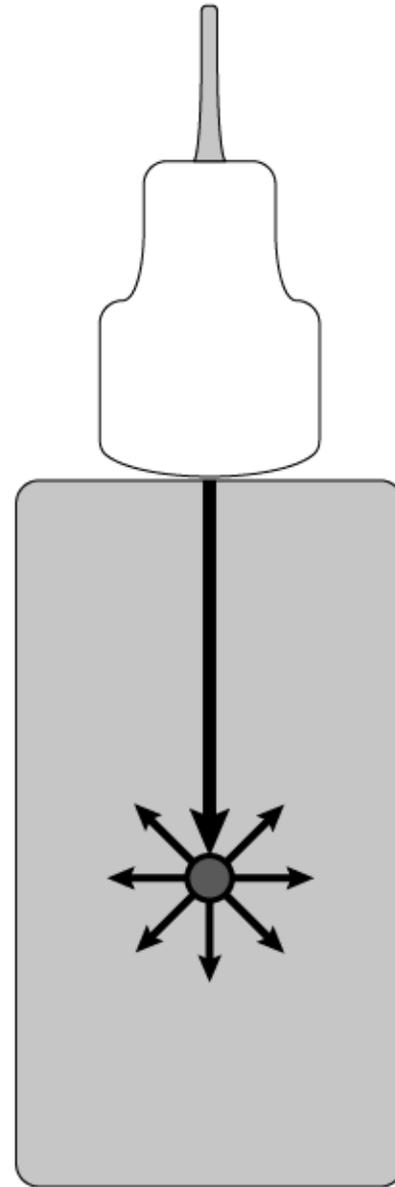
Reflection



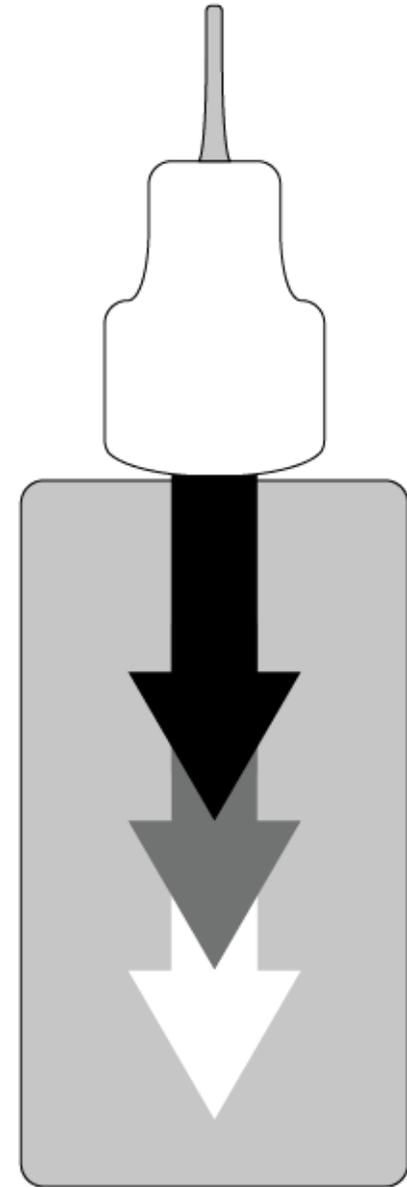
Refraction



Scattering



Absorption



Attenuation and Tissue Types

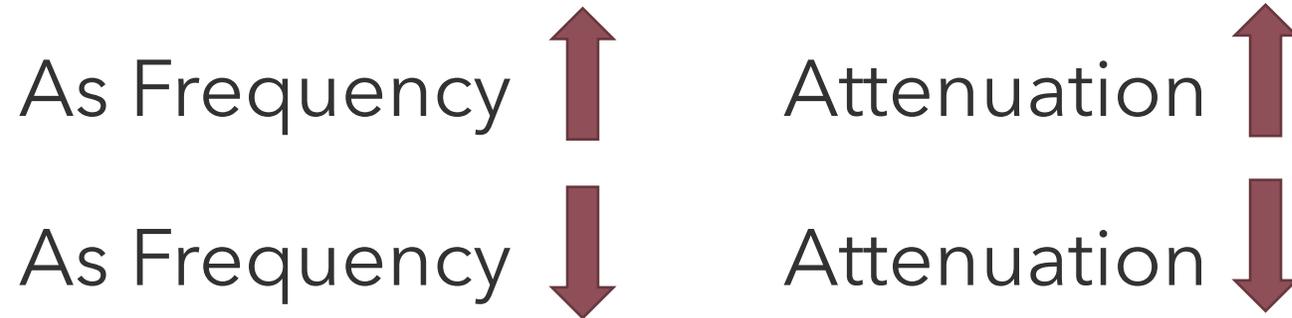
Medium	Attenuation
Water	Extremely low
Blood, urine, biologic fluids	Low
Fat	Low
Soft Tissue	Intermediate
Muscle	Higher
Bone and Lung	Even Higher
Air	Extremely High

Attenuation - Absorption

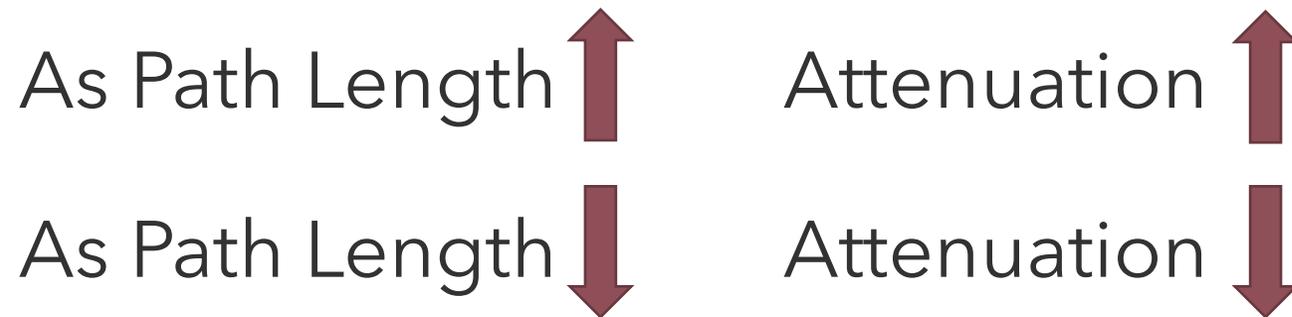
- Conversion of sound to heat
 - **Often studied closely due to thermal bioeffects**
- Absorption is the main contributor of attenuation when scanning in soft tissues
- As heat is produced, energy of the sound beam is decreased (conservation of energy)

