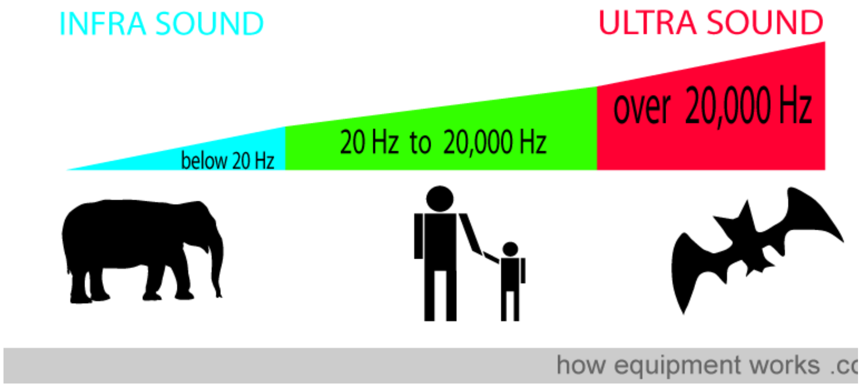
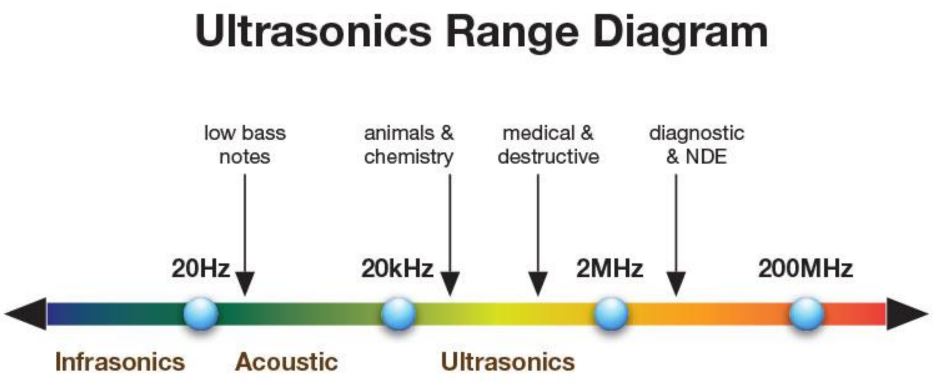
# Utrasound Physics

## 1 – Imaging Physics and Instrumentation

Keith Willson
Clinical Engineering
Royal Brompton and Harefield
NHS Trust

# What is ultrasound?



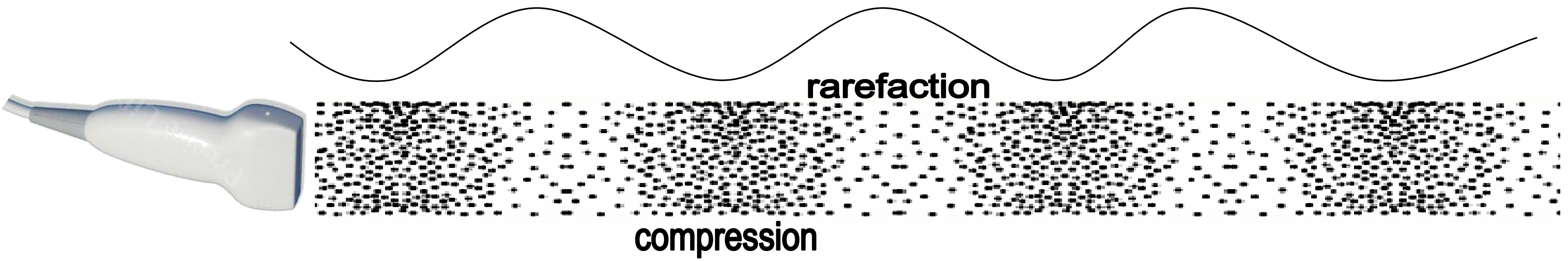



from Wikipedia article on Ultrasound

| | |
|---|---|
| **audible sound:** | **20-20 kHz** |
| **ultrasound:** | **>20kHz** |
| **diagnostic ultrasound:** | **2-12 MHz** |

# What is ultrasound?

Ultrasound is energy! …a vibration! It is not ‘sound’ it is ‘beyond sound’




Ultrasound is transmitted through the body as a longitudinal wave consisting of successive zones of compression and rarefaction.

# The Transducer

**Converts electrical energy into pressure waves on transmission.**

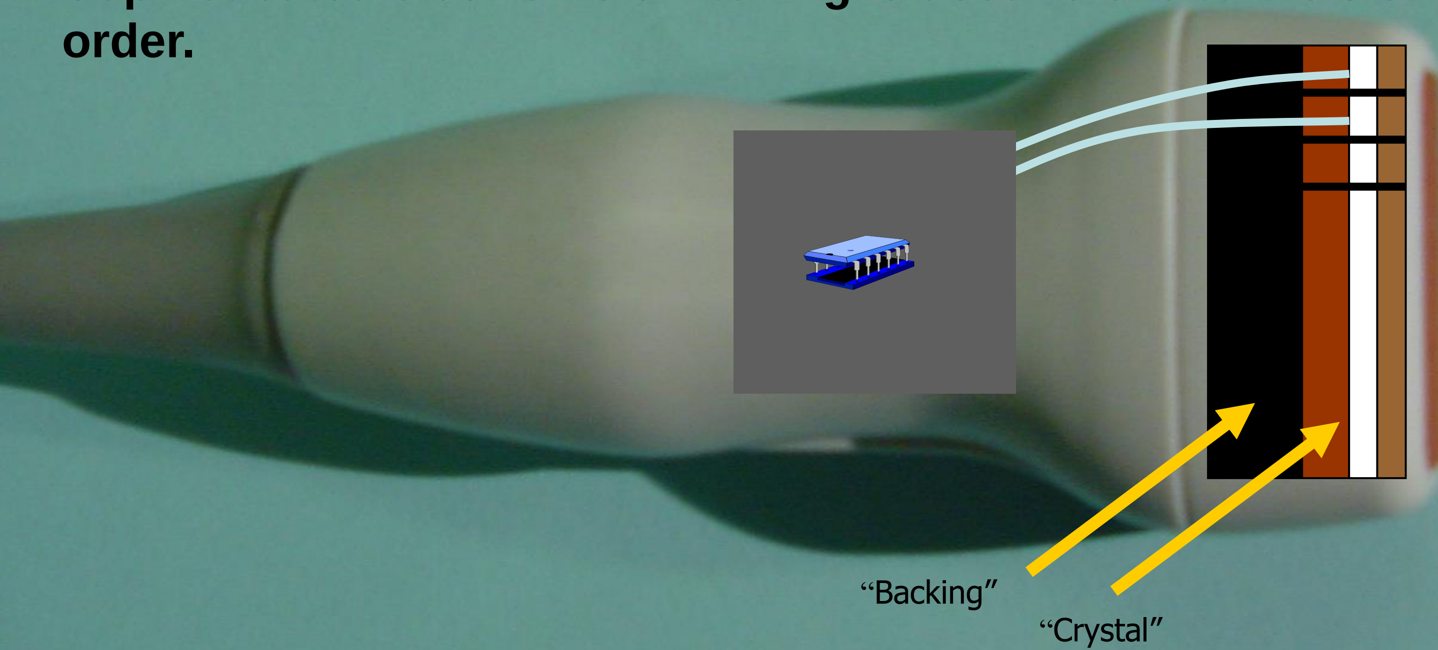

**Converts pressure into electricity on reception**

**Uses the *Piezoelectric Effect***

# The Transducer

**The transducer contains a piezoelectric layer which is sub-divided into smaller elements.**

**Sophisticated electronic switching is used to excite the elements in the right order.**



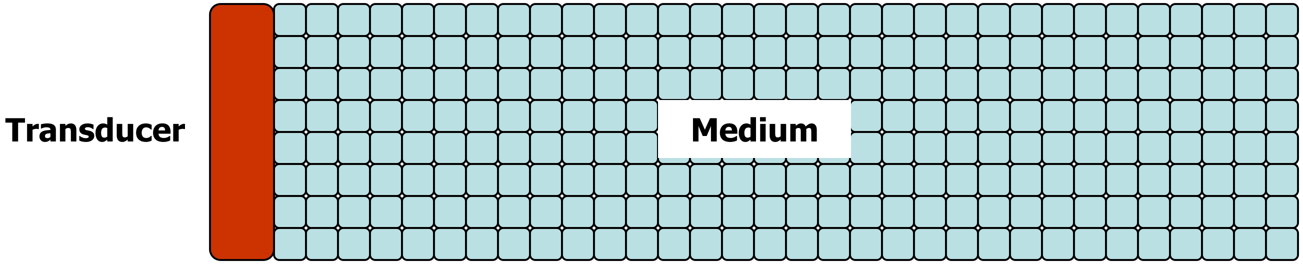

**“Backing” dampens the vibration in the piezoelectric layer– stops it “ringing” and so produces short pulses, also ensures energy is only transmitted forwards**

**Layers at the front of the transducer provide “acoustic matching”, for optimal energy transfer, and protection against damage.**

# Waves - properties

- Frequency
- Wavelength
- Velocity
- Continuous waves
- Pulsed waves
- Amplitude
- Intensity

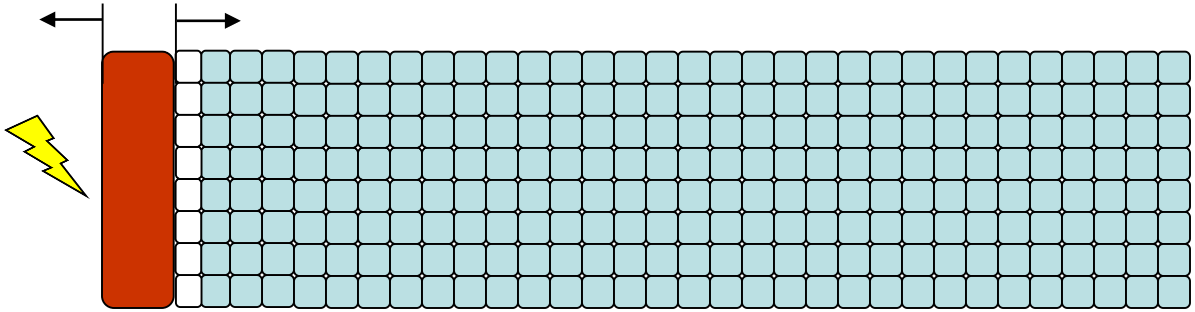
# Waves




The transducer is in contact with a “medium” through which the wave travels

The medium which concerns us is human tissue

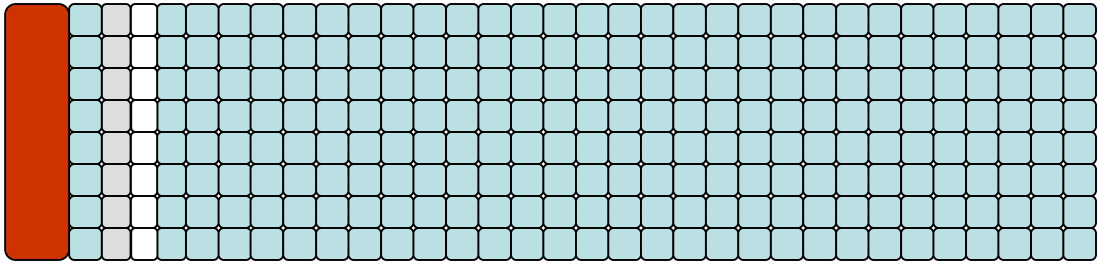
# Waves



An electrical impulse applied to the piezoelectric layer causes a change in thickness

