Ultrasound Physics

Part 1. Principles of Ultrasound, Transducers & Signal Generation

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Conflict of Interest

No financial conflicts of interest.

Recommended Sources

1. http://folk.ntnu.no/stoylen/strainrate/Basic_ultrasound#2D
2. Peter Fish, Physics and Instrumentation of Diagnostic Medical Ultrasound. Wiley 1990. (Some instrumentationa chapters are outdated but the physics content and diagrams are excellent).

A signal travelling 2 m/s is used for echolocation.

A pulse is sent out and echos are recieved at 1 and 3 seconds.

How far are the two detected targets from the pulse source?

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A pulse is sent out and echos are recieved at 1 and 3 seconds.
How far are the two detected targets from the pulse source?

- Return path to target #1: 2 m/s x 1 s = 2 m. Distance from source = 2/2 = 1 m.
- Return path to target #2: 2 m/s x 3s = 6 m. Distance from source = 6/2 = 3 m
- Range equation: **Target range (m) = Speed (m/s) x Time (s) / 2**

What is the average speed of sound in human soft tissue in m/s?

- In mm / ms?
- In cm / s?
- In cm / ms?

What is the average speed of sound in human soft tissue in m/s?

In mm / ms?

In cm / s?

In cm / ms?

- 1 540 m/s
- 1 540 mm/ms
- 154 000 cm/s
- 154 cm / ms

What are the approximate velocities in air and bone?

What are the approximate velocities in air and bone?

- 350 and 4000 m/s respectively

As air cools does the speed of sound increase or decrease? Why?
(Assume no change in barometric pressure)

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- Colder, Denser, Slower.
- Velocity of sound **decreases** with the density of the medium, so as air cools velocity of sound decreases.
- Sound in hot air travels faster.
  - Air 0°C: 331 m/s
  - Air 25°C: 347 m/s

Can a transducer generating a continuous tone be used for echolocation? Why/how?

Can a transducer generating a continuous tone be used for echolocation? Why/how?

- In general no, except at the on-set of the tone. After that, echos will be received continuously and the time between signal and echo cannot be measured.
- Only **pulses** can be used for echolocation.

https://youtu.be/p08Y0oRAX3g

Why does the frequency of the pulses speed up as the bat gets closer?

If using ultrsound pulses, how long do we need to wait between sending out pulses, if we are interested in all target within a distance ***d*** from the transducer?

What happens if we send out pulses more often?

If using ultrsound pulses, how long do we need to wait between sending out pulses, if we are interested in all target within a distance ***d*** from the transducer?

What happens if we send out pulses more often?

- We need to wait long enough for the signal to reach any potential targets at distance *d* and return. This is the Pulse Repetition Period (*PRP*).

$$PRP[s] = Return\ trip\ time\ distance\ d = \frac{2 \times d[m]}{1540[m/s]}$$

- Sending out another pulse before that will cause **range-ambiguity**: we will not know if the echo we received is from the first pulse or the second pulse.

How does the pulse repetition period (PRP) relate to pulse repetition frequency (PRF)?

If PRP is given in seconds, what are the units of PRF?

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If PRP is given in seconds, what are the units of PRF?

- They are inversly related. Each is the reciprocal of the other.
- If PRP is in seconds 1/PRP will be in s^{-1} or Hertz (Hz)

How does the frequency of pulses, Pulse Repetition Frequency (**PRF**) relate to the maximum distance/depth of imaging?

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$$PRP[s] = Return\ trip\ time\ distance\ d = \frac{2 \times d[m]}{1540[m/s]}$$

$$PRF[Hz] = 1/PRP[s] = \frac{1540[m/s]}{2 \times d[m]}$$

$$PRF[Hz] = \frac{1540[m/s]}{2d[m]} = \frac{154000[cm/s]}{2d[cm]} = \frac{770[cm/s]}{d}$$

https://youtu.be/p08Y0oRAX3g

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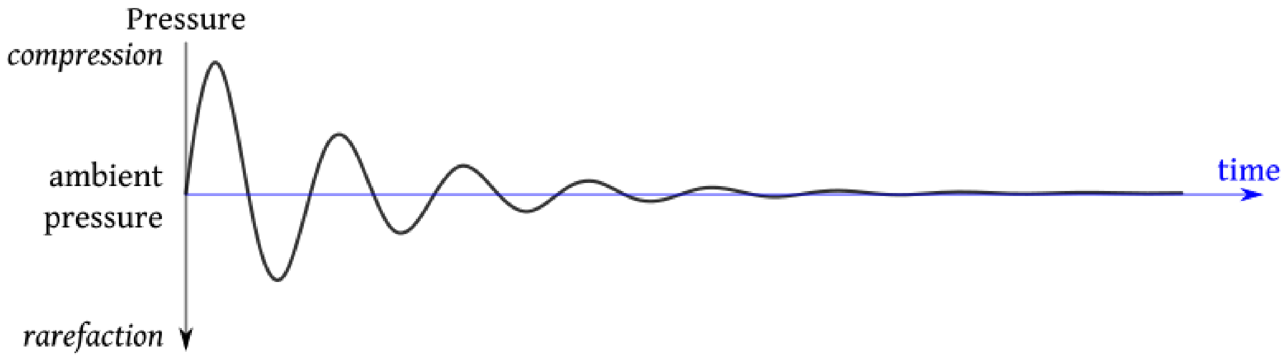
https://youtu.be/p08Y0oRAX3g

Why does the frequency of the pulses speed up as the bat gets closer?