Attenuation

- Frequency and attenuation are directly related



- Distance (aka path length) and attenuation are directly related



Attenuation

More Attenuation

Less Attenuation

Longer distances

Shorter distances

Higher frequencies

Lower frequencies

Attenuation

- Attenuation is measured in decibels and report as a **relative change** or a **ratio**
- We are looking at a comparison and need two values to understand how much change occurred in intensities (or power)
 - **Compare the initial and the end intensity**
- Decibels are based on a logarithmic scale

Logarithms

- A way of rating numbers
 - Logarithmic scales state that as the logarithm increases by "1," the actual number increases tenfold
 - Richter scale of rating earthquakes is logarithmic
- Represents the number of 10's that are multiplied to create the original number

Log of 100 is 2

Log of 1,000 is 3

Log of 10,000 is _____?

Decibels

- A logarithmic scale
- Common method of measuring:
 1. Strength of a sound beam
 2. Electrical signal strength
 3. Brightness of images
- Reports relative changes
 - "Signal strength has doubled"
 - "Signal is one-tenth as large as it used to be"

Decibels

- Are always comparisons
- Two intensities are required
 1. **Reference (starting level)**
 2. **Actual level**
- If an intensity or power level doubles, it has changed by **3 dB**
- If an intensity or power level decreases by half, it has changed by **-3 dB**
 - For every +3 dB change, you double the intensity/power
 - For every -3 dB change, you decrease the intensity/power by half

Positive Decibels

- **6 dB means 2×2**
4 times bigger than original
- **9 dB means $2 \times 2 \times 2$**
8 times bigger than original
- **20 dB means 10×10**
100 times bigger than original
- **30 dB means $10 \times 10 \times 10$**
1,000 times bigger than original

Positive Decibels

If a sound wave undergoes a 50 dB change from your initial intensity, how much larger is your ending sound wave?

Negative Decibels

- **Means getting smaller**

Intensity is decreasing

- **-3 dB means $\frac{1}{2}$**

$\frac{1}{2}$ the original value

- **-10 dB means $\frac{1}{10^{\text{th}}}$**

$\frac{1}{10^{\text{th}}}$ the original value

When reporting attenuation in dB, authors will often omit the negative sign. They may state "10 dB of attenuation occurred" and you need to understand that attenuation is weakening, which is a negative dB change.

For simplicity...

Decibel (dB) chart for Intensity/Power

Increasing Intensity/Power		Decreasing Intensity/Power	
0	No change	-0	No change
3	Double	-3	One-half
6	Quadruple	-6	One-fourth
10	10 times larger	-10	One-tenth
20	100 times larger	-20	One-hundreth



Questions??

The power of a system is at 100% and this is 0 dB. What is the dB change when the system's power is 50%?

- A. -10 dB
- B. -50 dB
- C. - 3 dB
- D. 3 dB
- E. 50 dB

The power of a system is at 100% and this is 0 dB. The system is changed to -6 dB. What is the system's power?

- A. 100%
- B. 75%
- C. 50%
- D. 25%
- E. 6%

A reduction of the intensity of a sound beam to $\frac{1}{2}$ of its original value is _____ dB.

A. -3

B. -6

C. -10

D. -20

A quadrupling in the intensity of a sound beam means it has undergone _____ dB.

A. -6

B. 6

C. -3

D. 3

Every 3 dB change means that the intensity will _____.

- A. Be halved
- B. Stay the same
- C. Double
- D. Triple

We need one intensity to calculate decibels.

A. True

B. False

Attenuation

- The **attenuation coefficient** (dB/cm) is the rate at which sound is attenuated per unit depth
 - **Based of the frequency of the transducer**
 - Answers the question "For every cm that the sound wave travels in the body, how much attenuation occurs?"

$$\text{Attenuation Coefficient (dB/cm)} = \frac{\text{frequency}}{2}$$

- The higher the frequency, the more attenuation that will occur!!!!

Attenuation

- **Total attenuation** is the total amount of sound (in dB) that has been attenuated at a certain depth
- To determine total attenuation, you need to know the attenuation coefficient and the path length (depth).

$$\text{Total atten. (cm)} = \text{atten. coeff. (dB/cm)} \times \text{path length (cm)}$$