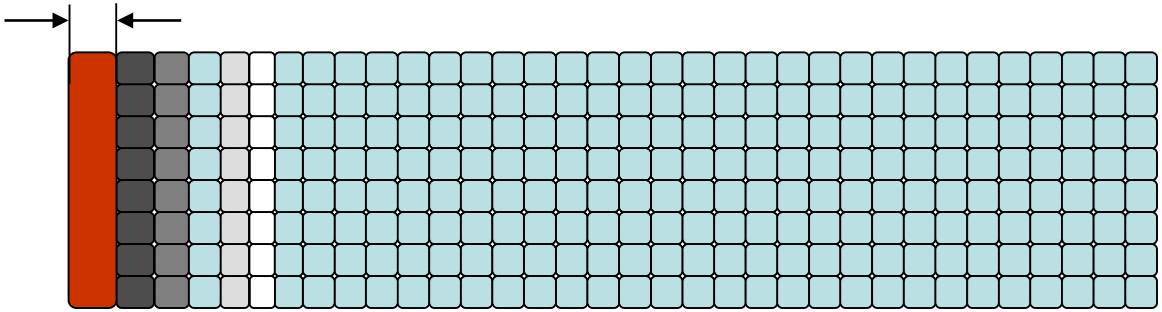
This compresses the tissue in immediate contact with the transducer (white)

# Waves



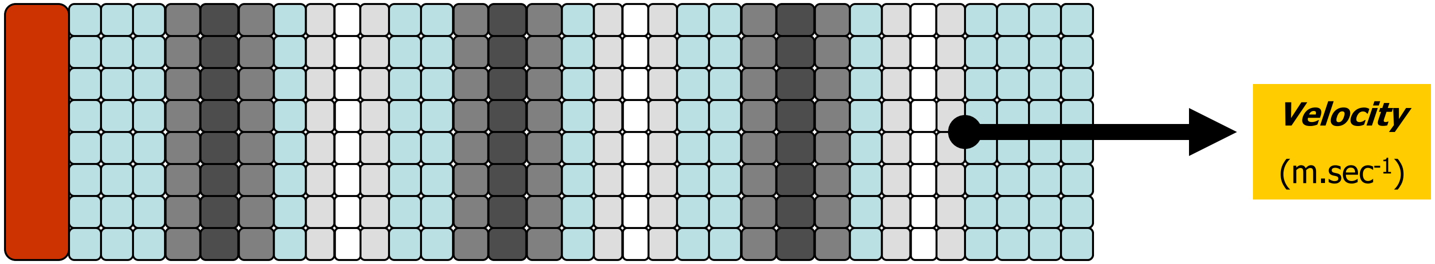
The compression region travels through the medium

# Waves



As the transducer relaxes a region of rarefaction is produced (grey).

# Waves



# Velocity of sound

$$c = \sqrt{\frac{E}{\rho}}$$

- *C velocity $ms^{-1}$*
- *E elastic bulk modulus*
- *p density*

| Material | Speed $ms^{-1}$ (mean *in vitro*) |
|---|---|
| | |
| Air | 330 |
| Fat | 1400 |
| Water | 1500 |
| Assumed soft tissue mean | 1540 |
| Muscle | 1580 |
| Blood | 1580 |
| Transducer PZT | 3000 |
| Tooth | 3600 |
| Bone | 3500 |
| Steel | 4000 |

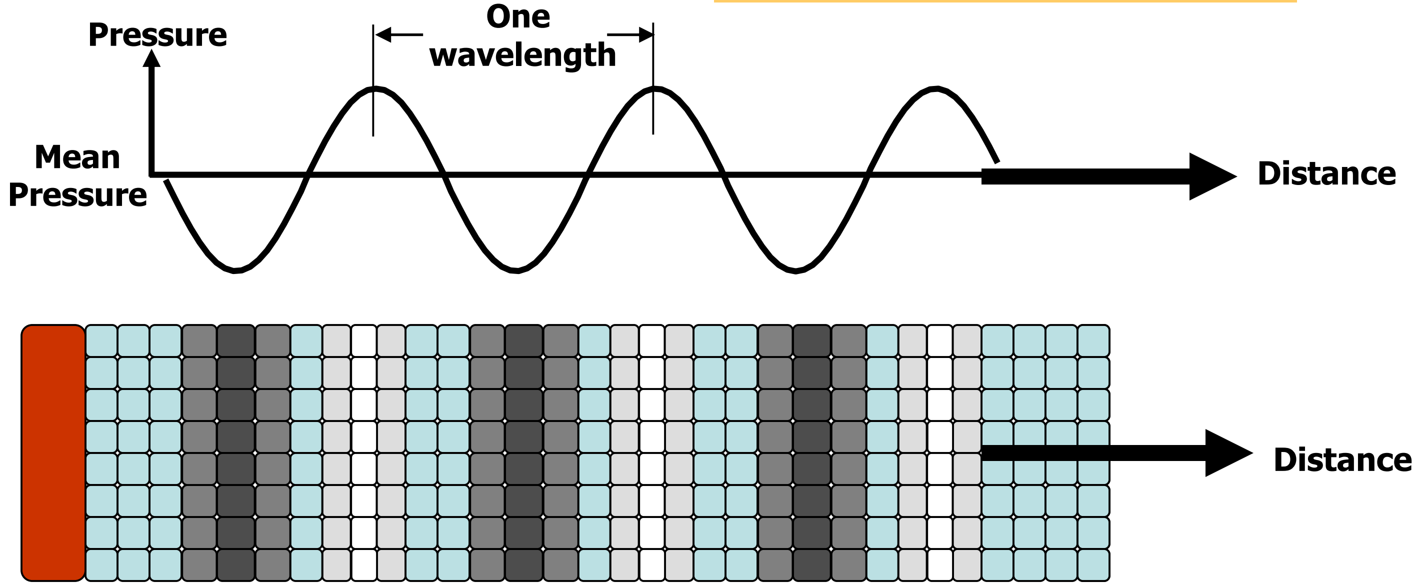
*We are able to produce images because the velocity of sound in all soft tissues is similar, hence the distance of an echo-producing structure can be inferred from the echo return time.*

# Wavelength

Looking along a line in the direction of travel of the wave, we see pressure variations that repeat in a cyclic pattern

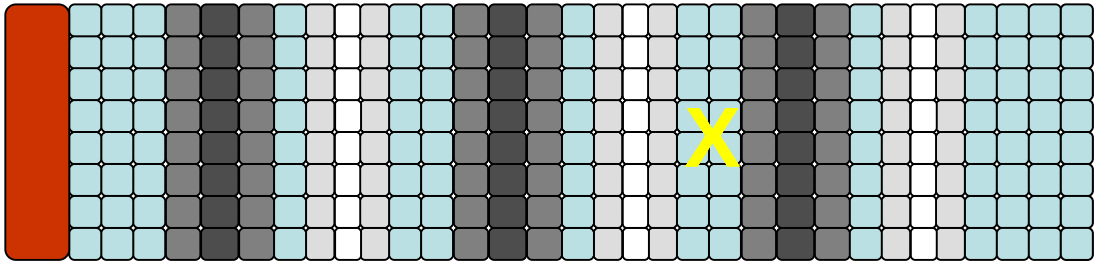
The diagram represents a "snapshot" of the medium at a single instant.

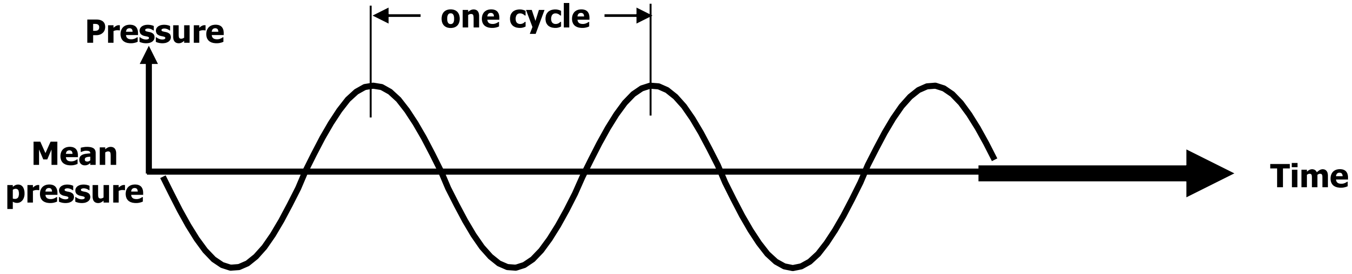
***Wavelength:*** length of a cycle (m);



# Frequency

If we observe how the pressure at a point e.g. “x” changes with time as the wave passes we will see a certain number of cycles passing in a second
- this is the frequency.