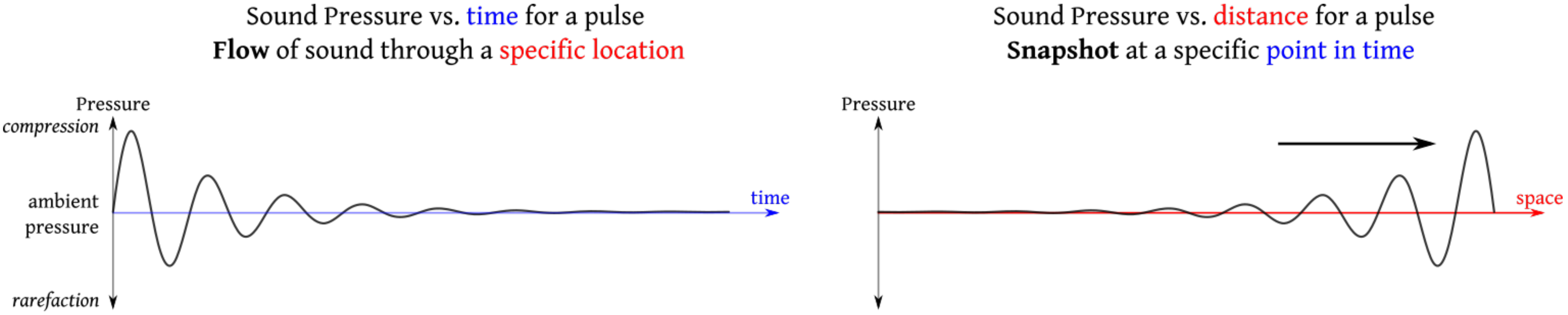
$$PRF[Hz] = \frac{pulse\ velocity}{2 * depth}$$

Sound Pressure vs. time for a pulse
Flow of sound through a specific location

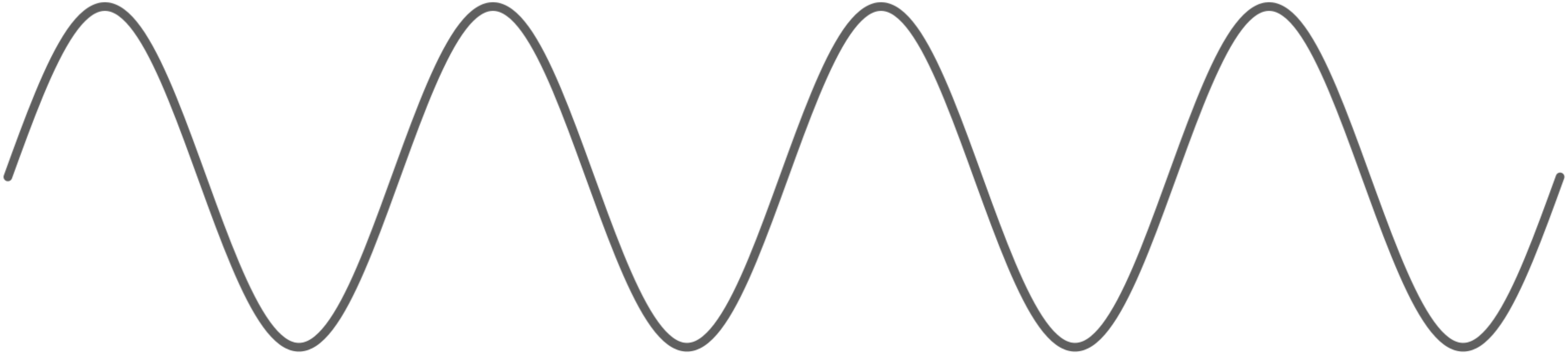


This diagram shows a sound pulse in the time domain. The curve represents the changes in sound pressure at a specific location over time. The pressure variations start out large and vanish over time.

Draw the same pulse in the distance (space) domain. That is draw a temporal snapshot of the sound pressure vs. distance with the pulse travelling from left to right.



The same sound pulse shown in the time and distance (space) domains.



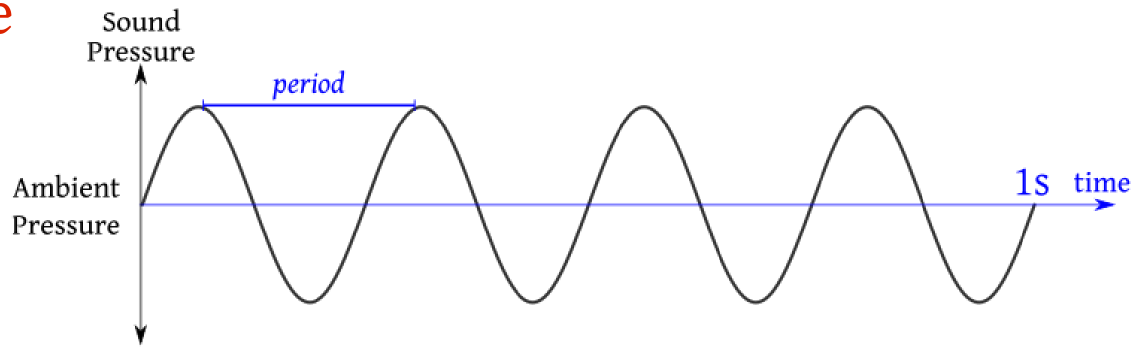
Ceci n'est pas du son

Picture a horse crossing the finish line in a race. In what order to the horses parts cross the finish line?

What is the frequency (*f*) of the wave shown?

What is the period (P)?

What information is needed to calculate the wavelength?