- As the path length increases, attenuation increases

Attenuation

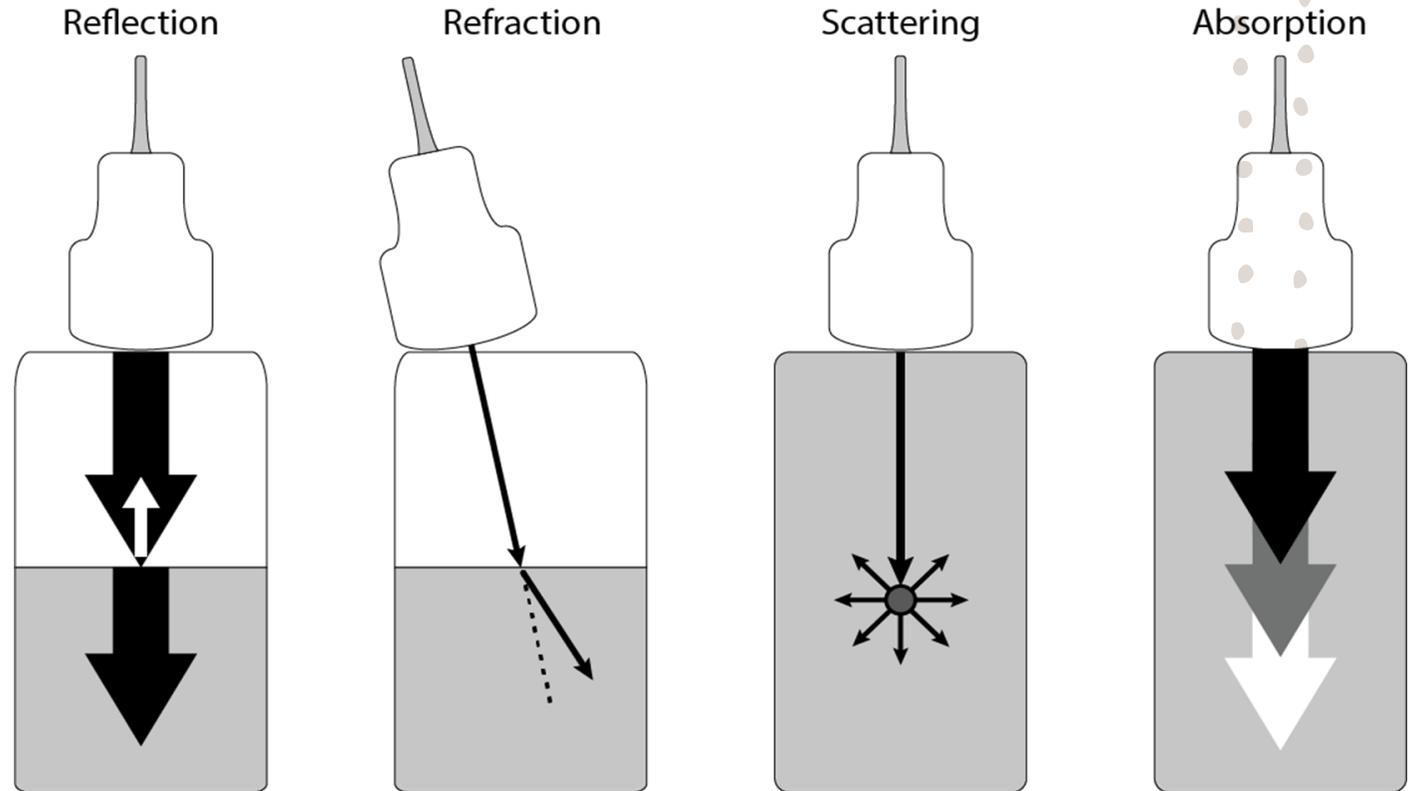
- Another term related to attenuation is half-intensity depth (HID), or the half-value layer thickness
 - **Answers the question "At what depth has the sound wave lost half, or -3 dB, of its intensity?"**

$$\text{Half-intensity depth (cm)} = \frac{6}{\text{frequency}}$$

- Remember, lower frequencies have less attenuation - you will be able to penetrate further into the body without losing half of your intensity!!!

Specular and Nonspecular Reflectors

- Interfaces are the dividing lines between two separate media
 - **This is where sound may be absorbed, reflected, scattered, transmitted, or refracted**
- We can classify reflectors in the medium as either specular or nonspecular reflectors



Specular and Nonspecular Reflectors

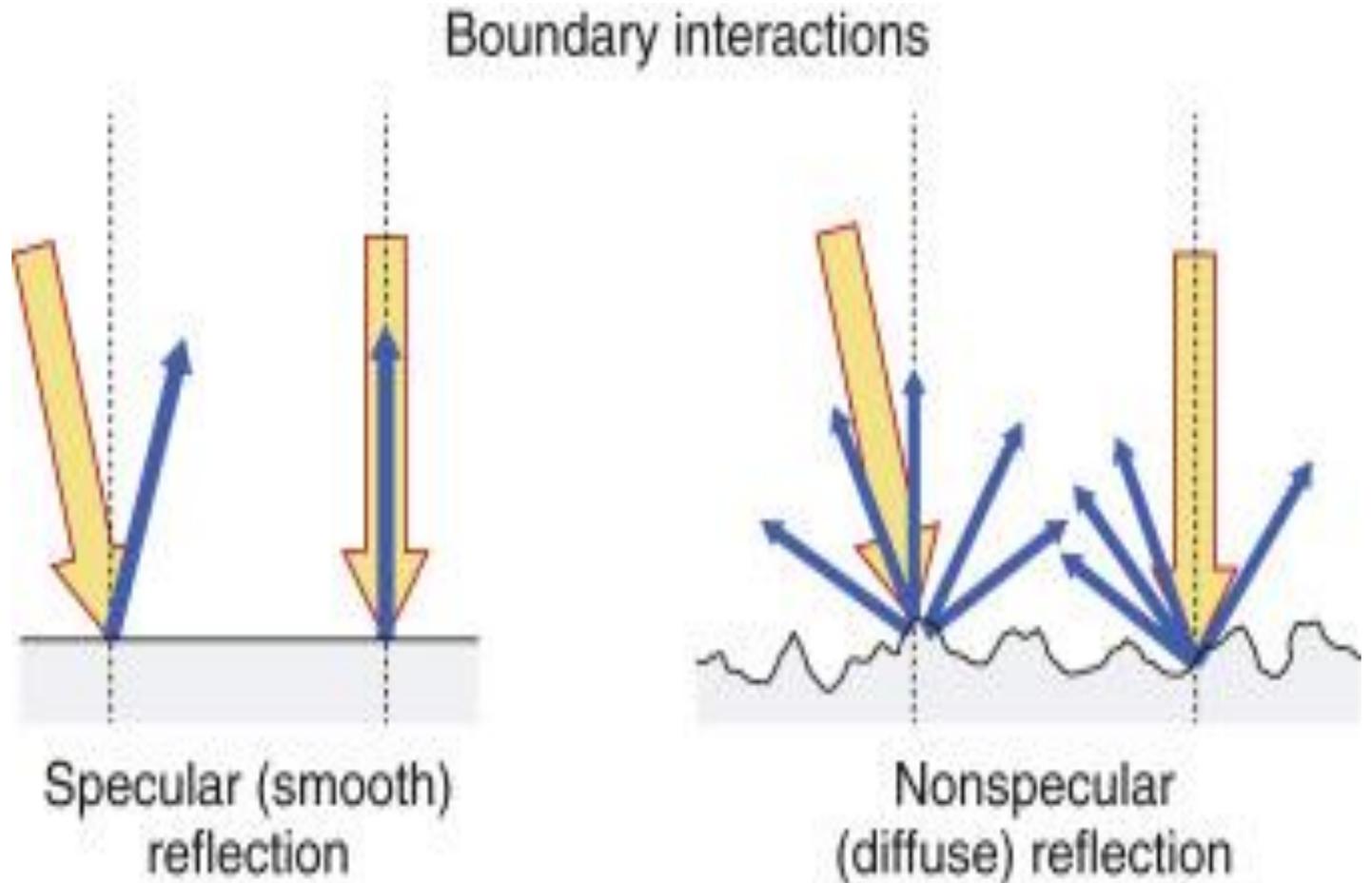
- **Specular reflections** occur when the sound strikes a large, smooth interface at a 90° angle
 - Specular is Latin for "*mirror*"
 - Good examples of specular reflectors are the diaphragm, organ capsules, and large vessel walls such as the Aorta
 - Size of the reflector is larger than the wavelength of sound that is striking it
- Highly angle dependent – best viewpoint is when the sound strikes the reflector at a perpendicular incidence