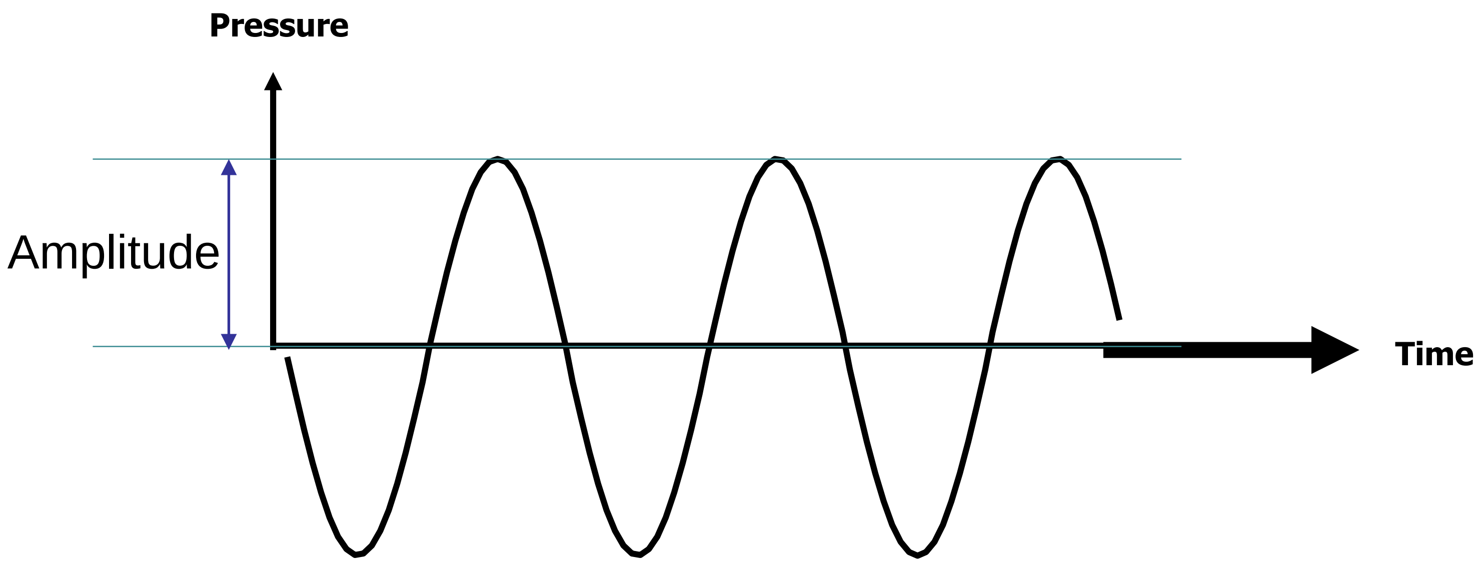




***Frequency*** : cycles per second (Hz)

# Amplitude and Intensity

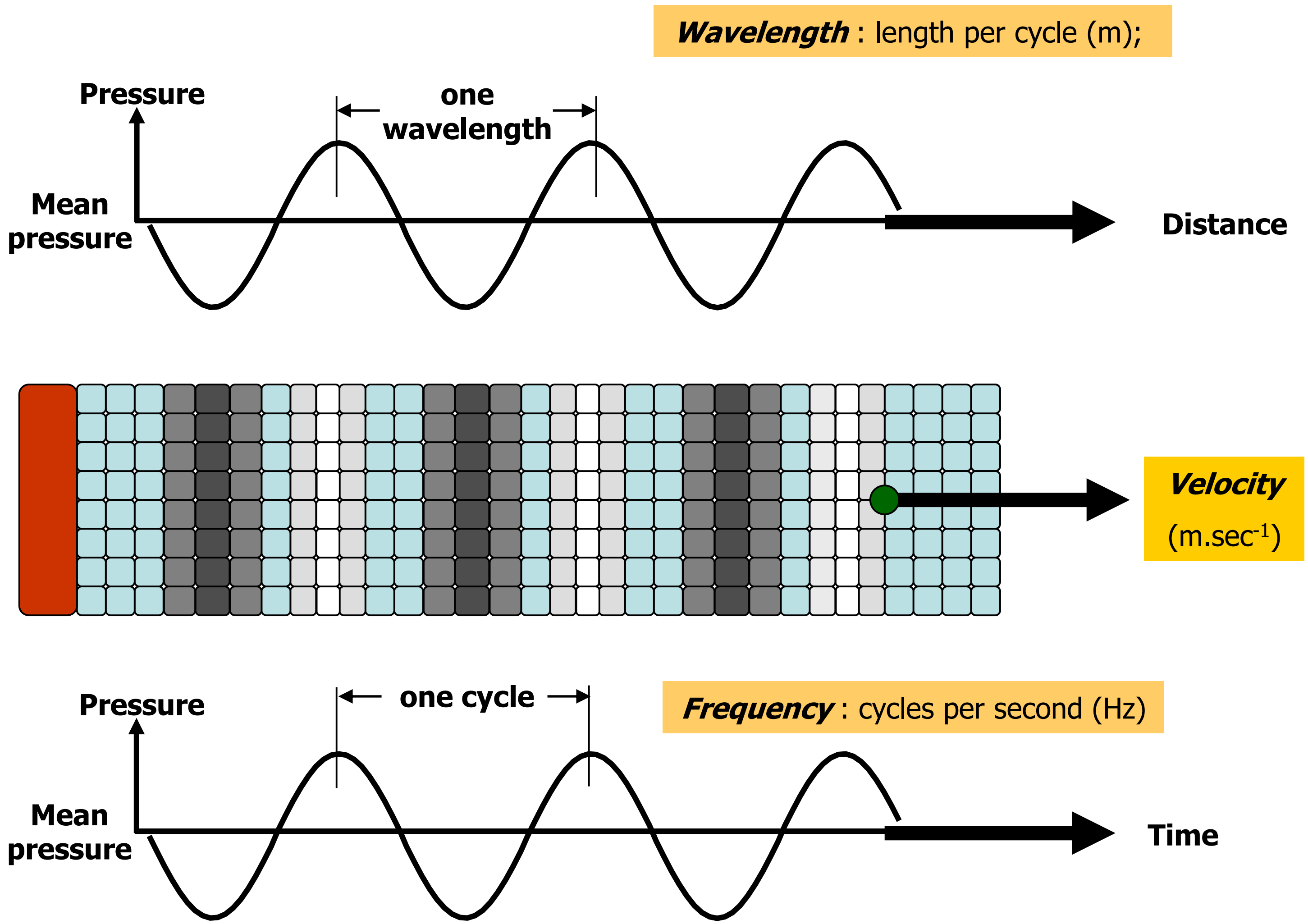
The amplitude is the peak pressure.

The Intensity is the power per unit area in the wave. (It is proportional to the square of the pressure).




***Amplitude*** : peak pressure in kPascal (kPa)

***Intensity*** : power per unit area Watts per square metre ($Wm^{-2}$)




There is a fundamental relationship between velocity, frequency and wavelength: the frequency gives the number of wavelengths passing per second, hence multiplying frequency by wavelength gives the length of wave which passes in one second, i.e. the velocity.

***Velocity***
($m.sec^{-1}$)

***Constant***
(material, frequency, temperature)

***1540***
($m.sec^{-1}$)

***Soft tissue***

= ***Frequency*** : cycles per second (Hz) **x** ***Wavelength*** : length of cycle (m)

***e.g. 3 MHz***

***~ 0.5 mm***

$$C = f\,\lambda$$

- $C$ *velocity* ($m\ s^{-1}$)
- $f$ *frequency* Hz ($s^{-1}$)
- $\lambda$ *wavelength* (m)

Frequency ↑ ⇨ Wavelength ↓

Wavelength ↓ ⇨ Resolution +

The frequency of the ultrasound is important in determining the *resolution*

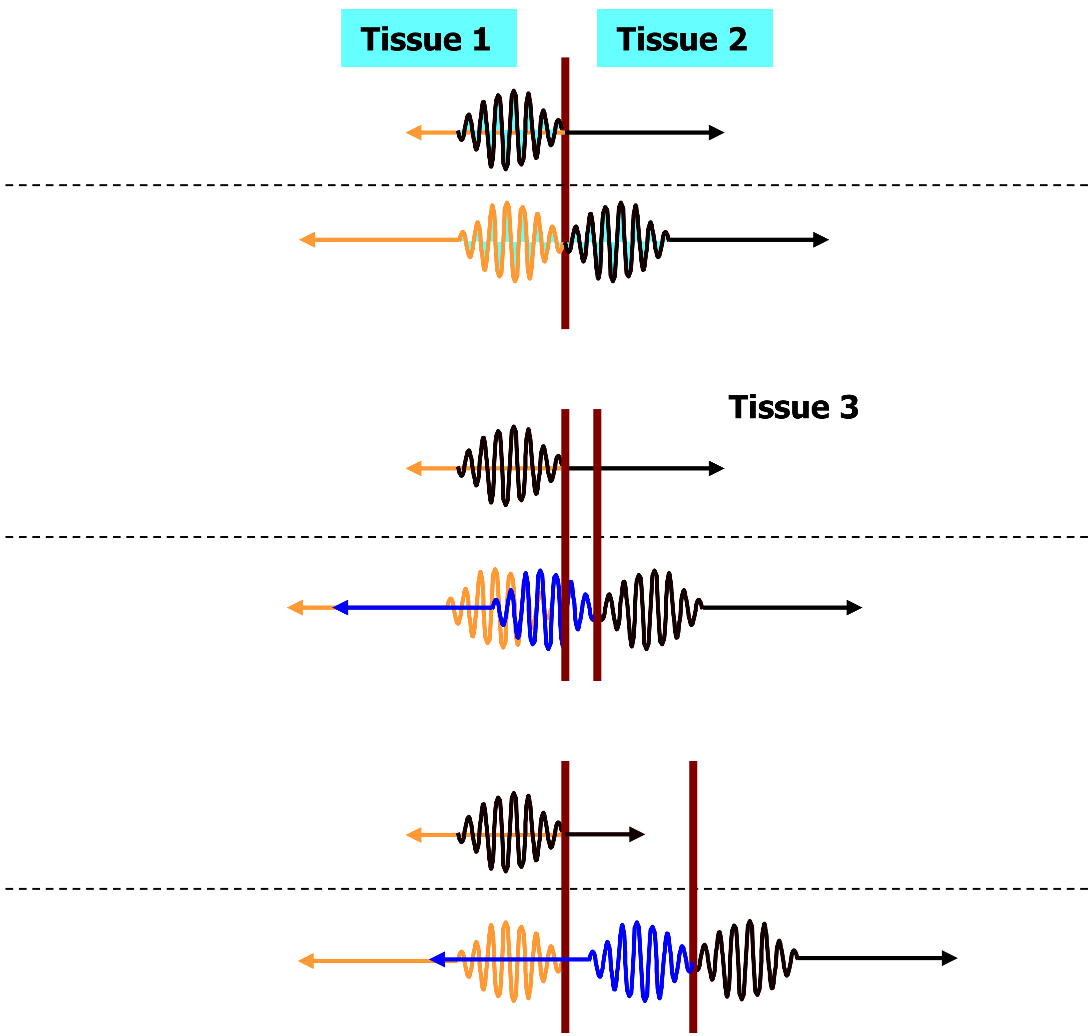
i.e. the ability to resolve fine detail in the image.

# Resolution

- Axial resolution
- Lateral Resolution
- Temporal Resolution

# Axial resolution

- the resolution in the direction of travel of the ultrasound. Depends on the pulse length.
Black – transmitted pulse (travelling left to right), orange and blue - reflected pulses



Frequency ↑ ⇨ Wavelength ↓

Wavelength ↓ ⇨ Resolution +

The frequency of the ultrasound is important in determining the *resolution*

i.e. the ability to resolve fine detail in the image.

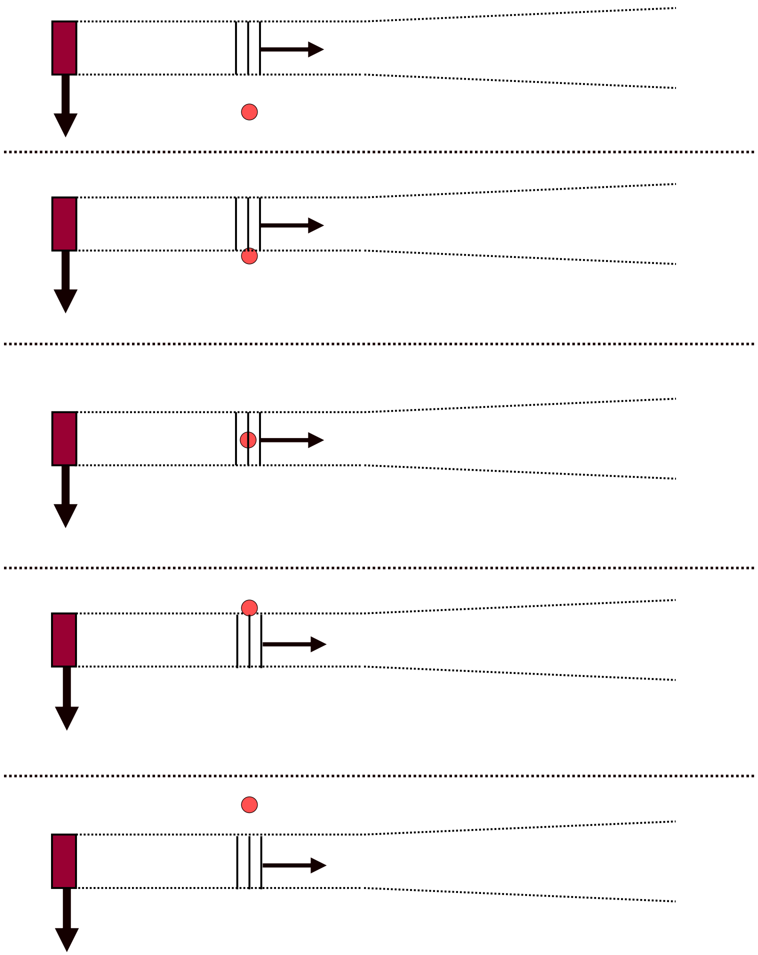
# Lateral Resolution

The ability to resolve scatterers at right angle to the direction of travel of the ultrasound. Depends on the width of the ultrasound "beam".