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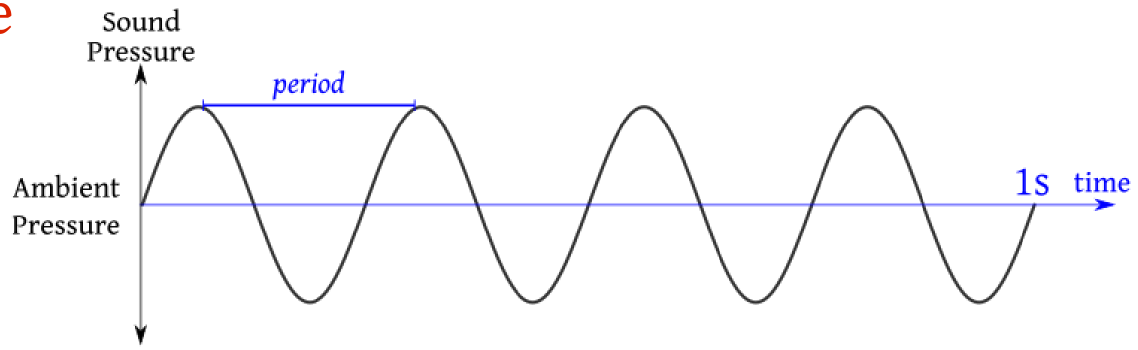
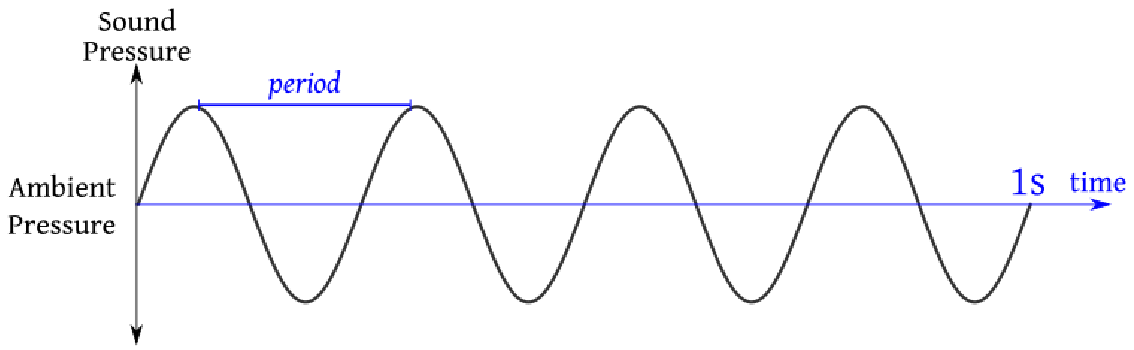


- $f = 4$ Hz
- $P = 1/f = 0.25$ seconds
- The wave velocity is needed to calculate the period.

What is the wavelength (λ) if the sound wave shown is travelling in air?



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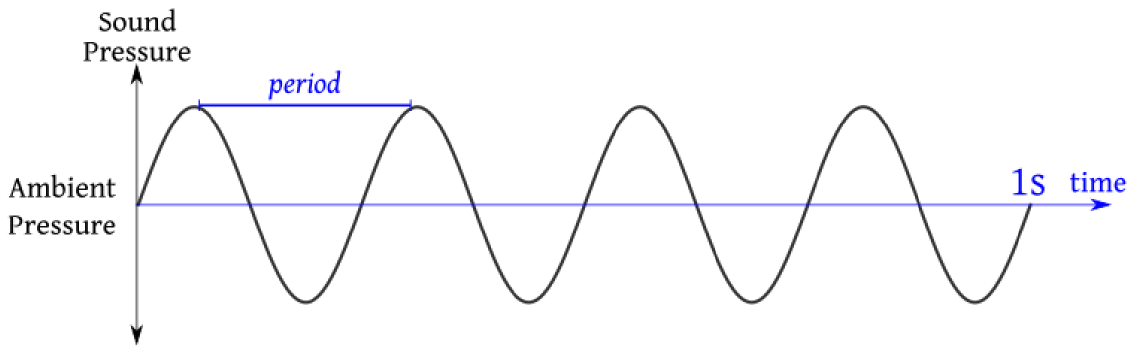
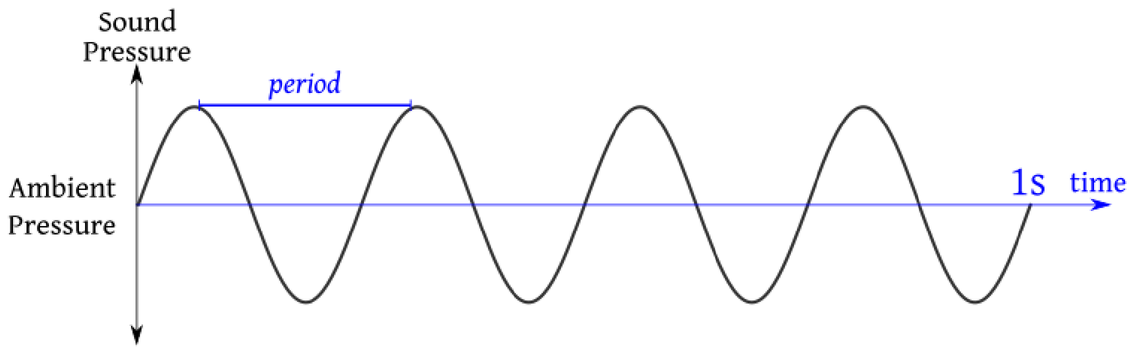


- Velocity (c) of sound in air ~350 [m/s]
- In one period the wavefront moves one wavelength (λ)

so $\lambda = c/f = P$ x c = 0.25 [s] x 350 [m/s] = 87.5 [m]

$$\lambda * f = c$$

What is the wavelength (λ) if the sound wave shown is travelling in tissue?



