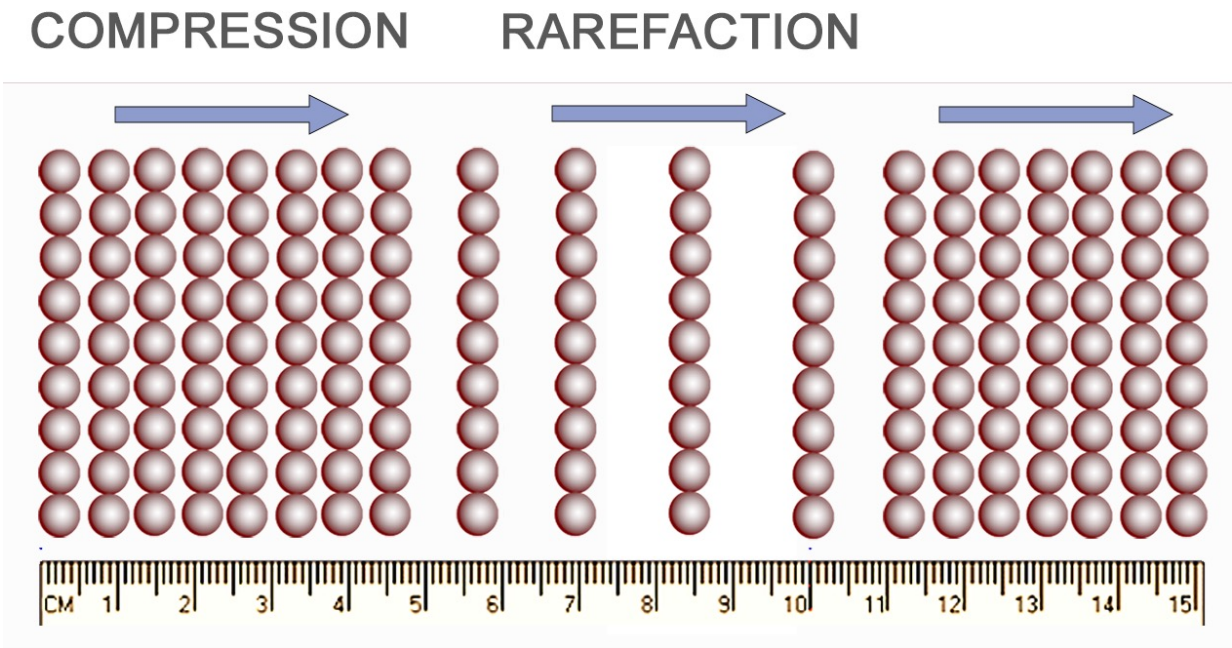
The Nature of Sound

Sonography: Acoustics to Images



Sound Waves

- Waves carry energy from one place to another
- Sound waves carry energy as area of *compression* and *rarefaction*

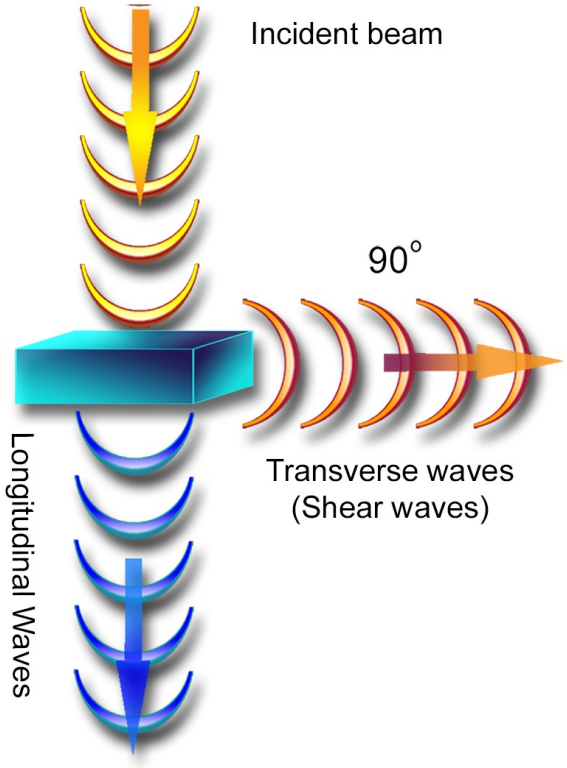


Sound Waves

- Require a medium within which to propagate
- Unlike electromagnetic waves which can propagate in a vacuum
- Media can include:
  - **Air**
  - **Water**
  - **Human soft tissue**
- Continue to travel in straight line within a homogeneous medium

Sound Waves

- Two classifications of acoustic propagation
  - **Longitudinal:** same direction as propagation of incident energy
  - **Transverse (*shear*):** right angles to propagation of incident energy



Sound Waves

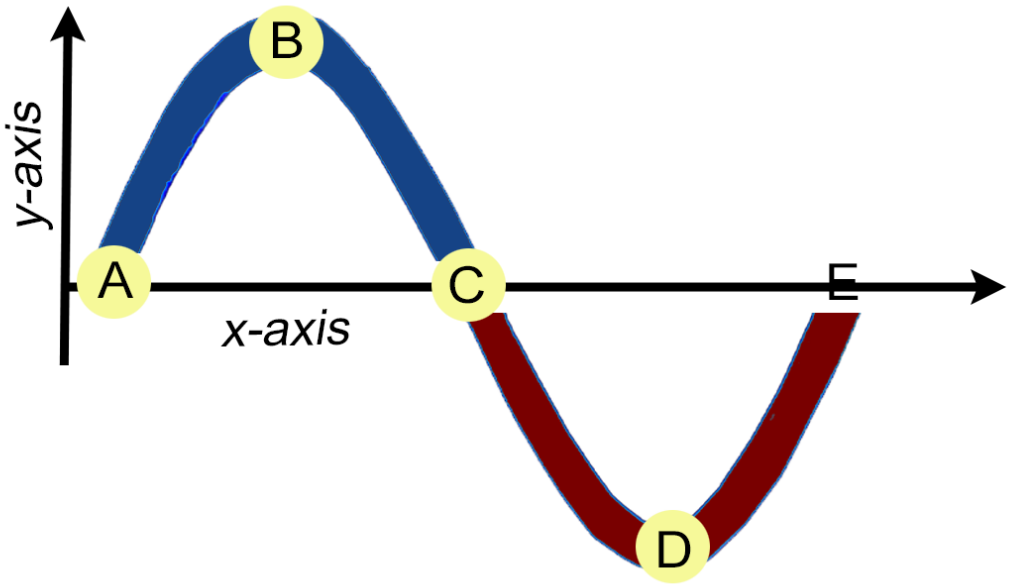
- Initiating mechanical force is required as a source of sound waves
- In US imaging, force is provided by a piezoelectric crystal
  - **Multiple crystal elements are incorporated into the transducer**
- Transmitted mechanical force pushes and pulls particles along its propagation path
  - **Compression**
  - **Rarefaction**