Specular and Nonspecular Reflectors

- **Nonspecular reflectors** are ones in which their size is smaller than the wavelength of the incident beam
 - This is what gives the organs their parenchyma texture
- This will scatter sound in different directions with only some of the sound coming back to the transducer to produce an image
 - **Backscatter**
 - Has a much lower intensity level than normal specular reflectors
 - When sound strikes several scatterers, the waves interfere with each other and end up back at the transducer creating an image

Specular and Nonspecular Reflectors

Which is better?
BOTH! We need specular reflections to image the organ boundaries and nonspecular reflections to image the parenchyma!



Specular and Nonspecular Reflectors

- Higher frequencies create a higher intensity of scattering
- Limit use of higher frequencies to shallower depths
 - **This will help to have more transmission into the tissue and less scattering**
- The more scattering we have, the weaker the sound beam becomes

Specular and Nonspecular Reflectors

- **Rayleigh Scattering** - special type of scattering that is seen only with red blood cells
 - **RBC's are very small reflectors and can send sound equally in all directions (omnidirectional)**
 - As frequency increases, the intensity of the scatter increases proportional to the 4th power of the frequency

Rayleigh scattering \propto frequency⁴

- When frequency doubles, Rayleigh scattering is 16 times greater!!!

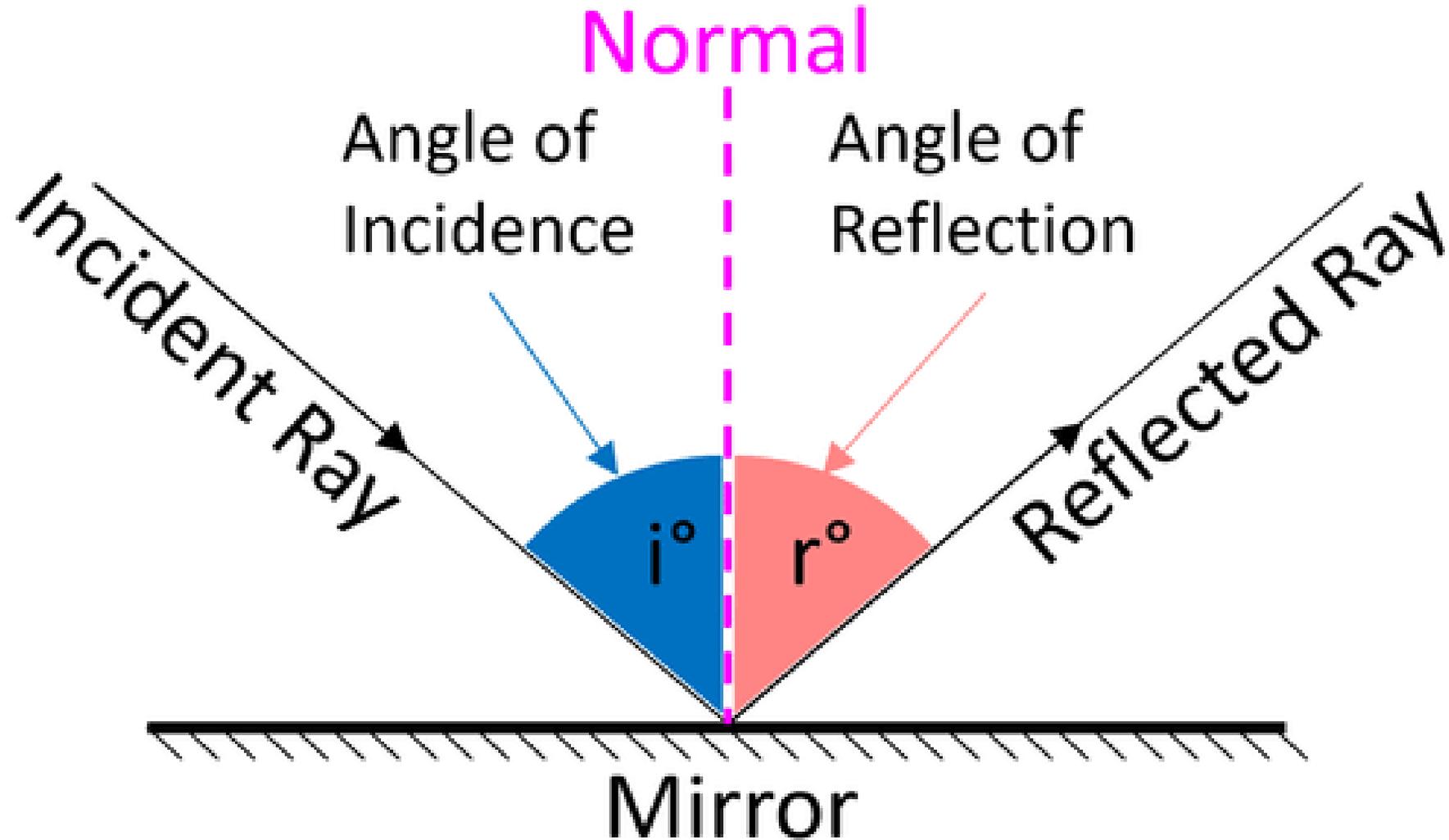
More about Reflection

- Reflections are formed when two criteria are met:
 1. **Normal incidence**
 2. **Media have different impedances**
- Normal incidence means that the incident sound beam strikes the boundary at exactly 90°
 - **AKA PORNN**
 - Perpendicular, Orthogonal, Right angle, Ninety degrees, Normal
- Oblique incidence is anything other than 90°
 - Not at right angles or non-perpendicular

More about Reflection

- Reflections are formed when two criteria are met:
 - 1. Normal incidence**
 - 2. Media have different impedances**
- If the impedances are identical, then there is no reflection - all the sound is transmitted through the tissue
- The angle of reflection always equals the angle of incidence

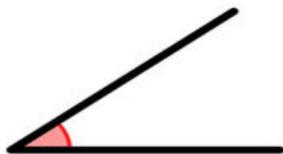
More about Reflection



More about Reflection

- **Oblique incidence** is complex, and reflection/transmission of sound cannot be predicted
 - Any sound that is reflected with an oblique angle of incidence does not return to the transducer
- However, as with normal incidence, the angle of reflection equals the angle of incidence.
- Two types of oblique angles are acute and obtuse.