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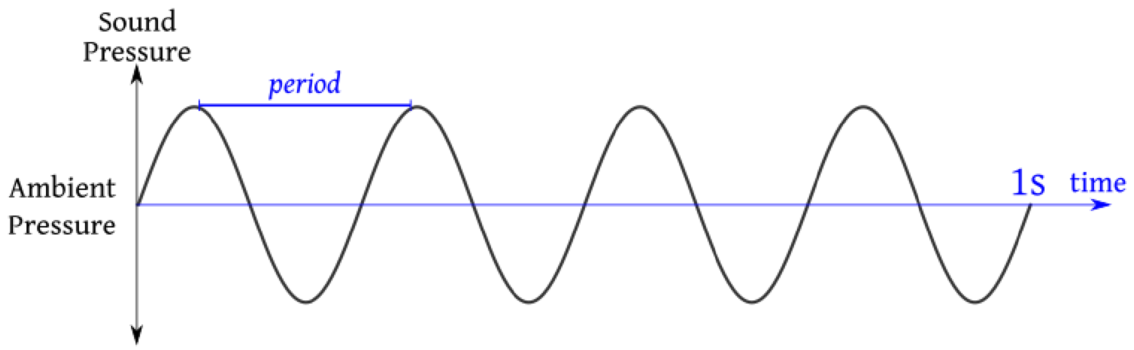


- Velocity (c) of sound in soft tissue 1540 [m/s]
- In one period the wavefront moves one wavelength (λ)

so $\lambda = c/f = P$ x c = 0.25 [s] x 1540 [m/s] = 385 [m]

$$\lambda * f = c$$

What is the wavelength of a 7 MHz ultrasound signal travelling through soft tissue?

What is the wavelength of a 7 MHz ultrasound signal travelling through soft tissue?

- $\lambda = c\,/\,f = 1540\ [\mathrm{m/s}]\ /\ 7{,}000{,}000\ [1/\mathrm{s}] = 0.00022\ \mathrm{m} = 0.22\ \mathrm{mm}$

What is the wavelength of a **3.5** MHz ultrasound signal travelling through soft tissue?

What is the wavelength of a **3.5** MHz ultrasound signal travelling through soft tissue?

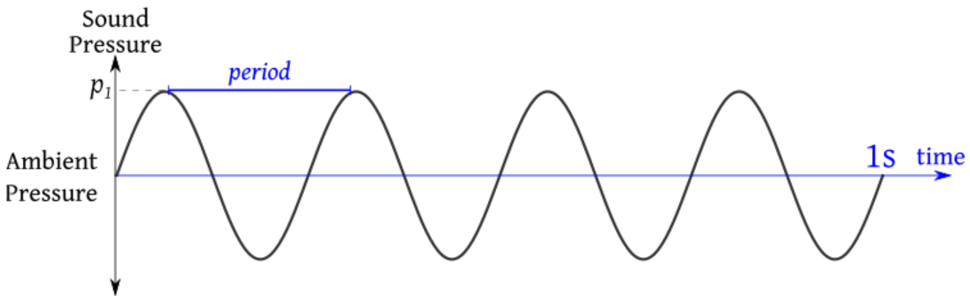
- Twice the wavelength of the 7 MHz signal 0.22 x 2 = 0.44 mm
- 1540 [m/s] / 3,500,000 [1/s] = 0.00044 m = 0.44 mm

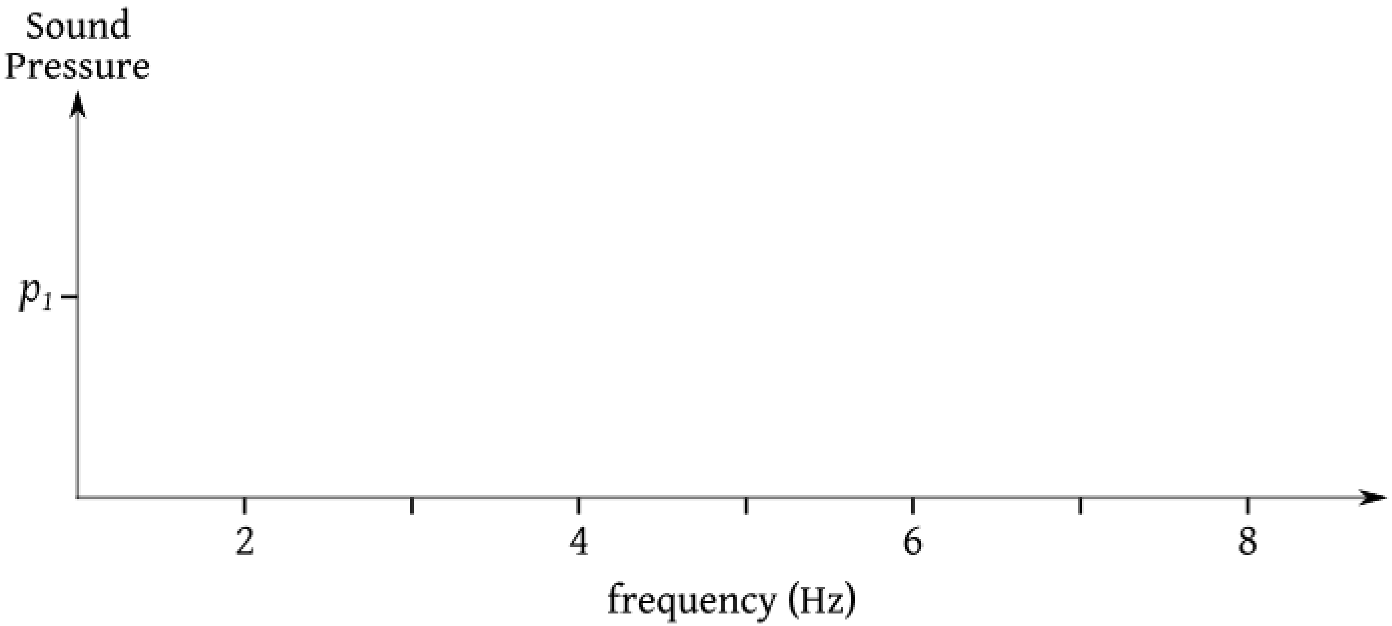
What does the Fourier Transform do? (i.e. what does it transform into what?)

What does the Fourier Transform do? (i.e. what does it transform into what?)