Sound Waves

- Distance that each particle moves from equilibrium point is function of acoustic **amplitude**
- Elastic forces pull particles back together after the wave has passed
- In US imaging, particles are small packets of human soft tissue

Sine Waves

- Wave characteristics can be represented by **sine waves**

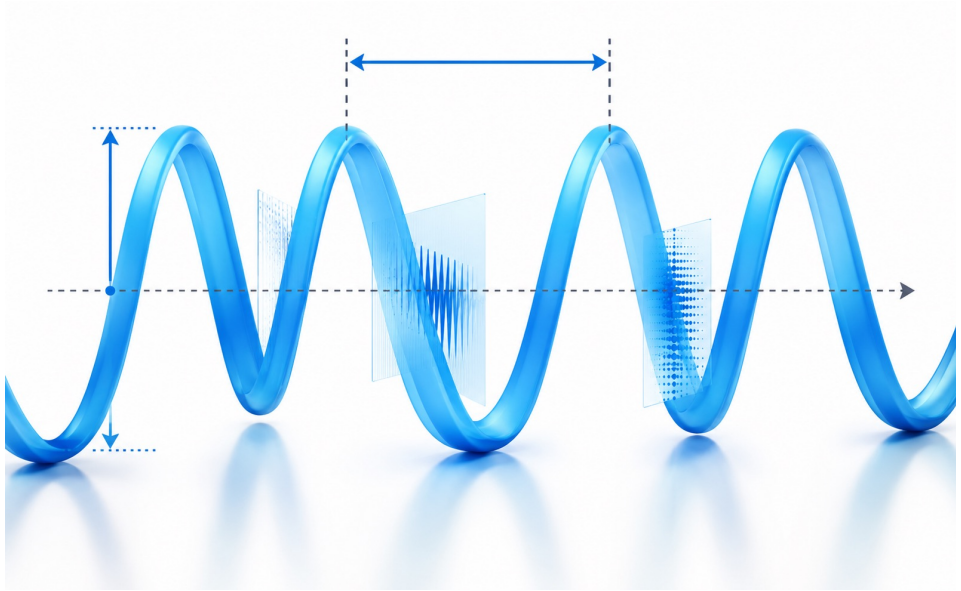


A = resting equilibrium
B = crest
C = crossing equilibrium
D = trough
E = ending equilibrium

Wave Parameters

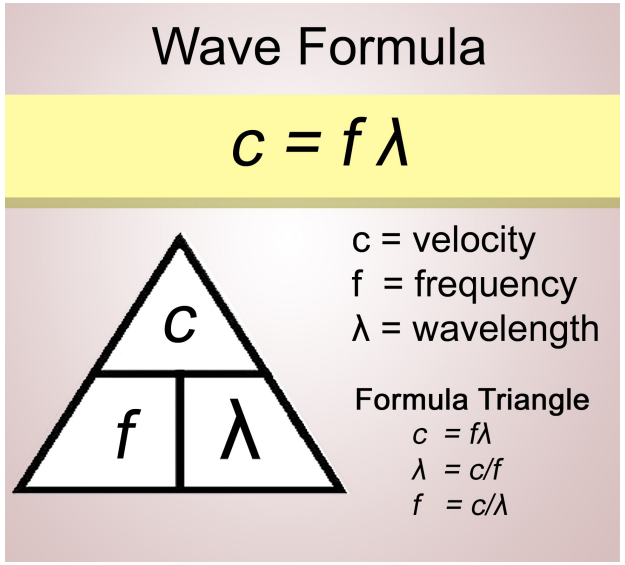
Wave Parameters

- Sound waves possess characteristics which define them:
  - **Propagation velocity**
  - **Frequency**
  - **Wavelength**
  - **Period**
  - **Amplitude**
  - **Power**
  - **Intensity**



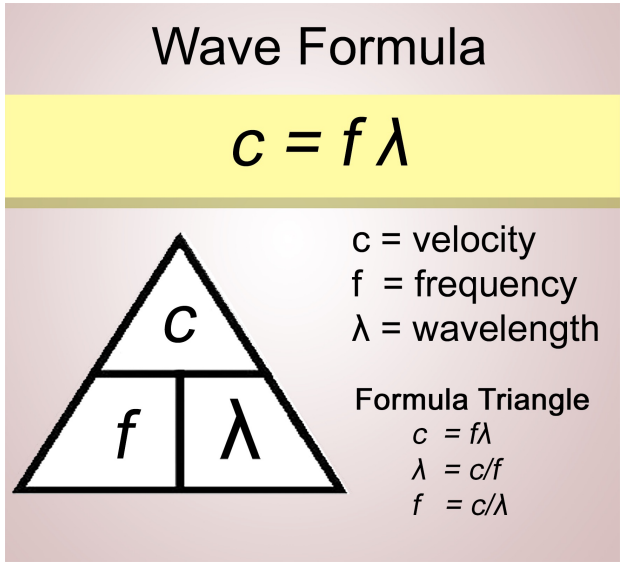
The Wave Formula

- Three of these parameters interact in a manner that directly apply to medical US imaging:
  - **Frequency (*f*)**
  - **Velocity (*c*)**
  - **Wavelength (*λ*)**