As the beam sweeps past a scatterer (downwards) it will appear on the image for the whole width of the beam and hence widened.

In the same way that scatterers in the axial direction cannot be resolved if they are closer together than the pulse length, those in the lateral direction cannot be resolved if they are closer together than the beamwidth.

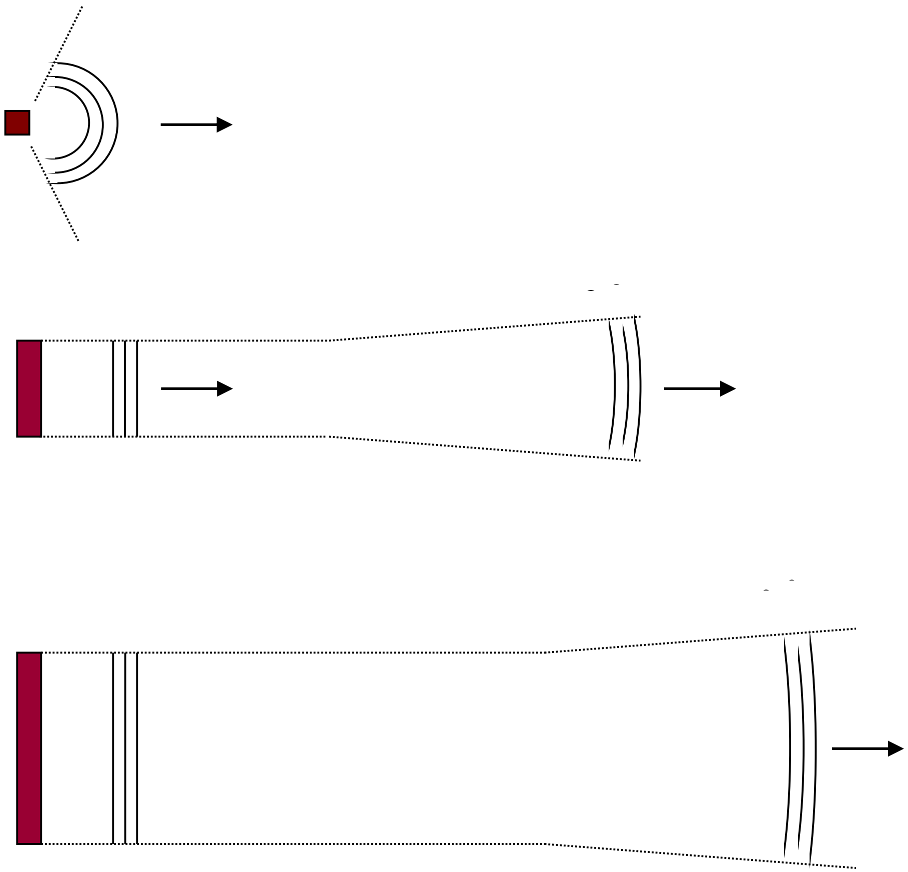
A scan of an ultrasound phantom (next two slides) shows the lateral resolution worsening as the beam spreads.




RMI 403GS


MI:1.4
S3
25 JAN 05
18:04:46
2/0/D/F4
ROYAL BROMPTON
RBH
TEST
2
01193
GAIN 75
COMP 70
18CM
53HZ
P
R
1
3
1 of 1

# Beamwidth



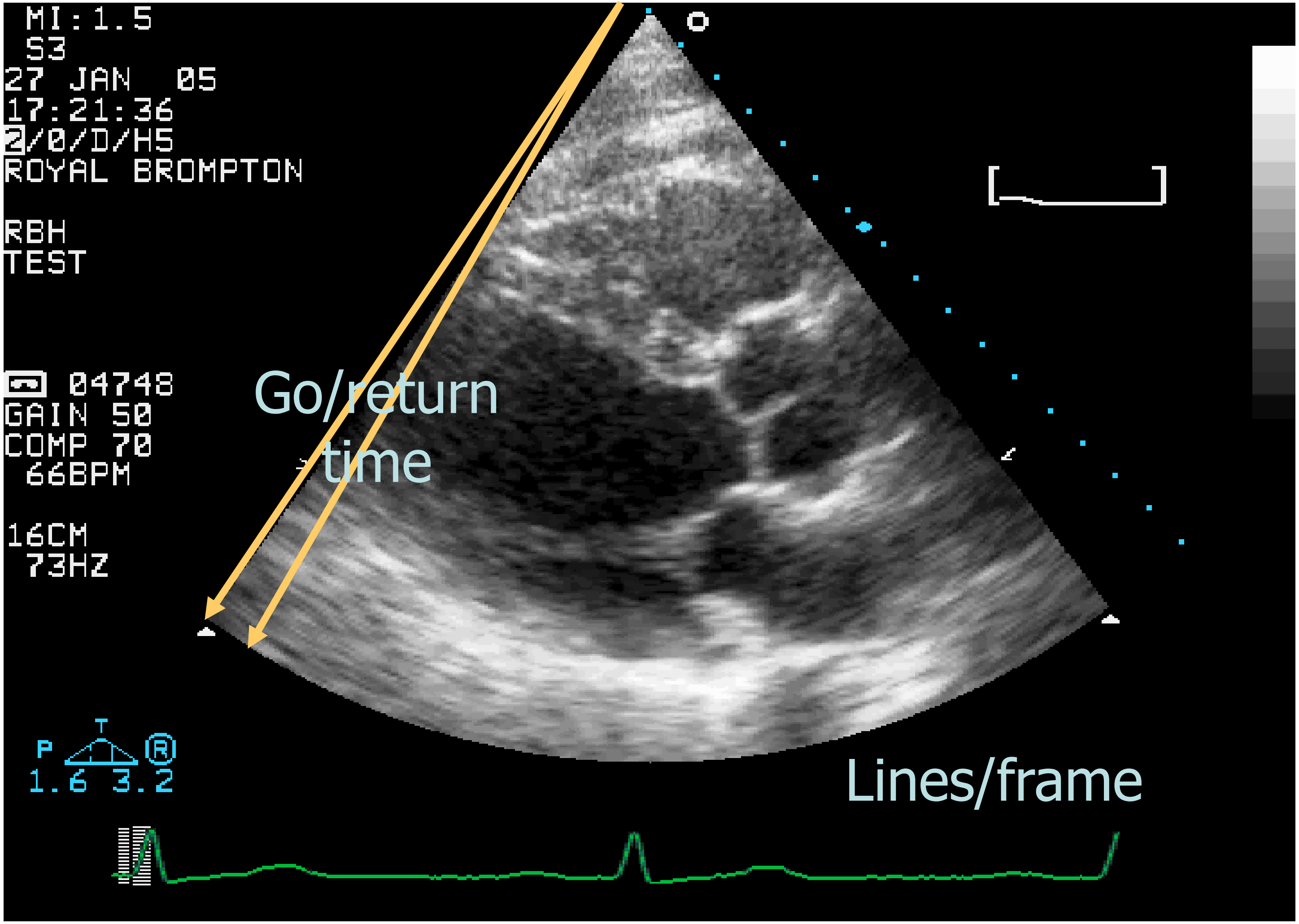
If the transducer is of the order of a few wavelengths, the beam spreads rapidly with distance from the transducer.

For wider transducers of many wavelengths, the beam spreading may be approximated by a near zone – the *Fresnel Zone* in which the beam cam be considered parallel sided, and a far zone – the *Fraunhofer* Zone in which it diverges with a particular angle. Wider transducers give a longer near zone and a smaller angle of divergence.

# Temporal resolution

…. is the ability of the ultrasound machine to accurately determine the position of a moving reflector at a particular time

= FRAME RATE



MI:1.5
S3
27 JAN 05
17:21:36
2/0/D/H5
ROYAL BROMPTON
RBH
TEST
04748
GAIN 50
COMP 70
66BPM
16CM
73HZ
P
1.6 3.2
Go/return
time
Lines/frame

# Temporal resolution: frames and frame rate

FR is reduced when multifocus is in use due to multiple pulses per scan line.

# Temporal vs lateral resolution

To improve frame rate you can:

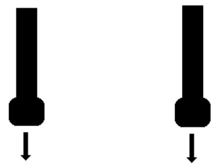
↓ sector width

↓ depth

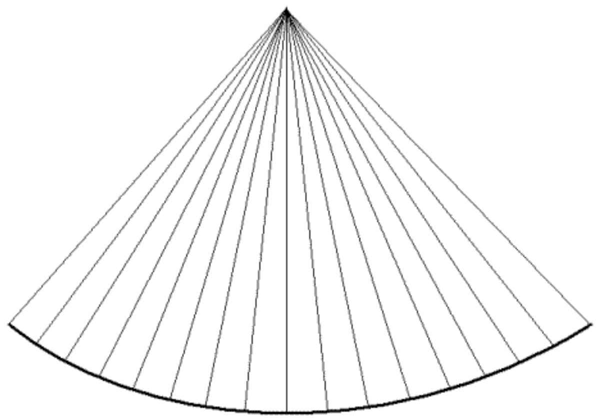
☒ turn off multifocus

Or, reduce line density but this will be at the expense of lateral resolution.

# Temporal resolution: frames and frame rate

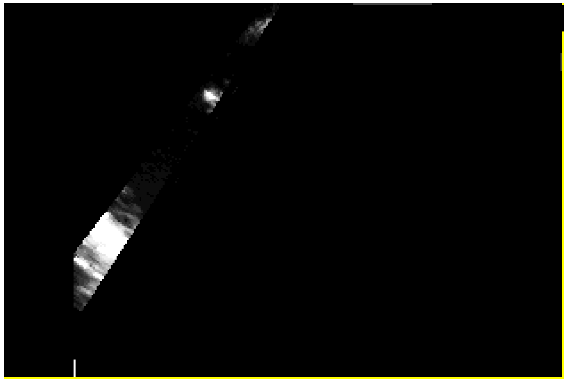


The pulse repetition frequency (PRF) is the number of pulses emitted per second and is dictated by depth so FR is limited by depth.