Transforms a representation of the signal from the time domain (i.e. pressure amplitude vs. time) or the frequency domain (pressure amplitude vs. frequency)

Draw the frequency domain representation (fourier transform) of this pure tone





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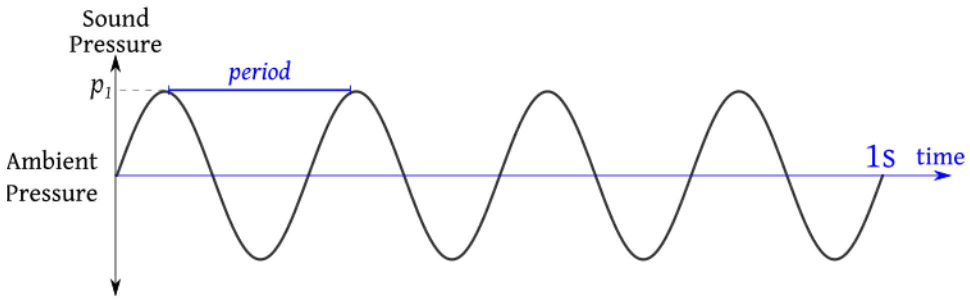
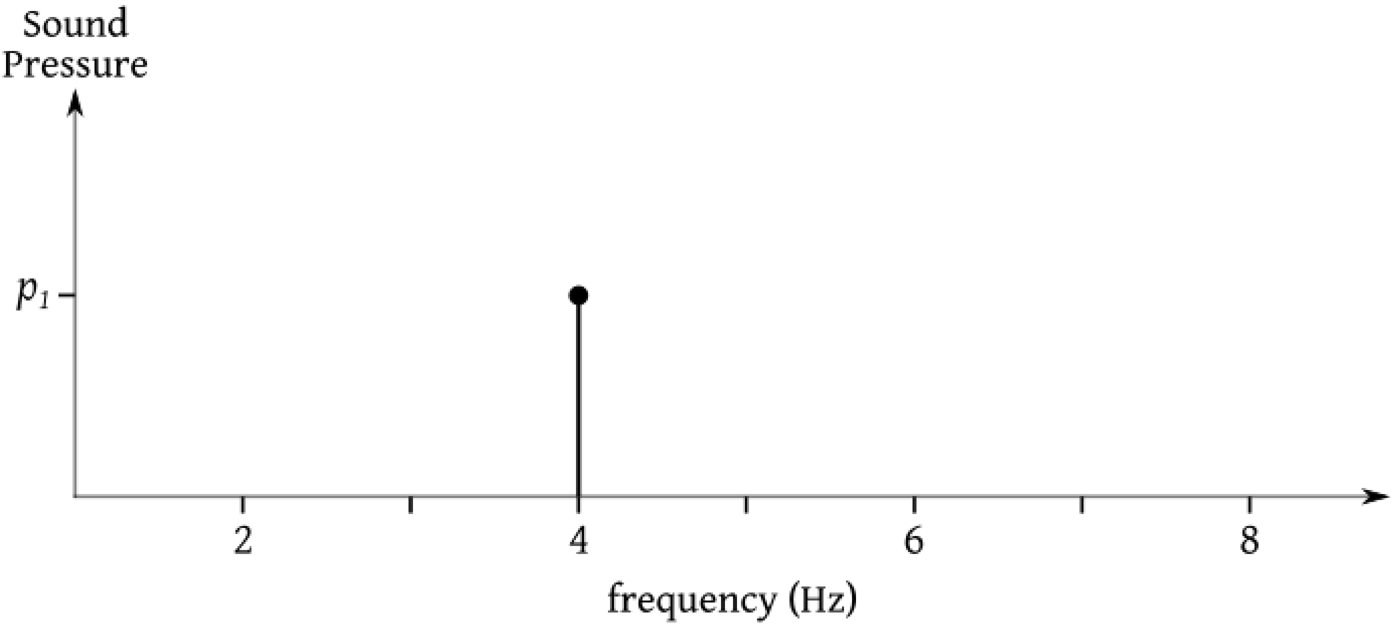
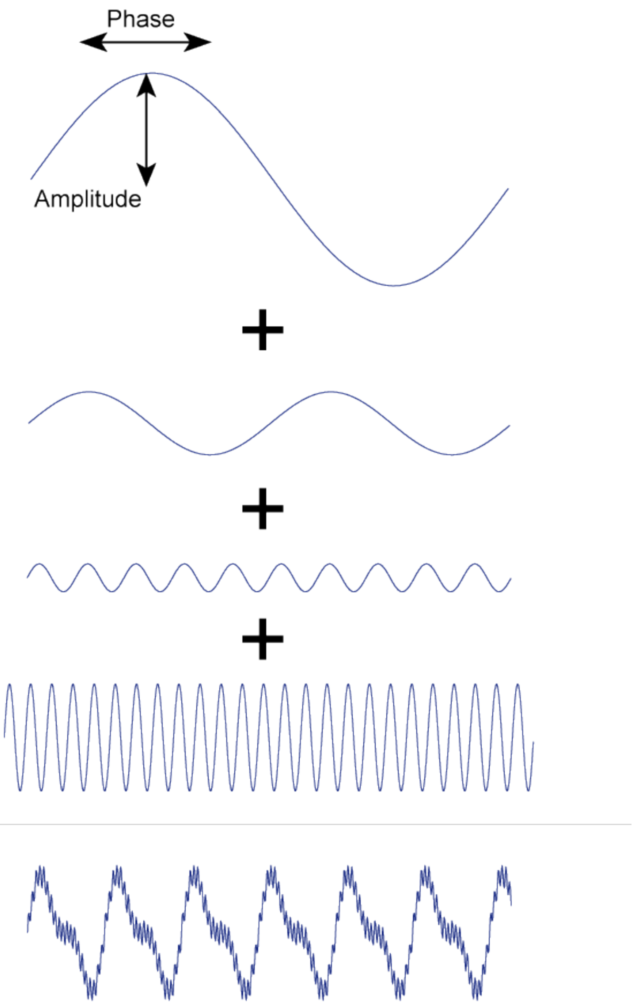