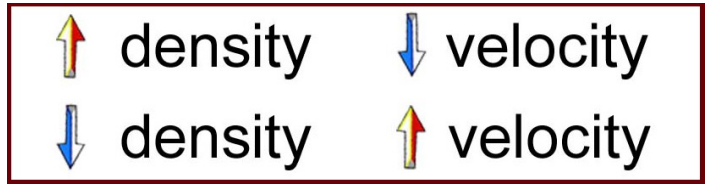
Propagation Velocity

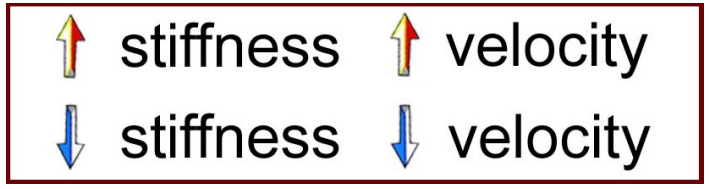
- The speed with which a wave travels through a medium
- Different tissues transmit sound at different velocities
- Units of measurement:
  - **cm/sec, m/sec, cm/μsec**
- Average sound speed is:
  - **1,540 m/sec**
  - **1.54 mm/μsec**



Propagation Velocity

- Sound speed is determined by tissue
  - **Density**
  - **Stiffness**

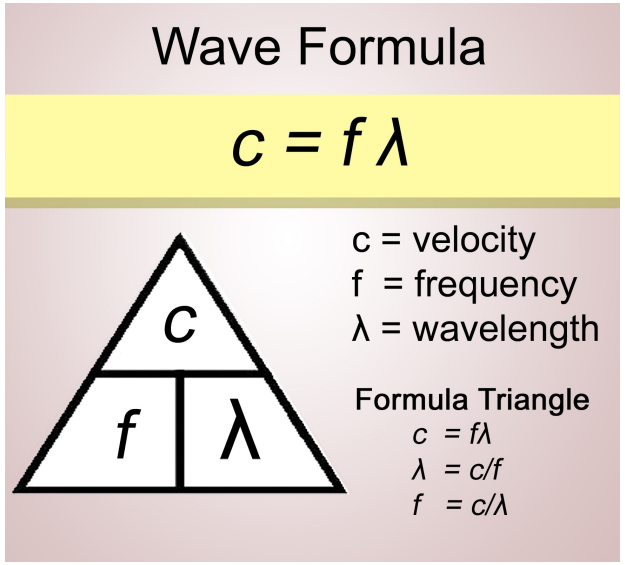




Propagation Velocities	
Medium	**M/sec**
Air	330
Fat	1460
Water (20° C)	1480
Soft tissue (ave.)	1540
Water (50° C)	1540
Liver	1559
Blood	1570
Muscle	1580
Bone	3500
PZT (crystal)	4000

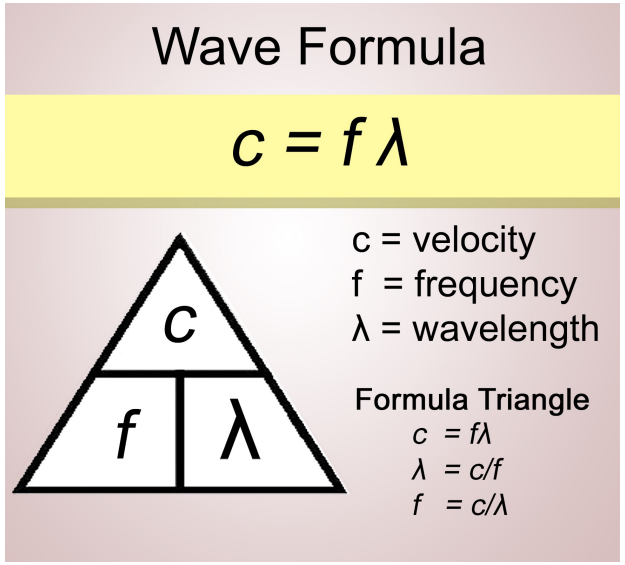
Frequency

- Number of waves (*cycles*) passing a single point over a given period of time
- Units of measurement:
  - **cycles/sec (*cps*), Hertz (*Hz*)**
- Audible sound = 20 – 20,000 Hz
- Ultrasound > 20,000 Hz



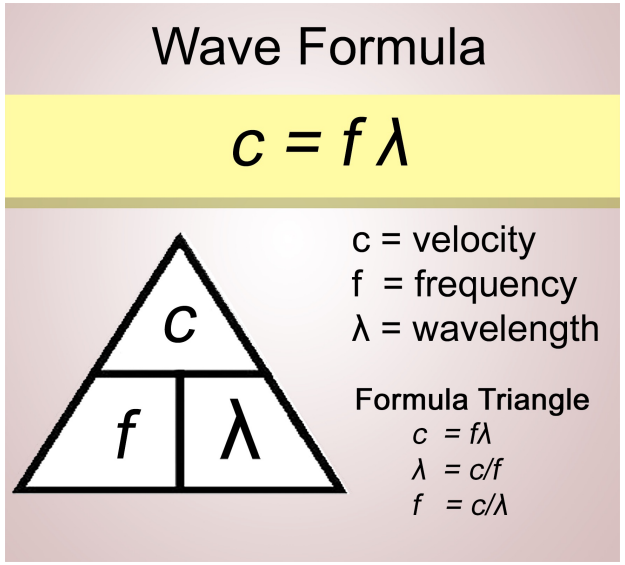
Frequency

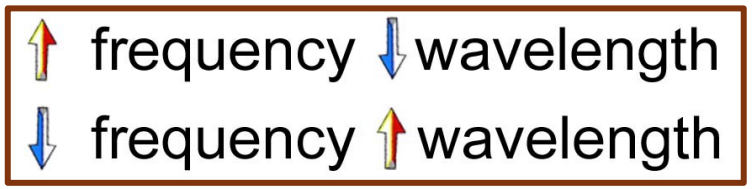
- Frequency is constant within a given medium
- Determined by sound source (*transducer*)
- 2 exceptions:
  - **Harmonics**
  - **Doppler shift**