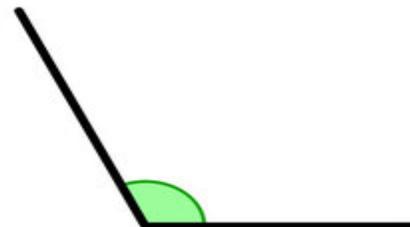
Acute angle



Right angle



Obtuse angle



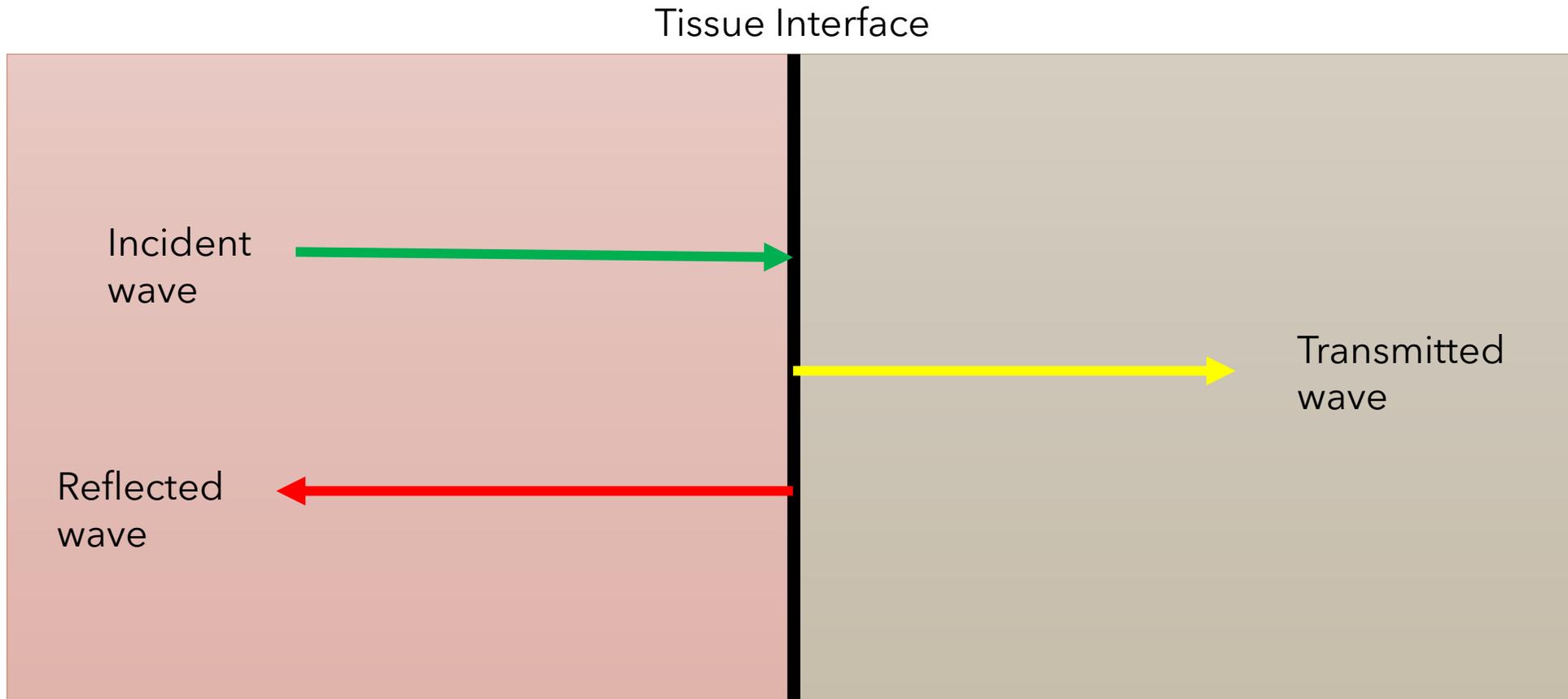
More about Reflection

- The intensity of sound reflected at an interface is dependent upon the intensity of the transmitted sound and the difference in impedances between the two media
 - **The bigger the impedance mismatch, the stronger the reflection**
 - **If impedances are identical, then there is 100% transmission and no reflection**

More about Reflection

- The percentage of sound transmitted at an interface, or **intensity transmission coefficient** (ITC) is equal to 1 minus the percentage of sound reflected at an interface, or **intensity reflection coefficient** (IRC)
 - The IRC is the percentage of intensity that bounces back when sound beam strikes the boundary between 2 media
 - The ITC is the percentage of intensity that passes forward when sound beam strikes the boundary between 2 media
- The IRC plus the ITC must always equal 100%
- If the impedances of the media are the same, then there is no reflection, and the ITC is 100%

IRC and ITC



Intensity Transmission coefficient (ITC) = 1 - Intensity Reflection Coefficient (IRC)

IRC and ITC

- Sound travels through an interface at normal incidence, and 40% of the sound is reflected to the transducer. How much sound was transmitted at the interface?

More about Reflection

- With a **NORMAL incidence**:
 1. **No reflection** will occur if the 2 media have identical impedances
 2. **Small reflection** will occur if the impedances are slightly different
 3. **Large reflection** will occur if impedances are substantially different
- Impedances of the 2 media are the driving force between how much reflection and transmission occurs



Questions??

What are the three components of attenuation?

- 1. Absorption**
- 2. Scattering**
- 3. Reflection**

As the path length increase, the attenuation of ultrasound in soft tissue _____.

- A. Increases**
- B. Decreases**
- C. Stays the same**

As frequency decreases, depth of penetration _____.