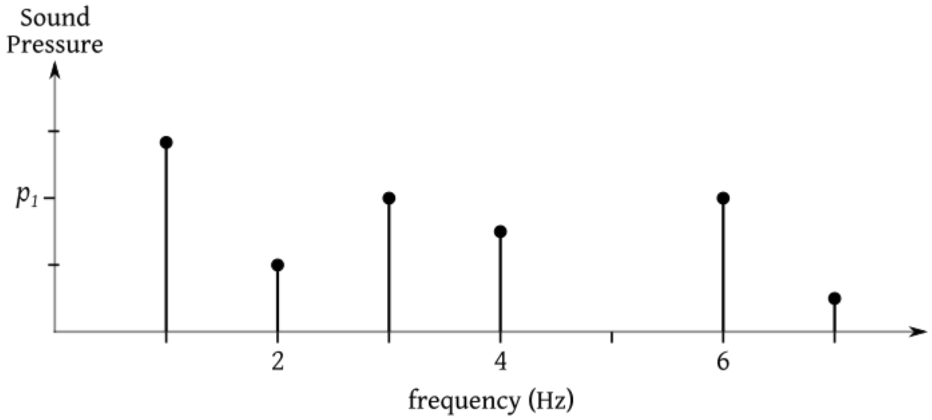


Fourier Transform (Discrete)




```
amp = [2 1 .1 .5];
freq = [1 2 10 20];
out = amp * sin(2*pi*freq'*t);
```

How would you create a time domain representation of this wave?



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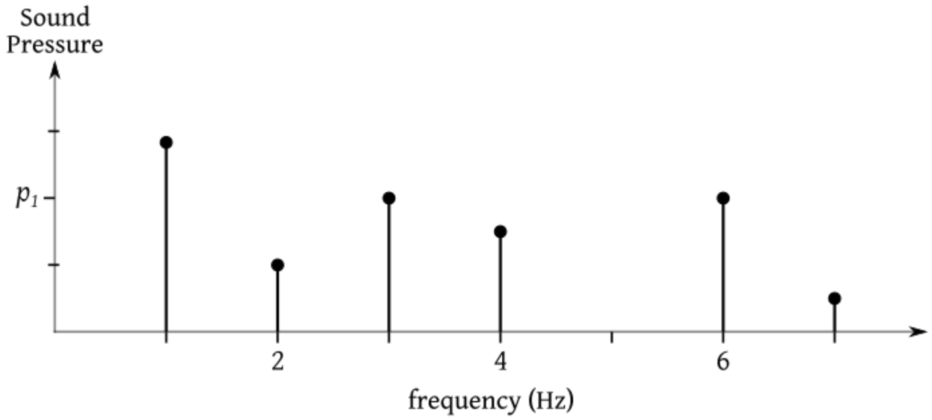
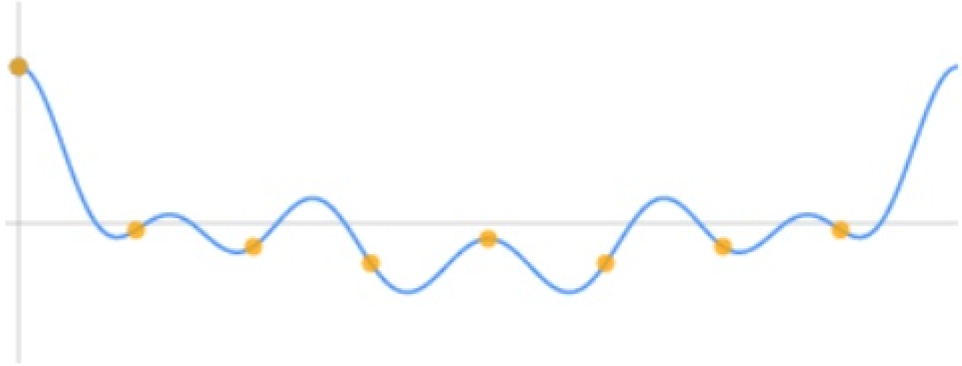


By adding up the following sine waves

- 1 Hz, Amplitude 1.5 x *p1*
- 2 Hz, Amplitude 0.5 x *p1*
- 3 Hz, Amplitude *p1*
- 4 Hz, Amplitude 0.75 x *p1*
- …



https://betterexplained.com/articles/an-interactive-guide-to-the-fourier-transform