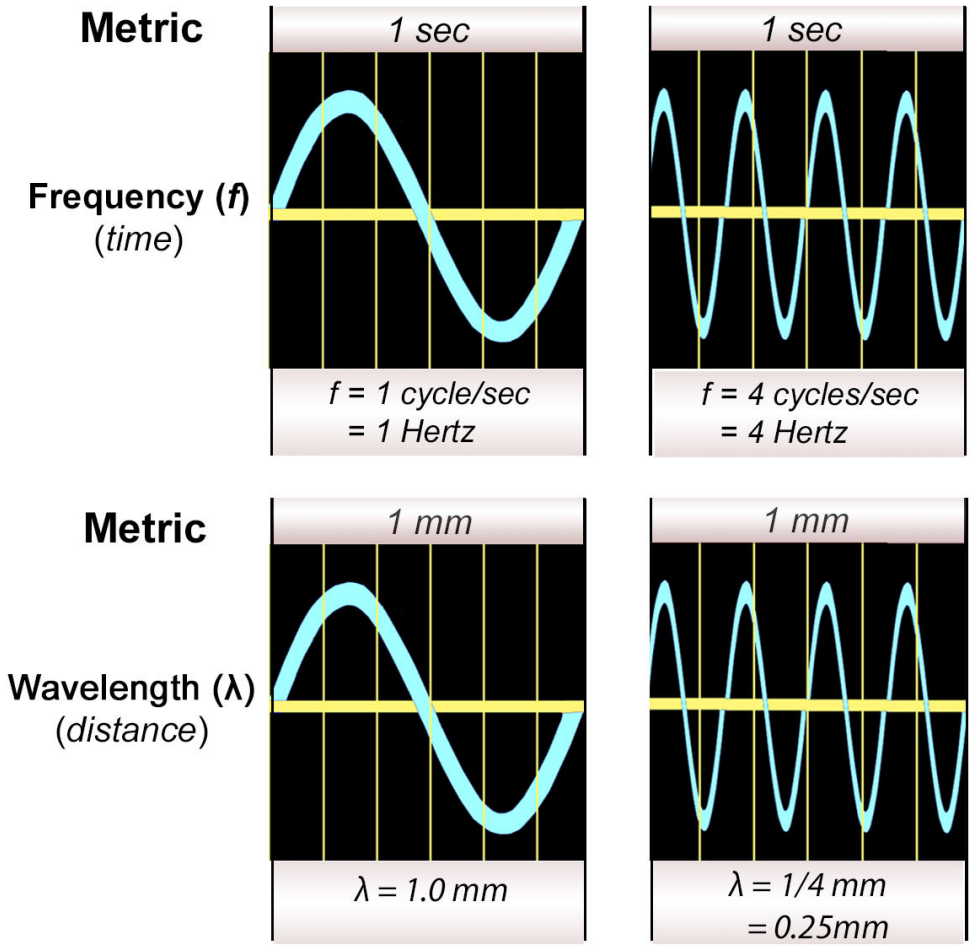
Wavelength

- Spatial dimensions of a wave
- Units of measurement:
  - **meters, cm, mm, μm**
- Inversely proportional to frequency
- Significant parameter in US image quality (*resolution*)





Wavelength vs. Frequency

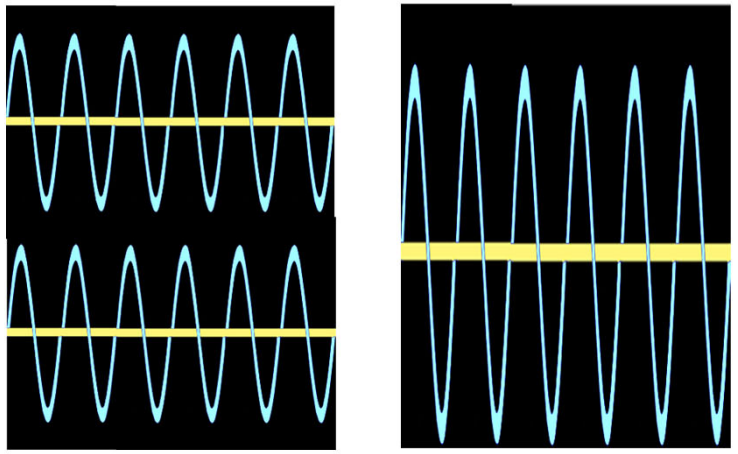


Wave Phase

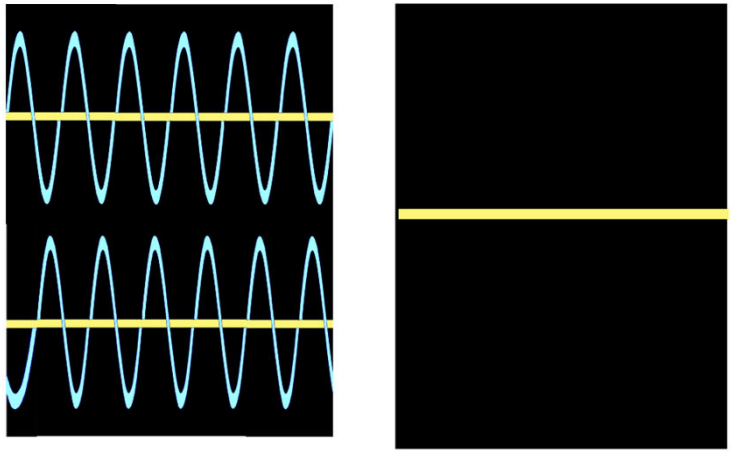
- The particular stage, or point, of advancement of a single cycle
- Measured from an arbitrary point of origin
- Related to *when in time* an even occurs
  - **Constructive interference:** when two waves superimpose at the same point in time (*in-phase*)
  - **Destructive interference:** when two waves superimpose at different points in time (*out-of-phase*)

Wave Interference

Constructive
Waves *in phase* superimpose and increase amplitude of transmitted energy



Destructive
Waves *out of phase* superimpose and cancel out transmitted energy



Period

- Length of time to complete a single wave cycle
- In US imaging, typical period:
  - **0.15 – 1.0 μsec**
- Units of measurement:
  - **(*time*) seconds, μs, ns**
- Reciprocal of frequency (*inversely proportional*)