- A. Increases**
- B. Decreases**
- C. Stays the same**

As the path length increases, the half boundary layer (half-intensity depth) _____.

- A. Increases**
- B. Decreases**
- C. Stays the same**

Sound is traveling from bone to soft tissue.

The impedances of the media differ significantly, and 90% of the beam's intensity is reflected. What percentage of intensity is transmitted?

A. 0%

B. 10%

C. 90%

D. 100%

Sound is traveling in Jell-O, passes through an interface at 90° and continues to travel in whipped cream. The impedance of Jell-O and whipped cream are nearly identical. What percentage of intensity is transmitted?

A. 2%

B. 25%

C. 78%

D. 99%

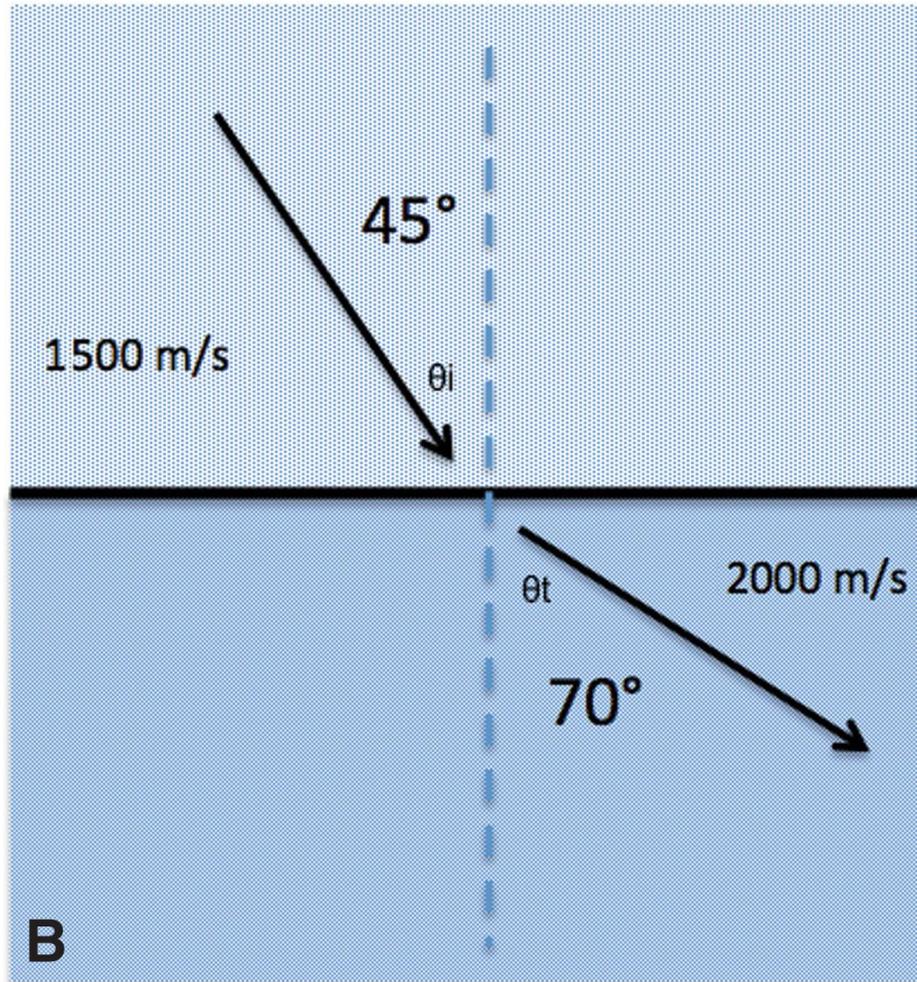
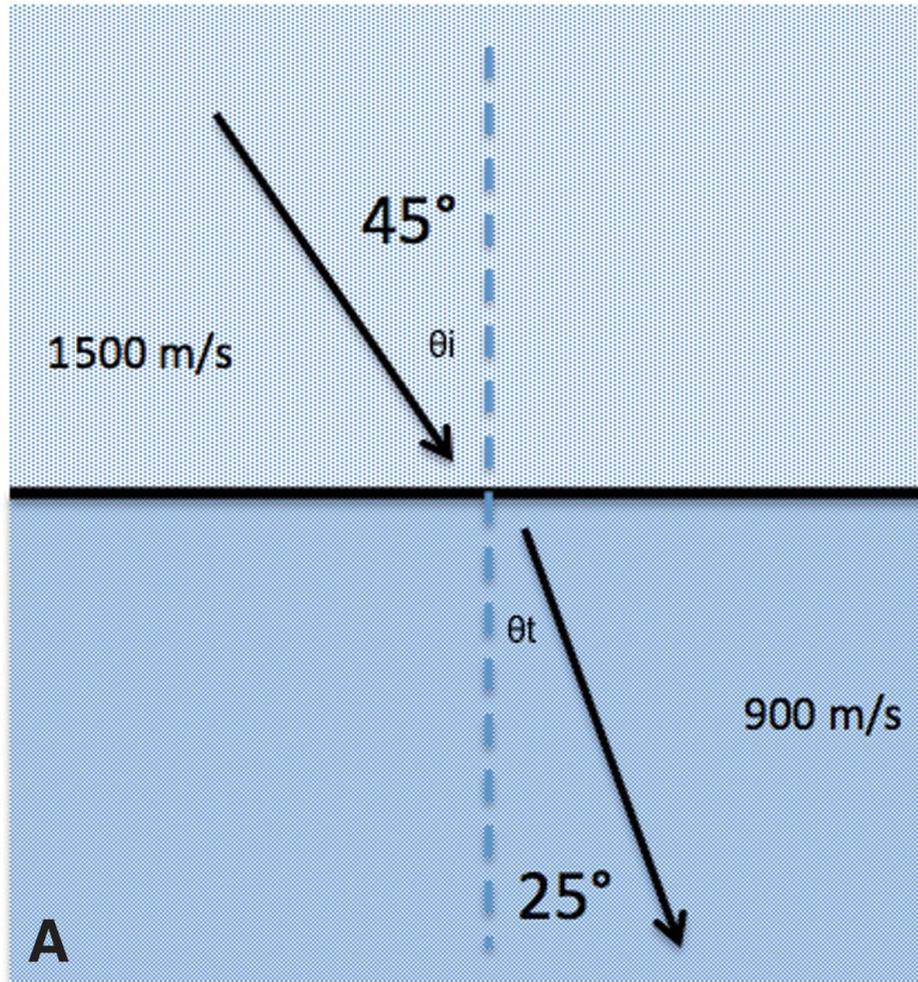
Refraction

- Refraction is a redirection of the transmitted sound beam
 - **Transmission with a bend**
- Occurs only if two conditions are met:
 1. **Oblique incidence**
 2. **Propagation speed of 2 media are different**
- If transmission occurs and these 2 conditions are met, the sound wave will never travel in a straight line but instead it will bend
- Do not confuse Refraction with Reflection!!!