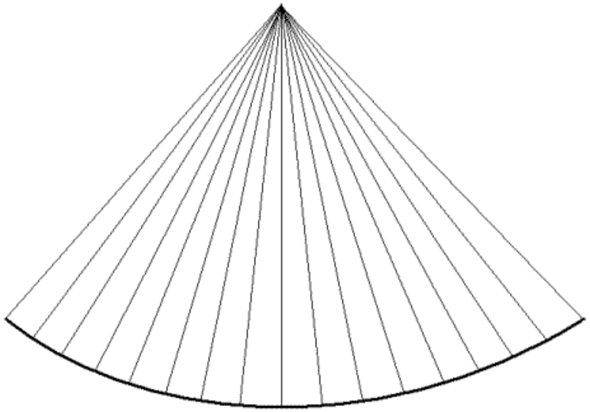
$$PRF_{max} = \frac{c}{2D}$$

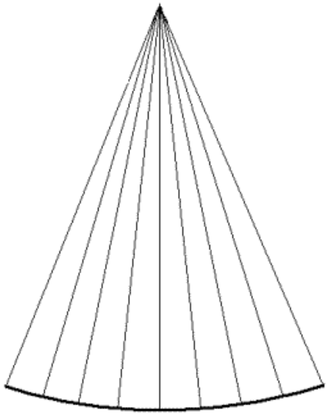
# Temporal resolution: frames and frame rate



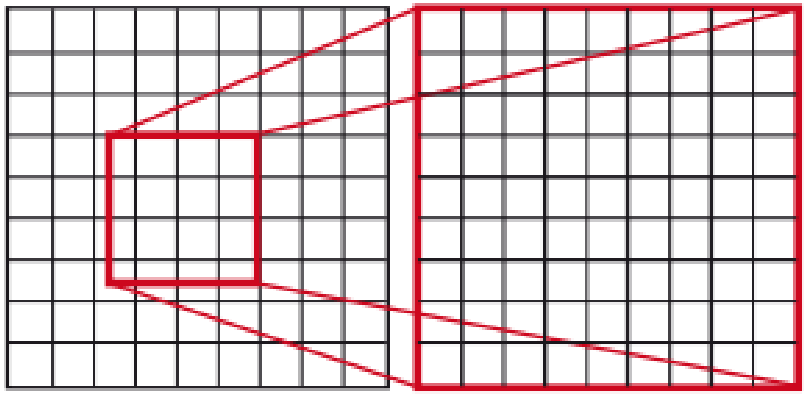
A frame consists of an accumulation of pulses/scan lines.

FR is limited by line density and sector width.





# Write Zoom



↑screen picture size

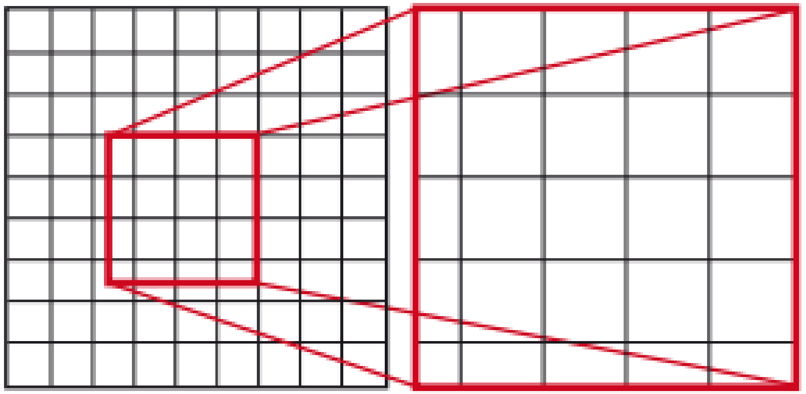
Cropped image

↓width → ↑line density → ↑lat res

↓depth → ↑PRF

Likely ↑ FR

# Read Zoom



↑screen picture size

Whole original image continues to be captured

Pixels magnified

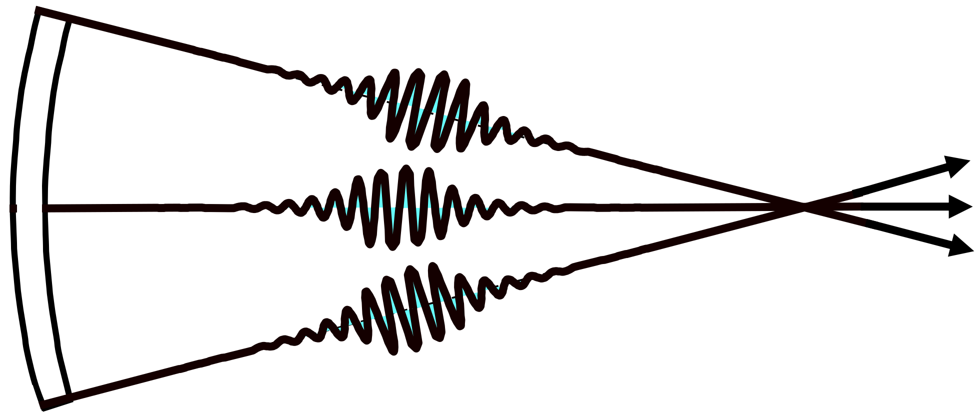
No change in FR/lat res

# Focussing and Beam Steering

- Mechanical focus
- Electronic focus
- Beam Steering

# Mechanical Focussing

$$F = d^2/4\lambda$$



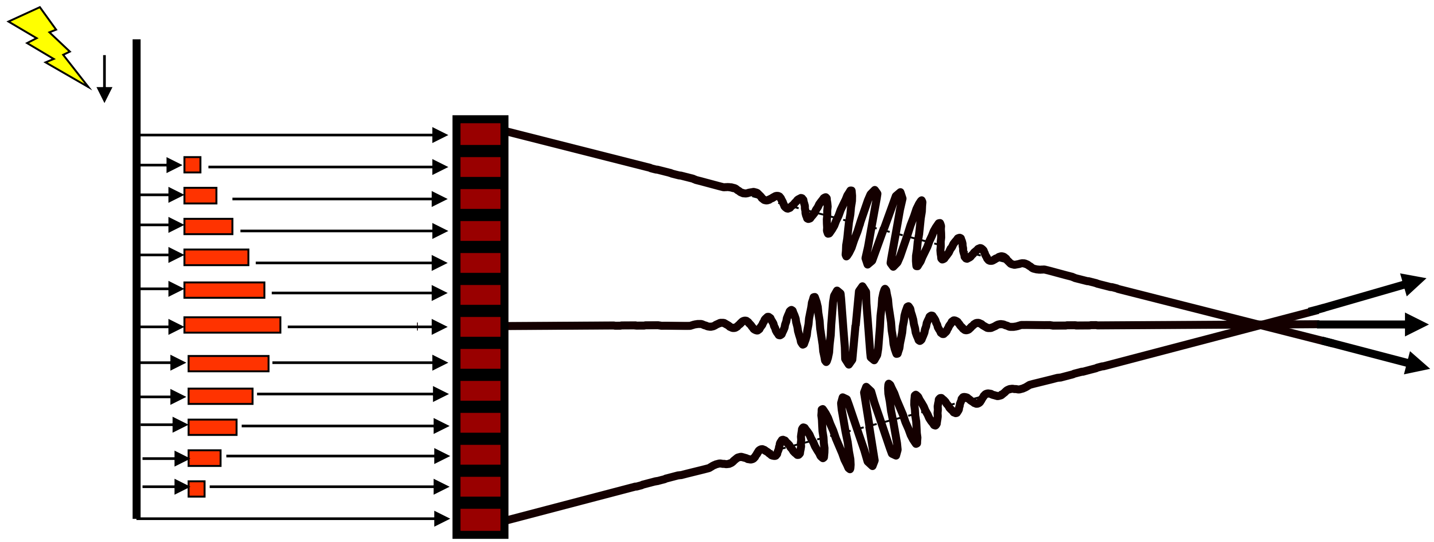
By applying a curvature to the transducer face, the beam can be focussed. This improves the resolution at the focus, but worsens it at locations past the focus.

Mechanical focussing has been superseded by electronic focussing in the plane of the image , but is still applied on 2D transducers in the plane at right angles to this.

The distance of the focus F from the transducer is given by the transducer width d squared divided by four times the wavelength *λ.*

**Slice Thickness** As well as axial and lateral resolution the beam has a thickness at right angles to the plane of imaging.

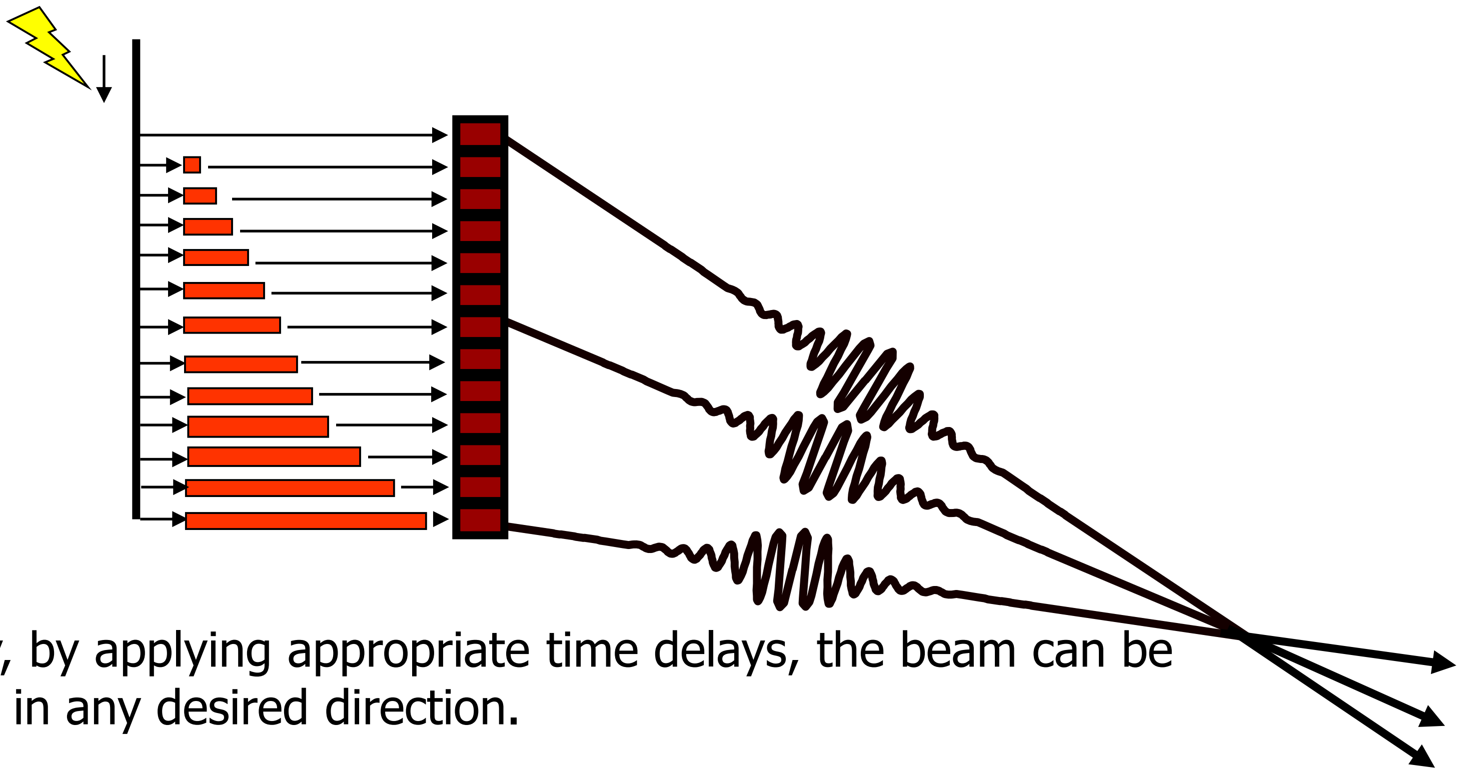
# Electronic Focussing



By cutting the piezoelectric layer into a number of elements, focussing can be achieved by exiting the different elements at different times, such that the ultrasound pulses from all the elements reinforce each other around a focus.

As with mechanical focussing the resolution worsens at locations past the focus, but the advantage of electronic focussing is that the excitation times can be modified to change the focus ; composite images can be built up with more than one focus to improve resolution overall.

# Beam Steering



Similarly, by applying appropriate time delays, the beam can be *steered* in any desired direction.