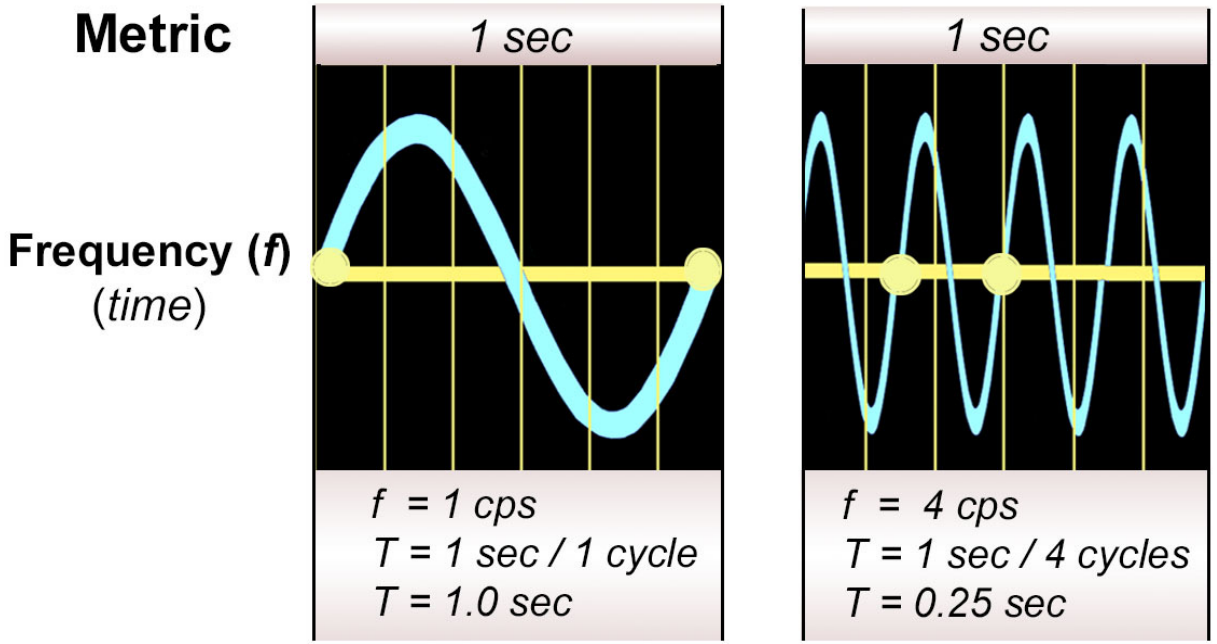
Period

$T = 1/f$

P = period
f = frequency

↑ frequency ↓ period
↓ frequency ↑ period

Period

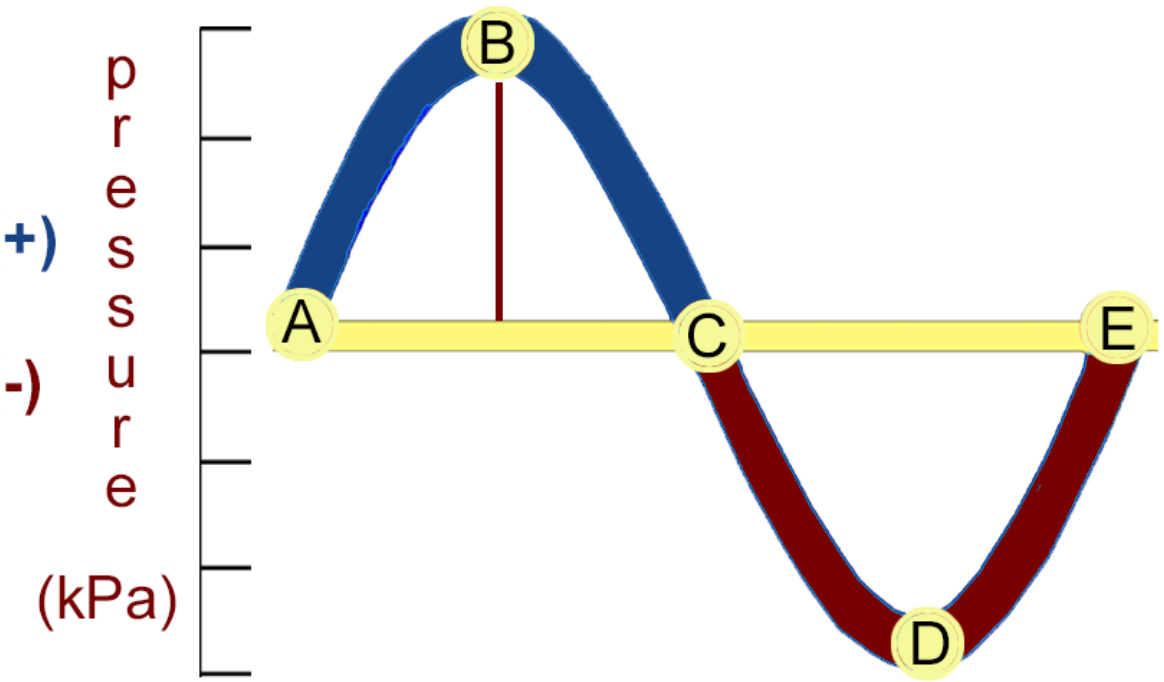

Metric
Frequency (f)
(time)
1 sec
f = 1 cps
T = 1 sec / 1 cycle
T = 1.0 sec
1 sec
f = 4 cps
T = 1 sec / 4 cycles
T = 0.25 sec

Amplitude

- Strength of the **pressure** in a sound wave
- Difference between average and maximum value of an acoustic variable
- Represents degree of change in a variable
- Units of measurement (*varies with acoustic variable measured*):
  - **Particle motion – units of distance (*cm, mm, inches*)**
  - **Density: grams/cc^3**
  - **Pressure: lbs/in^2, Paschal (*Pa*), mmHg**

Amplitude

A = resting equilibrium
B = maximum amplitude (+)
C = crossing equilibrium
D = maximum amplitude (-)
E = ending equilibrium



Power

- Rate at which work is performed
- Rate at which acoustic energy is transferred into a medium
- Determined by sound source
- Important consideration in patient exposure to acoustic energy (*bioeffects*)
- Units of measurement:
  - **watts, milliwatts**