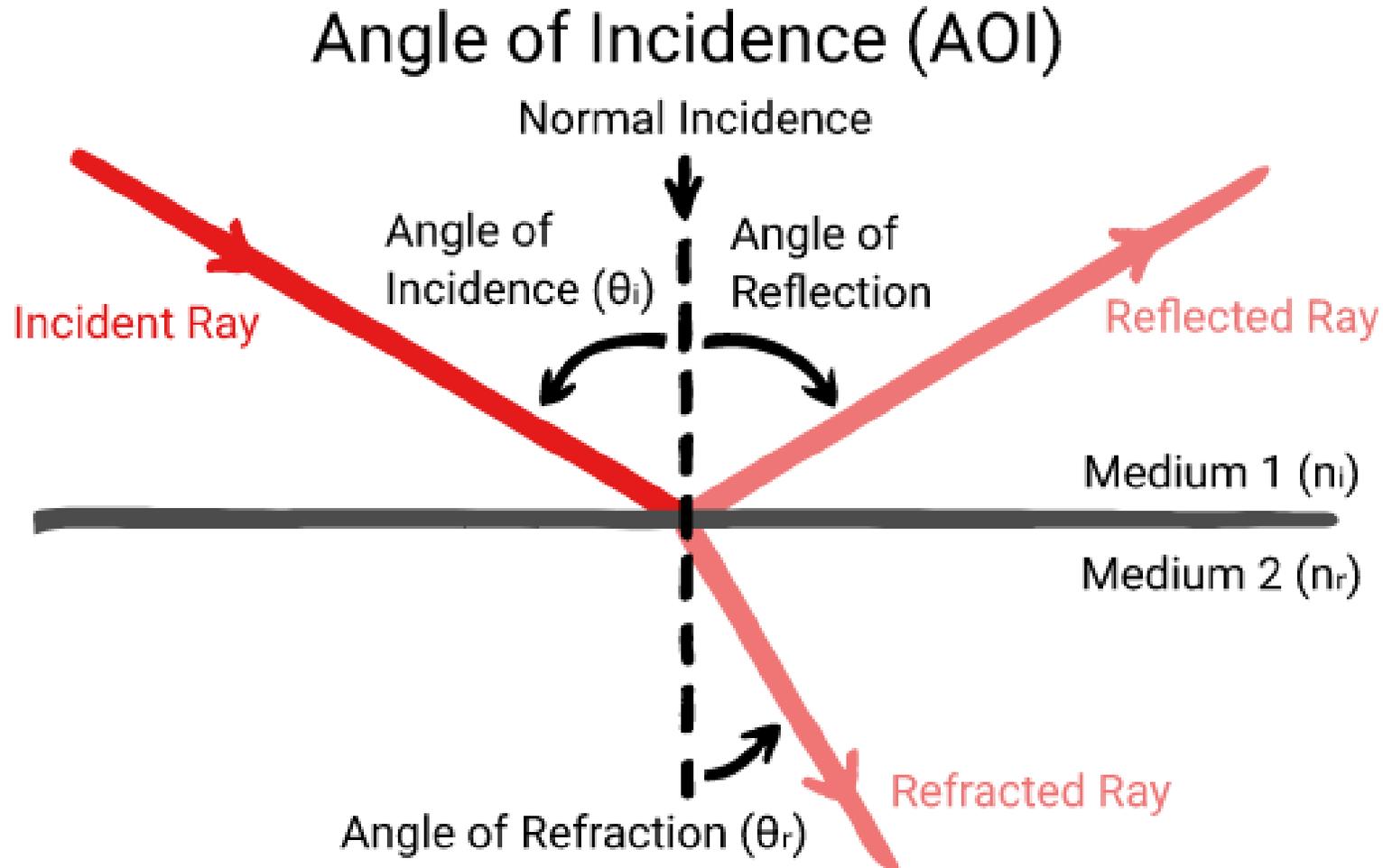
Snell's Law

- “The Physics of Refraction” are described by Snell’s Law
 - Describes the angle of transmission at an interface based on the angle of incidence and the propagation speeds of the two media
- Remember: Refraction requires an oblique incidence and different propagation speeds in the two media
- Snell’s Law can predict how much bending of the sound beam will occur based off the propagation speeds and incident angles
 - **The media that has the faster speed, will have the greater angle (or bend)**

Snell's Law aka Refraction



Snell's Law aka Refraction



A sound wave strikes a boundary at a normal incidence. The impedances of the two media are identical. What percentage of the sound wave is refracted?

A. 100%

B. 75%

C. 0%

D. 25%

E. 90%

Reflection versus Refraction

Reflection <u>What is it?</u> Percentage or intensity of sound that is reflected or transmitted at an interface	Refraction <u>What is it?</u> Angle of transmitted sound
Normal (perpendicular) incidence	Oblique incidence
Impedance mismatch	Propagation speed mismatch
Percentage or intensity of sound reflected and transmitted at an interface	Angle of transmitted sound