Interactive guide to the Fourier transform

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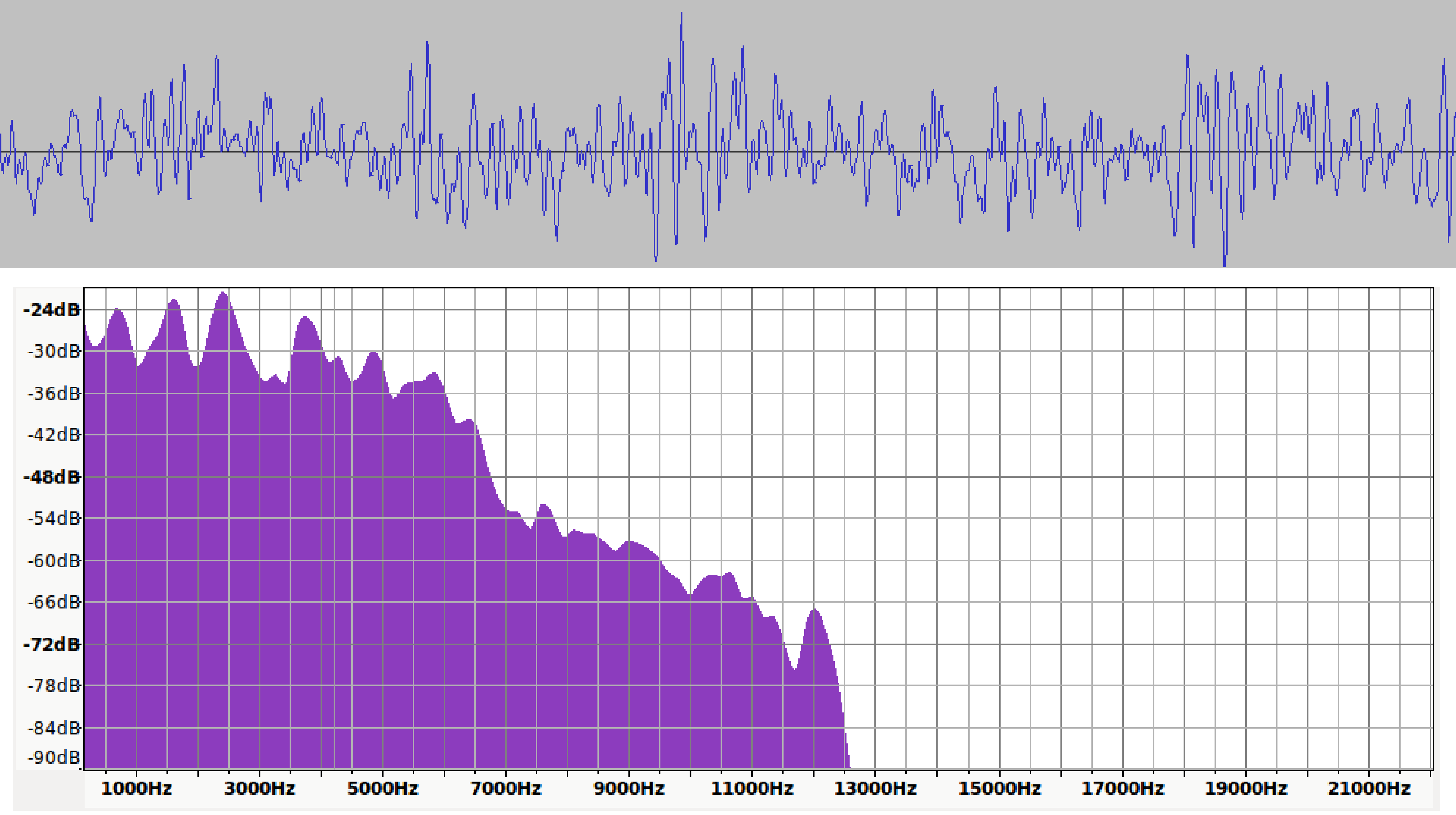

-24dB
-30dB
-36dB
-42dB
-48dB
-54dB
-60dB
-66dB
-72dB
-78dB
-84dB
-90dB
1000Hz
3000Hz
5000Hz
7000Hz
9000Hz
11000Hz
13000Hz
15000Hz
17000Hz
19000Hz
21000Hz

https://youtu.be/UIVe-rZBcm4?t=2m10s

In the Garden of Eden by I. Ron Butterfly. Fair Use.

If the Spatial Pulse Length is 3 mm, what is the minimum distance required between two objects before their returning echos will be separate from each other?

If the Spatial Pulse Length is 3 mm, what is the minimum distance required between two objects before their returning echos will be separate from each other?

- For the echos to distinguishable from each other, there has to be a gap between them.
- Assuming that the target is not moving, the echo of the pulse should be same length as the pulse, i.e. 3 mm.
- If the start of the two echos are less than 3 mm apart then the echo pulses will merge into one longer pulse.
- So the return path to the farther object must be at least 3 mm longer than the return path to the nearer object, so they must be at least 3/2 or 1.5 mm apart.

What is the relationship between spatial pulse length and axial resolution?

What is the relationship between spatial pulse length and axial resolution?

$$Axial\ Resolution = \frac{Spatial\ Pulse\ Length}{2}$$

What is the range of sound frequencies audible to human ears?

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- 20 Hz to 20 KHz

What is ultrasound? What is the typical frequency range of clinical ultrasound?

What is ultrasound? What is the typical frequency range of clinical ultrasound?

- Ultrasound = beyond audible range, i.e. > 20 Khz
- Clinical ultrasound ~ 2 – 10 **M**Hz
- Some applications like ophthalmic ultrasound use higher frequencies (~12MHz)

What is the range of wavelengths encountered in clinical ultrasound?
(assume average soft tissue sound velocity)

What is the range of wavelengths encountered in clinical ultrasound? (assume average soft tissue sound velocity)

- Velocity ~ 1540 [m/s]
- Frequency 2-10 MHz
- $\lambda 1 = c / f$ = 1540 [m/s] / 2,000,000 [1/s] = 0.000770 m = **0.77 mm**
- $\lambda 2$ = 1540 [m/s] / 10,000,000 [1/s] = **0.154 mm**

Can we use these values to calculate the axial resolution range of clinical ultrasound?