Steering and focussing can be combined, giving versatile control to build up focussed images simply by changing the excitation delays.

Mechanical movement of the transducer can also be used to steer the beam, but this process is virtually obsolete as electronic systems are much more reliable and can be easily modified by re-programming.

# Frame rate and parallel processing

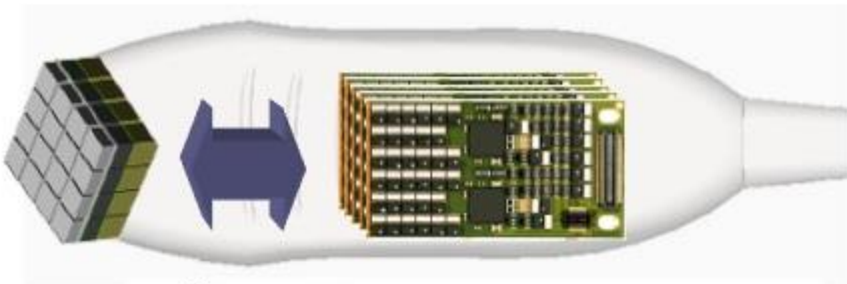
Data acquisition rate limited by speed of sound and therefore PRF.

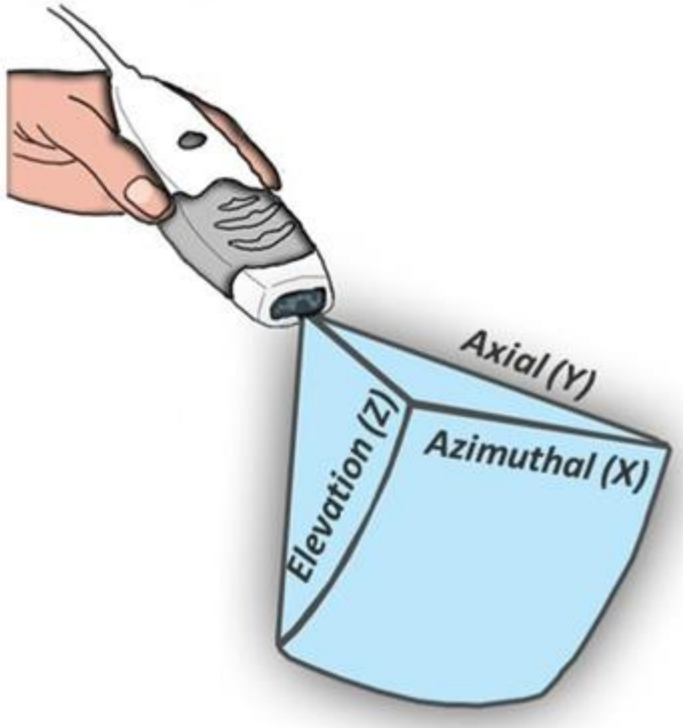
Instead → parallel processing allows multiple lines to be acquired and therefore increases FR and/or line density.

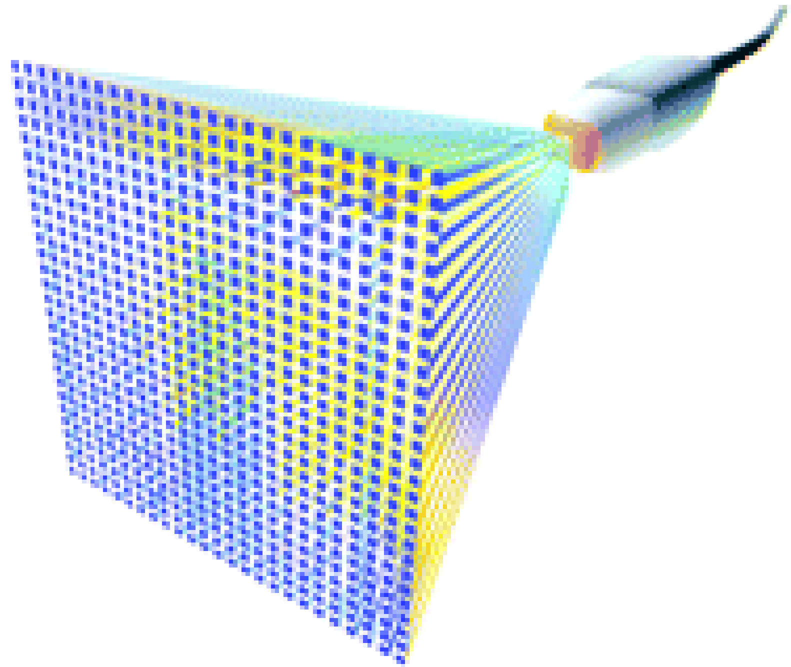
How? transmission of a less focused "fatter" beam then receiving multiple simultaneous “narrow" beams.

Enables the data acquisition rate to increase through the simultaneous acquisition of B-mode image lines from each individual broadened transmit pulse.

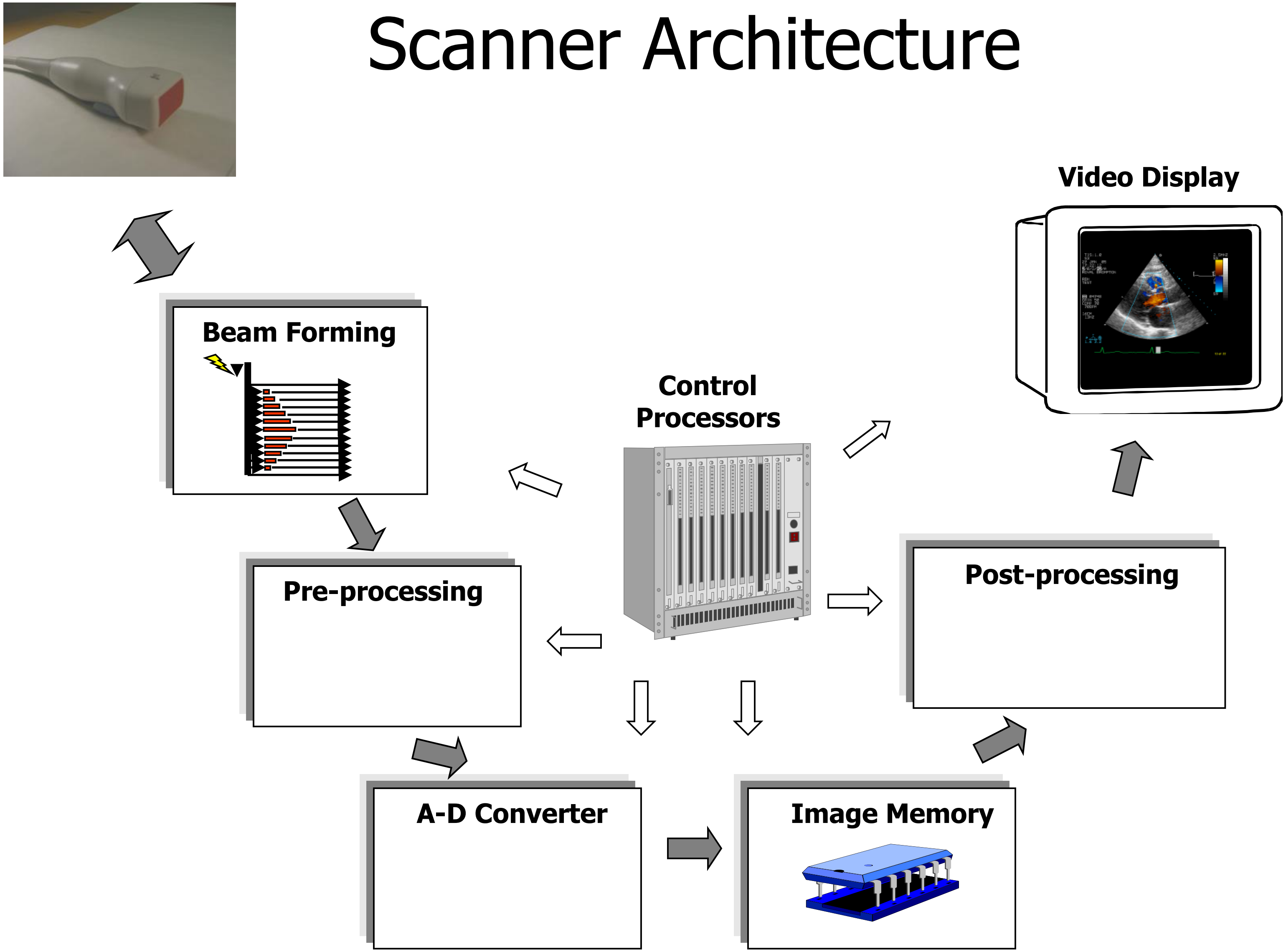
# Matrix Array Transducers





# Scanner Architecture



# Propagation

- Attenuation
- Absorption
- Diffraction
- Scattering
- Reflection
- Refraction

# Attenuation

Ultrasound waves attenuate (i.e. lose energy) due to:

-absorption (heat)

-reflection and scattering (energy redirected by beam spread)

-diffraction (energy redirected)

Measured in decibels (dB) where each 3dB loss is a 50% reduction in intensity.

*Attenuation coefficient in soft tissue = 1dB/cm/MHz*

# Attenuation: absorption

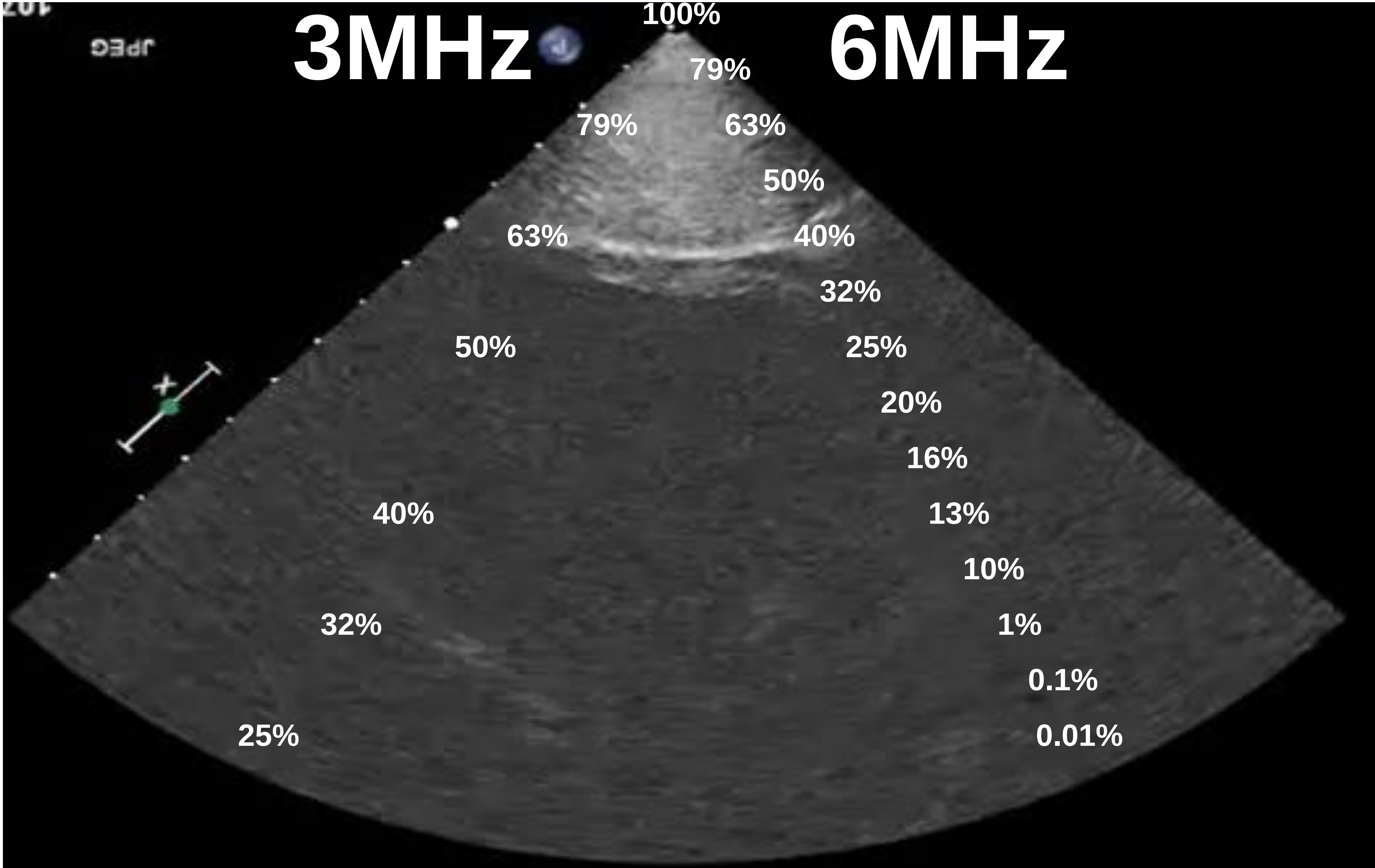
Ultrasound energy dissipates within a media due to energy absorbed as heat.