Power

$$P = A^2$$

P = power
A = amplitude

Intensity

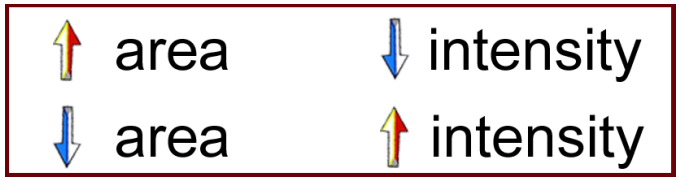
- How much energy transferred per unit of *time* per unit *area*
- Important consideration in acoustic exposure levels (*bioeffects*)
- FDA has established maximum intensity levels permissible in commercial US systems
- Categorized along spatio-temporal lines:
  - **Spatial intensity –** energy delivered per cm of tissue
  - **Temporal intensity –** energy delivered to same tissue area over time

Spatial Intensity

- Function of both quantity of energy delivered (*E*) and volume of insonated tissue (*A*)
- Units of measurement
  - **Watts/cm^2, mWatts/cm^2**
- Proportional to both quantity (*directly*) and area (*inversely*)

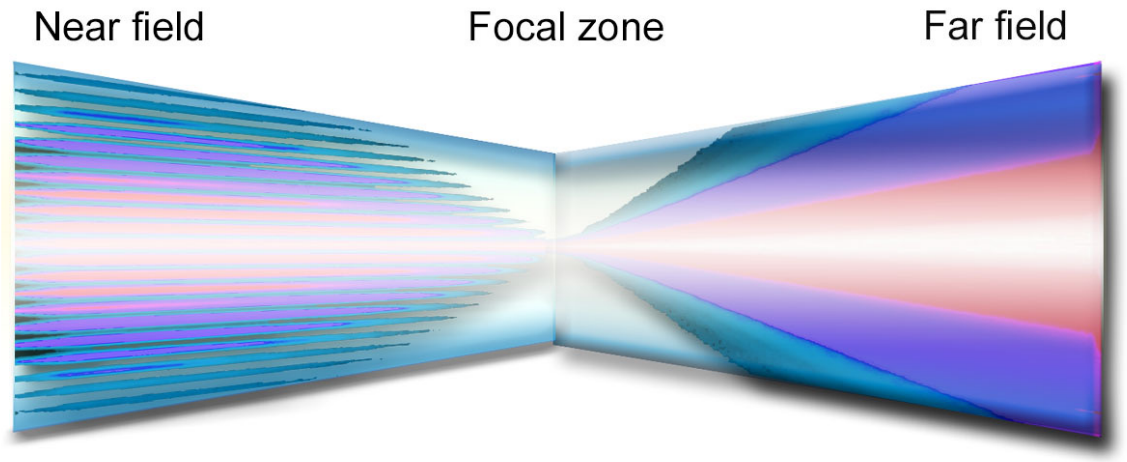
Spatial Intensity
SI = E/A
SI = spatial intensity E = acoustic energy (*watts*) A = area insonated (*cm^2*)





Spatial Intensity

- Inversely proportional to insonated **area**
- Beam focusing increases spatial intensity



Spatial Intensity
$SI = E/A$
SI = spatial intensity E = acoustic energy (*watts*) A = area insonated (cm^2)

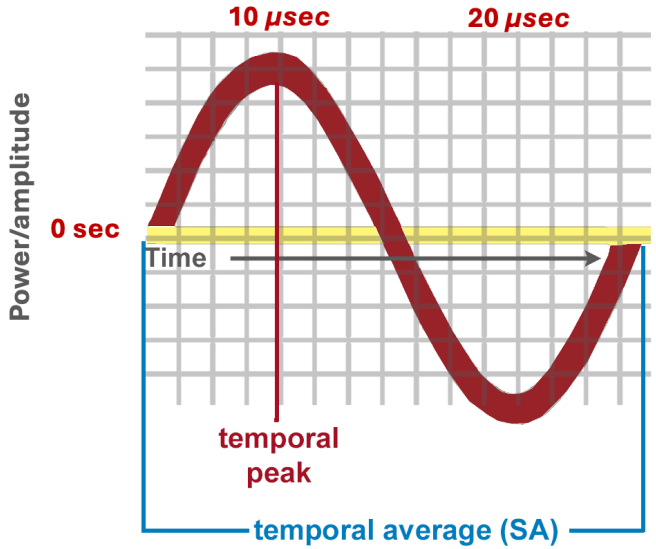
Spatial Intensity – Methods of Measurement

- **Spatial peak** (*SP*): maximum intensity at a given location
- **Spatial average** (*SA*): average intensity over entire acoustic field
- **SP/SA Factor**: beam uniformity ratio

$$\text{SP/SA Factor} = \frac{\text{Spatial Peak Intensity} \quad (\text{W/cm}^2)}{\text{Spatial Average Intensity} \quad (\text{W/cm}^2)}$$

Temporal Intensity

- Amount of energy delivered to human soft tissue over **time**
- Less energy delivered at beginning and end of each pulse
- Takes a few microseconds for transmitted pulse to reach its maximum value after voltage is applied to PZ crystal



Temporal Intensity - Methods of Measurement

- Temporal peak (*TP*): maximum intensity over entire pulse time
- Temporal average (*TA*): average intensity over entire pulse time
  - **Function of maximum intensity over time (*TP*) and transducer "ON" time (*DF*)**

Temporal Average Intensity

$$TA = TP \times DF$$

TA = temporal average intensity
TP = temporal peak intensity
DF = duty factor

↑ temporal peak	↑ temporal average
↓ temporal peak	↓ temporal average

↑ duty factor	↑ temporal average
↓ duty factor	↓ temporal average

Intensity Definitions

- Four definitive terms relate to measurement of US intensity:
  - **SPATIAL:** where in ***space*** intensity is measured
  - **TEMPORAL:** when in ***time*** intensity is measured
  - **PEAK:** maximum value
  - **AVERGAGE:** average, or mean, value