More About Intensity

- Intensity is the concentration of the power in a beam

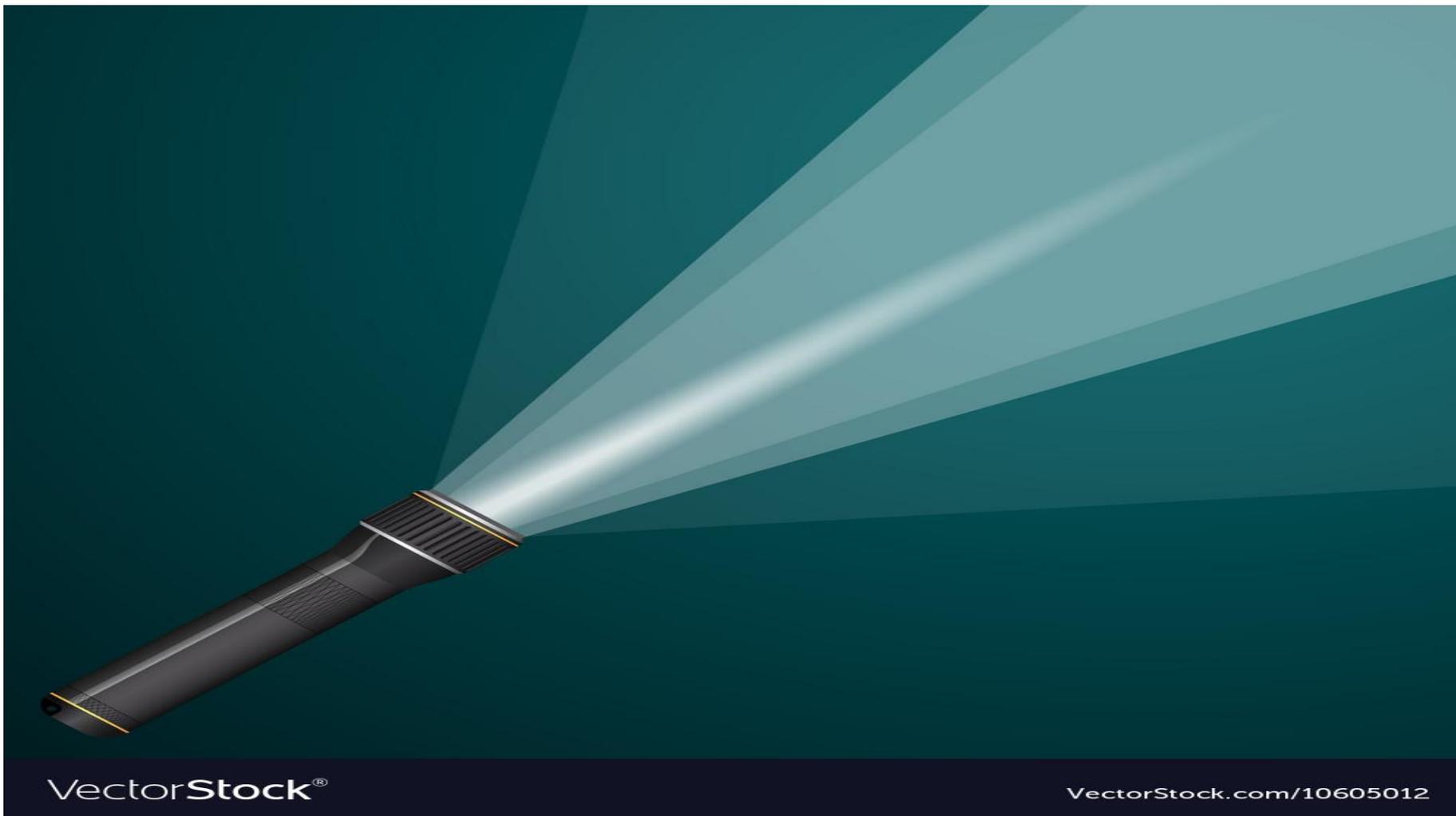
$$\text{Intensity (W/cm}^2\text{)} = \frac{\text{power}}{\text{beam area}}$$

- Typically, sound intensity is assumed to be 100 mW/cm²
- With PW, the intensity of the beam varies with *space* and *time*
 - **Spatial = where, aka space**
 - **Temporal = when, aka time**
- Multiple ways to evaluate the intensity using the spatial and temporal descriptors

Terms Related to Intensities of PLW

- **Spatial - distance or space**
- **Peak - maximum value**
- **Average - mean value**
- **Temporal - all time (transmit/receive)**
- **Pulsed - time the pulse exists (transmit)**

More About Intensity



More About Intensity

- Spatial average (SA), and spatial peak (SP), refer to *where* the beam was measured
 - **The SP intensity is measured at the center of the beam**
 - **The SA intensity is the average intensity across the face of the entire beam**
- The beam uniformity ratio (BUR), also referred to as the SP/SA factor or beam uniformity coefficient (BUC), is the ratio of the center intensity to the average spatial intensity

More About Intensity

- The temporal intensities depict when the beam was measured
- The temporal peak (TP) is the intensity measured at the highest intensity, or peak, of the pulse and is therefore the highest of all the temporal intensities
- The temporal average (TA) is the average of all the intensities during both transmission and the listening period

More About Intensity

- It is important to note that when the transducer is waiting for the pulse to come back, the intensity is zero (sound is produced only during the transmission phase)
- Because the beam is transmitting only less than 1% of the time in PW operation, the TA is the lowest of all the temporal intensities.
 - **This means that 99% of the time, the intensity is zero.**

More About Intensity

- With CW operation, where the DF is equal to 1, the TA is equal to the PA because there is no listening time
- Spatial and temporal intensities provide a specific explanation for the measurement of the intensity of the sound beam in both space and time
- **It is most important to note that SATA is the lowest of the intensities, SPTP is the highest, and the SPTA intensity is used when describing thermal bioeffects**

More About Intensity

	All Intensities have units of W/cm^2
SPTP	Spatial peak, temporal peak
SATP	Spatial average, temporal peak
☆ SPTA ☆	Spatial peak, temporal average
SATA	Spatial average, temporal average
SPPA	Spatial peak, pulse average
SAPA	Spatial average, pulse average

More About Intensity

- The **hydrophone**, or microprobe, is a device used to measure output intensity of the transducer
- It can be a needle-type device or a broad, disk-shaped device. Both types of hydrophones consist of a transducer that is placed into the path of the beam to measure PRP, PD, and period



More About Intensity

- From these measurements, other parameters, such as frequency, wavelength, SPL, PRF, and DF, can be derived
- The hydrophone is also used to determine pressure amplitude and intensities, which are important for patient safety

Summary

Process	What is Required
Reflection with normal incidence	Look for different impedance
Reflection with oblique incidence	We don't know; too complex!
Transmission	Derive this from reflection information
Refraction	Look for oblique incidence and different speeds