A higher frequency ultrasound wave causes more molecular motion and loses more energy to absorption (loss to heat).

Therefore at any given depth a higher frequency ultrasound wave will be weaker.

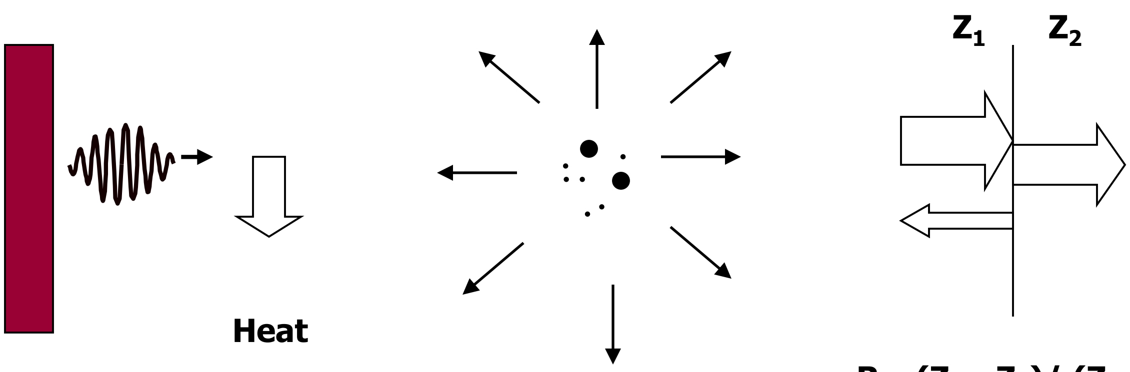
*Attenuation coefficient in soft tissue = 1dB/cm/MHz*

<u>double the frequency, double the rate of absorption</u>



3MHz
6MHz
100%
79%
63%
50%
40%
32%
25%
79%
63%
50%
40%
32%
25%
20%
16%
13%
10%
1%
0.1%
0.01%

**Absorption** **Scattering** **Reflection**




**~ 0.3 dB cm$^{-1}$ MHz$^{-1}$**

**$R = (Z_2 - Z_1) / (Z_2 + Z_1)$**

**Typical ~ 3 %**

**between soft tissues**

# Attenuation: reflection

The strength of the reflected beam is related to the difference in acoustic impedance (Z).

$$\text{Percentage reflected} = [(Z_2 - Z_1)/(Z_2 + Z_1)]^2 \times 100\%$$

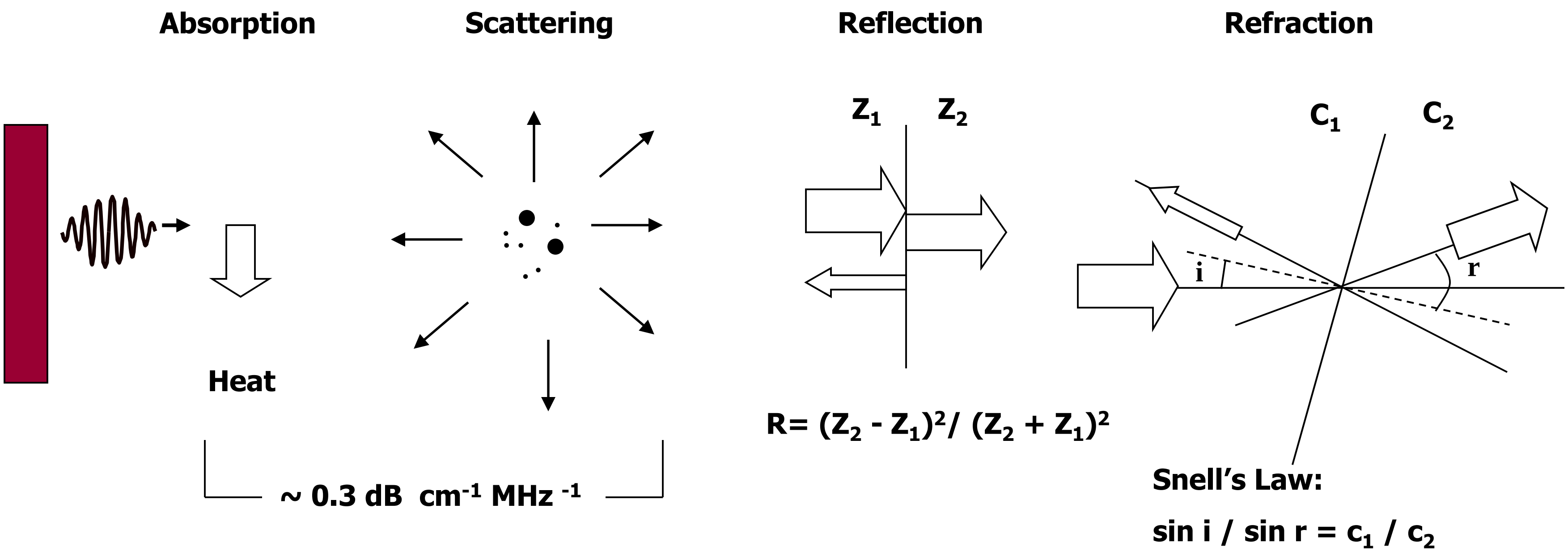
| **Material** | **Acoustic Impedance (Z)** |
|---|---|
| Air | 0.0004 |
| Lung | 0.26 |
| Soft-tissue (avg) | 1.63 |
| Bone | 7.8 |

% reflected at an air/soft tissue interface?

**??**

% reflected at an bone/soft tissue interface?

**??**


Absorption
Scattering
Reflection
Refraction
Heat
~ 0.3 dB cm-1 MHz -1
Z1
Z2
R= (Z2 - Z1)2/ (Z2 + Z1)2
C1
C2
i
r
Snell's Law:
sin i / sin r = c1 / c2

# Practical Implications

**Use**

- Need appropriate ultrasound “Window”
- Use frequency suited to resolution and penetration required
- Need coupling gel

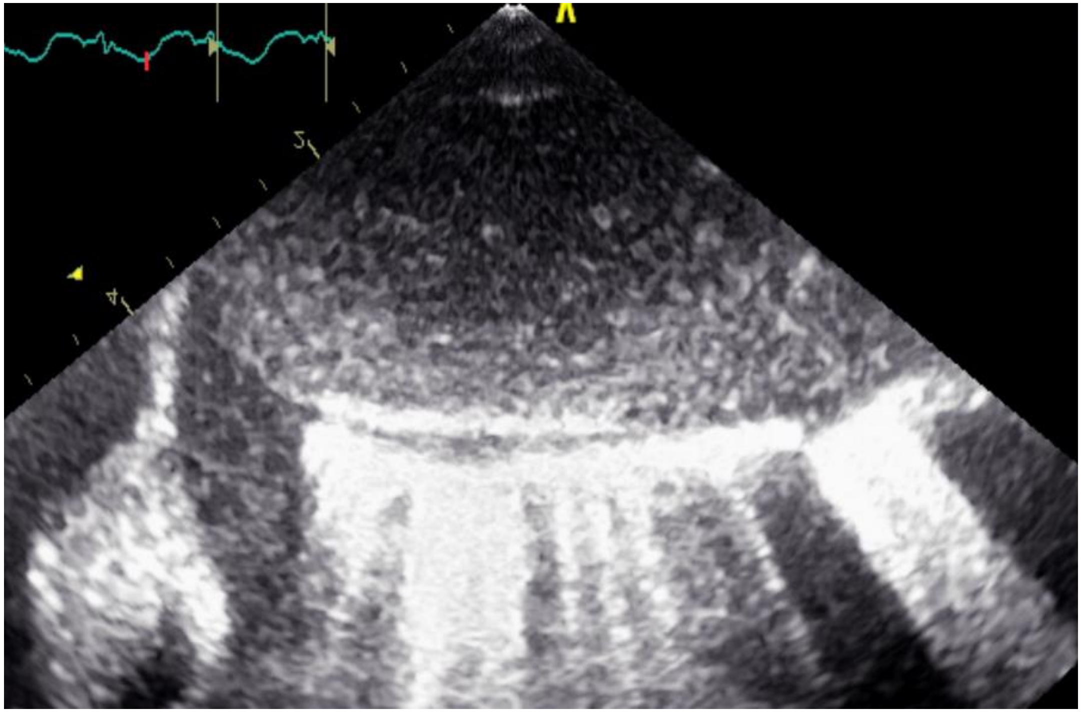
**Artefacts**

- Shadowing
- Specular reflection
- Distortion
- Different image quality at different depths
- Mirror images

# Reverberation artefact

Assumption: ultrasound beam is reflected only once.