INTENSITY DEFINITIONS	
SPATIAL (*S*)	where in *space* intensity is measured
TEMPORAL (*T*)	when in *time* intensity is measured
PEAK (*P*)	maximum value
AVERAGE (*A*)	average, or mean, value

Intensity Metrics - Clinical

INTENSITY METRICS		
SPTP	spatial peak, temporal peak	HIGHEST VALUE
SATP	spatial average, temporal peak	
SPTA	spatial peak, temporal average	most commonly referenced in bioeffects
SATA	spatial average, temporal average	LOWEST VALUE
SPPA	spatial peak, pulse average	average over duration of a single pulse

FDA Exposure Limits for Diagnostic Ultrasound (SPTA)

- General diagnostic ≤720 mW/cm^2
- Fetal imaging ≤ 94 mW/cm^2

Decibel Notation

- Describes magnitude of a particular quantity compared to a reference level
- Logarithmic function useful for expressing huge differences in values such as:
  - **Power and intensity output of acoustic beam**
  - **Attenuation levels in human soft tissue**
  - **Range of echo and RF signal amplitudes**
  - **Range of brightness levels in a grayscale image**

Decibel Notation

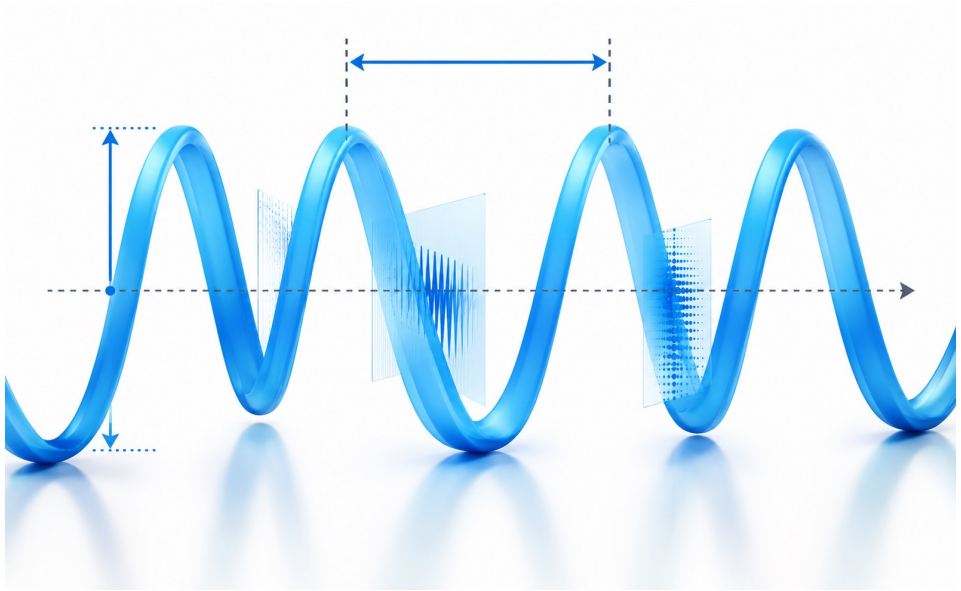
$$dB = 10\log_{10}\left(\frac{I_2}{I_1}\right)$$

dB = decibels
I_1 = initial value (reference level)
I_2 = measured value
$10\log_{10}$ = logarithm base 10

Acoustic Variables

Acoustic Variables

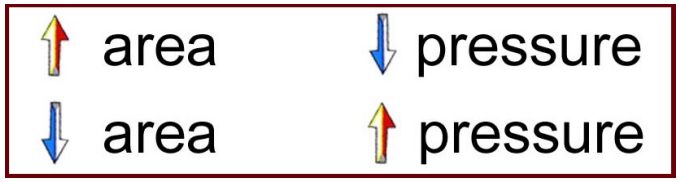
- Measurable variables that describe various parameters of propagating US waves:
  - **Pressure**
  - **Density**
  - **Particle displacement**
  - **Temperature**

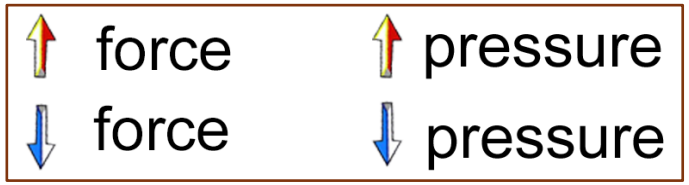


Pressure

- Ratio of a force acting on the surface of an object
- In US, pressure refers to the areas of wave compression
- Units of measurement:
  - **Newtons/m^2**

Pressure
$P = F/A$
P = pressure F = force A = area





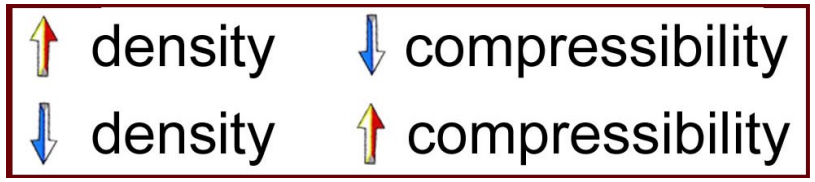
Pressure

- **Peak-to-peak pressure**: variation between point of maximum pressure (*maxima*) and maximum rarefaction (*minima*)
- Elasticity:
  - **Ability of a material to return to its normal shape after being stretched or compressed**
- Compressibility:
  - **Measure of relative volume change of a medium in response to a pressure change**

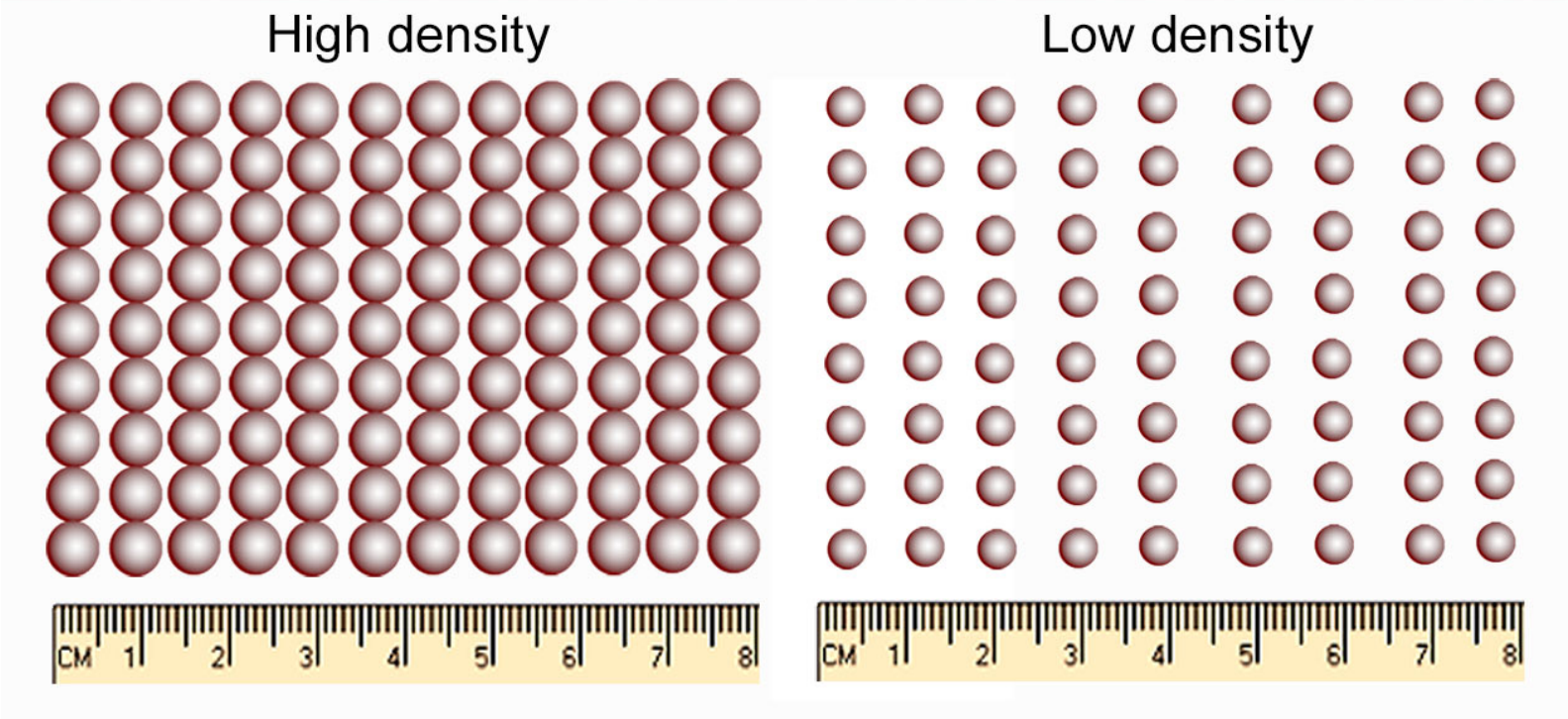
Density

- Mass per unit volume
- In US imaging, it is an important property of the medium (*soft tissue*)
- Has direct effect on US transmission properties
  - **Propagation speed**
- Units of measurement:
  - **g/cm³, kg/M³**

Density
$d = m/V$
d = density m = mass V = volume

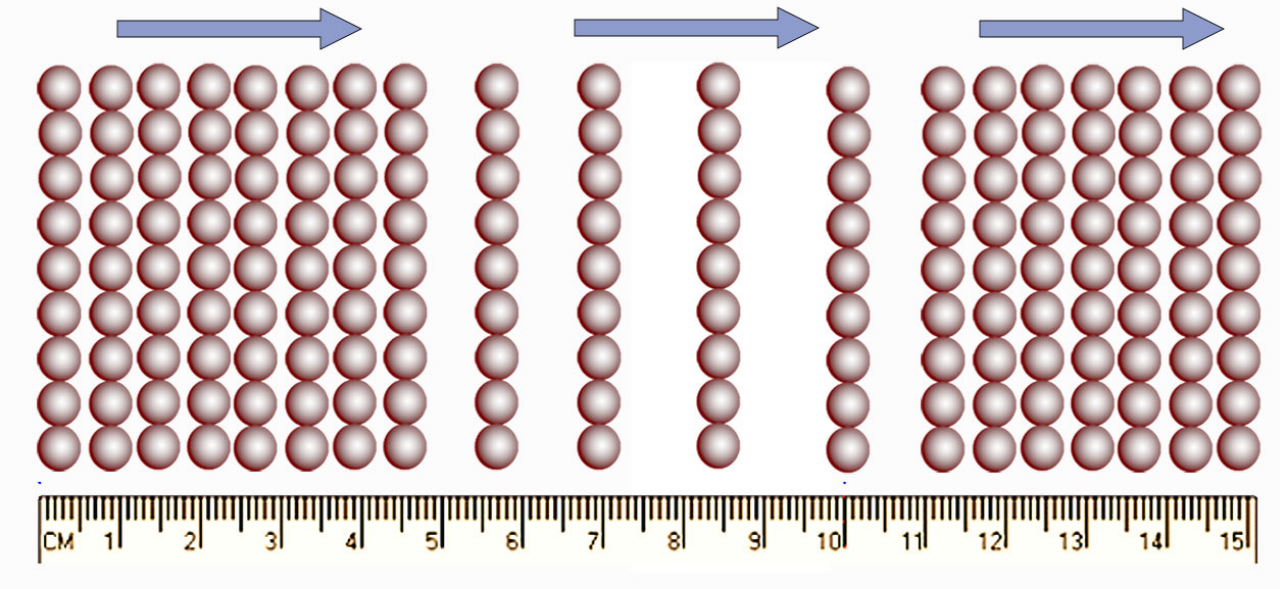


Density



Particle Displacement

- Distance a particle moves after being impinged upon by a force
- Units of measurement:
  - **Meters, cm, mm, μm**



Temperature

- Measure of relative warmth or coolness of an object
- Measurement of relative kinetic energy of a molecules in a medium
- Significance in US imaging
  - **Sound speed varies with temperature of medium (*slightly*)**
  - **Temperature of medium may be increased with introduction of large quantities of acoustic energy (*acoustic bioeffects*)**

The Nature of Sound

Sonography: Acoustics to Images



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