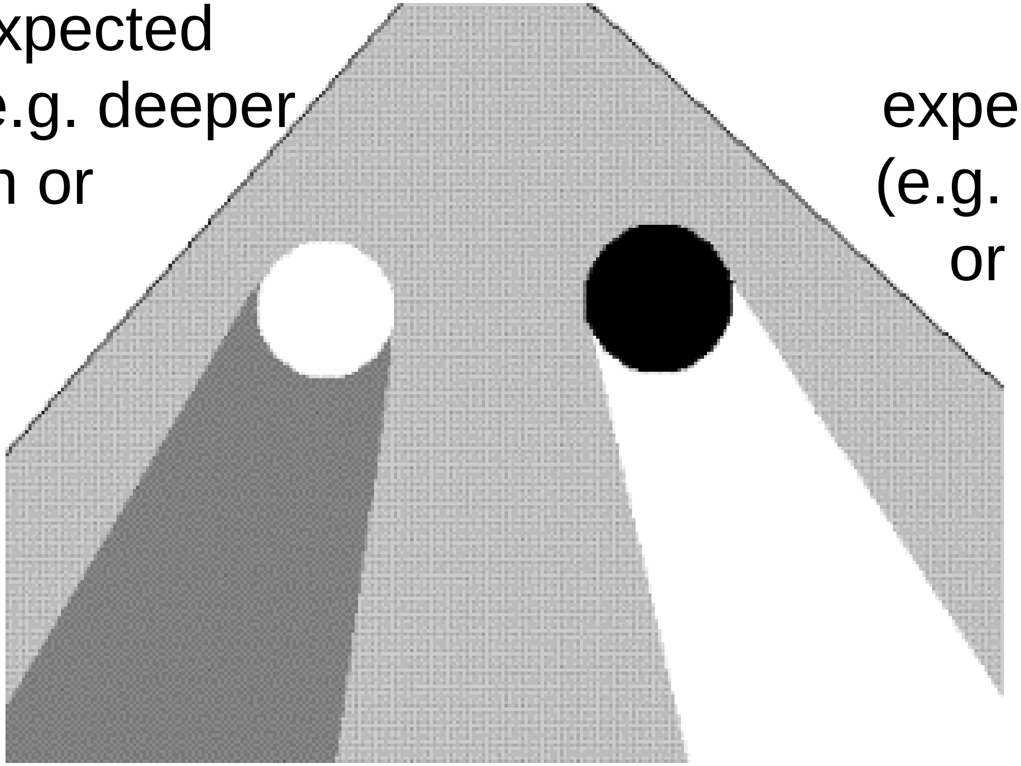
Reverberation artefact occurs when echoes bounce between two highly reflective interfaces resulting in depth perception errors.



# Attenuation artifacts

Acoustic shadow from higher than expected attenuation (e.g. deeper to calcification or prosthesis)

Acoustic enhancement from lower than expected attenuation (e.g. deeper to a cyst or pericardial fluid)



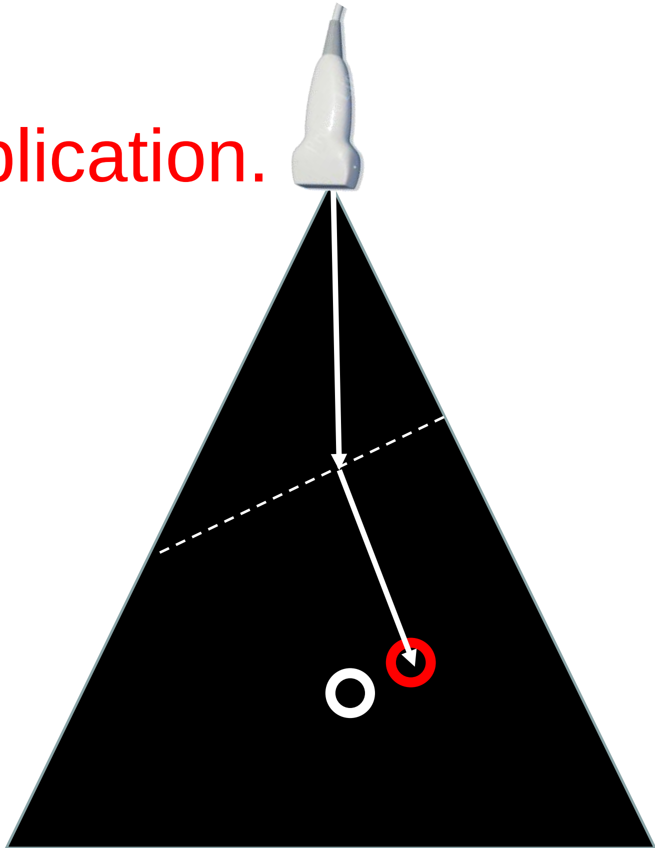
Attenuation assumed to be 1dB/cm/MHz

# Refraction artifact

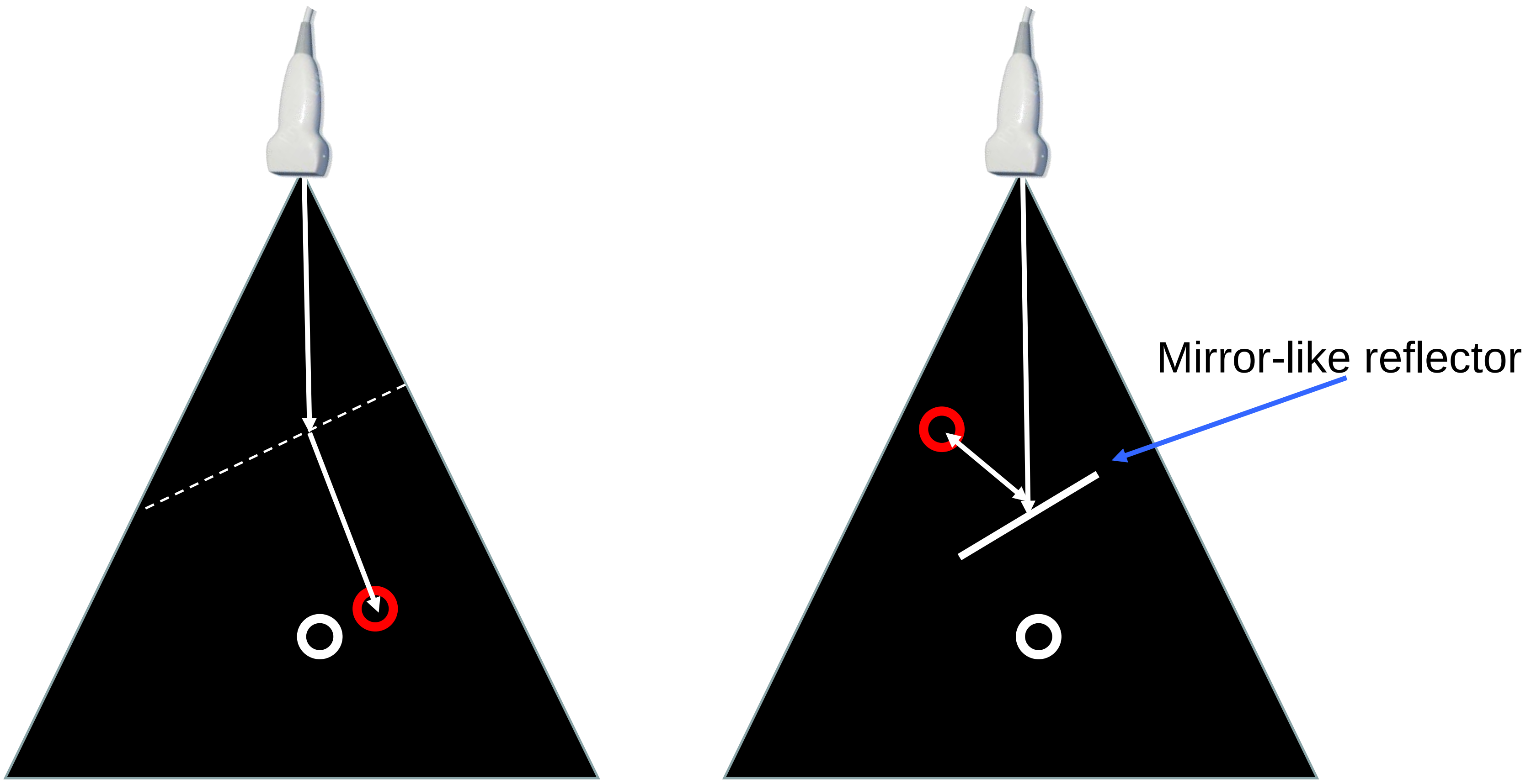
Assumption: ultrasound beam travels in a straight line

Refraction occurs when the ultrasound beam strikes an interface at an angle and where the speed of sound is different (according to Snells Law).

Results in improper placement or duplication.



# Refraction vs mirror image artifacts

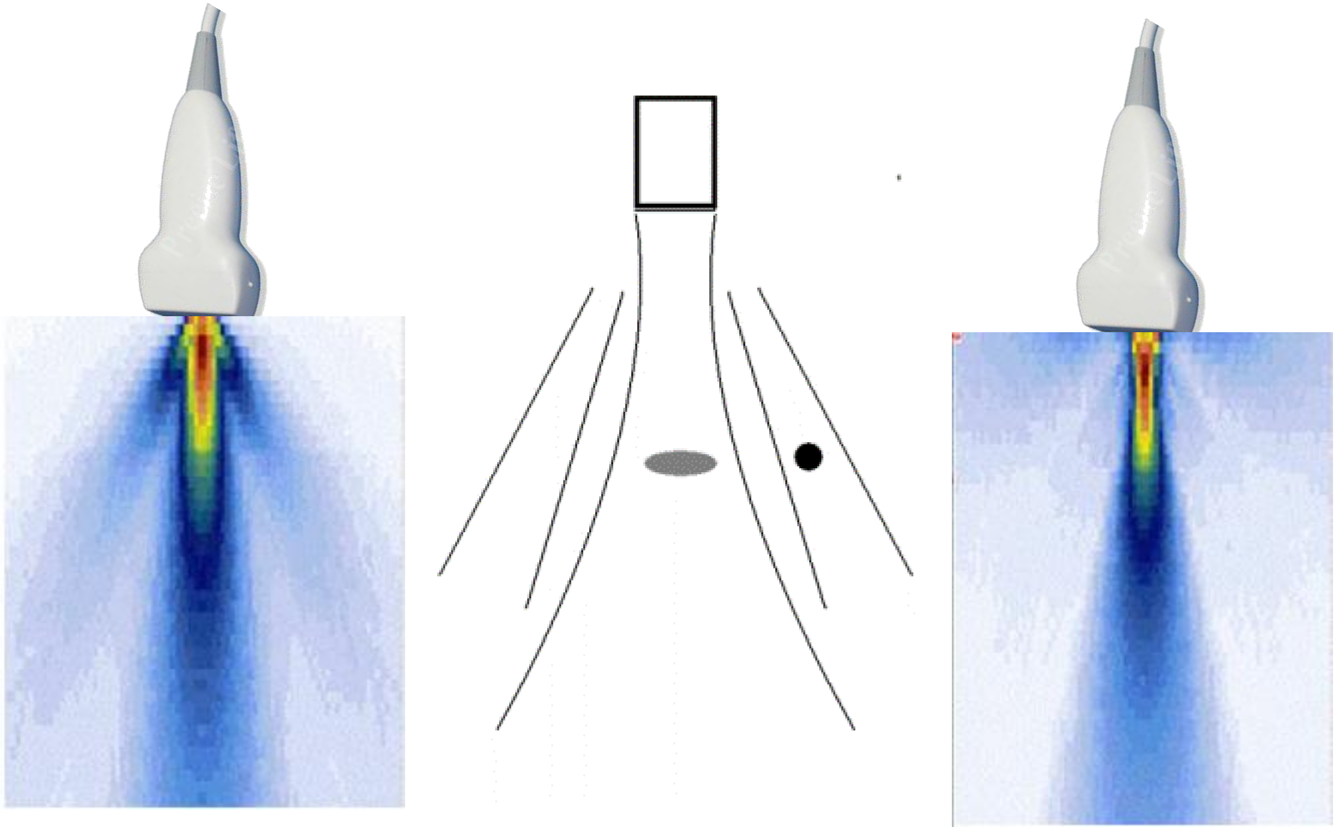



 = actual object, usually displayed in correct position

 = object duplication as displayed

# Transmission: grating artifacts

Assumption: all echos arise from the central axis of the ultrasound beam



# Trade offs

- Penetration
- Resolution
- Frame rate
- Depth
- Line density
- Focus / frame rate