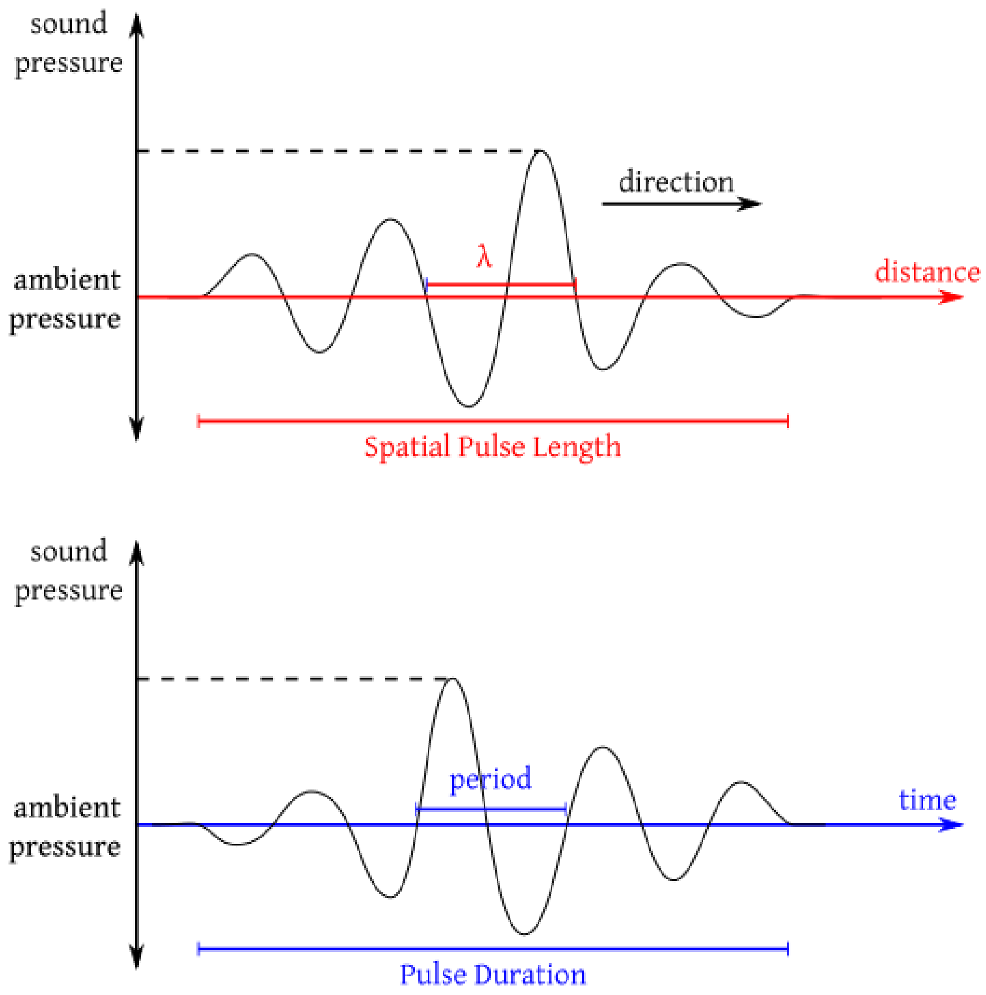
Can we use these values to calculate the axial resolution range of clinical ultrasound?

- No. This is the wavelength of the oscillations within the pulse not the spatial pulse length.

The Pulse

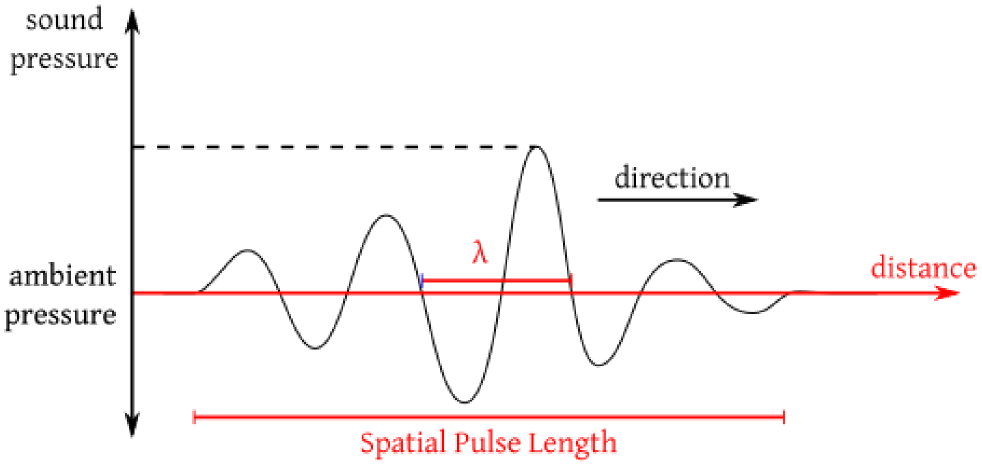
This is a rough approximation of an ultrasound pulse in the distance and time domains.

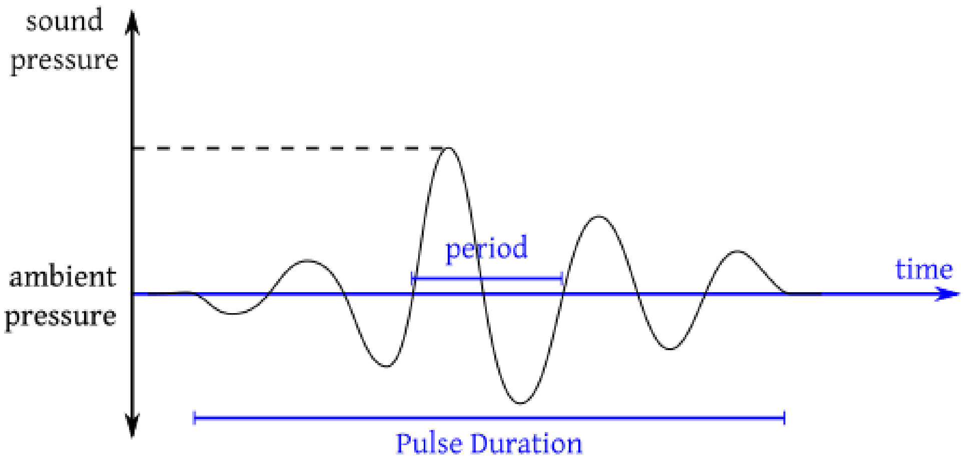
Note again that the time representation is a horizontally flipped version of the distance representation.



The Pulse

If this pulse is generated by a 10 MHz transducer (λ = 0.154 mm) then what is the axial resolution?





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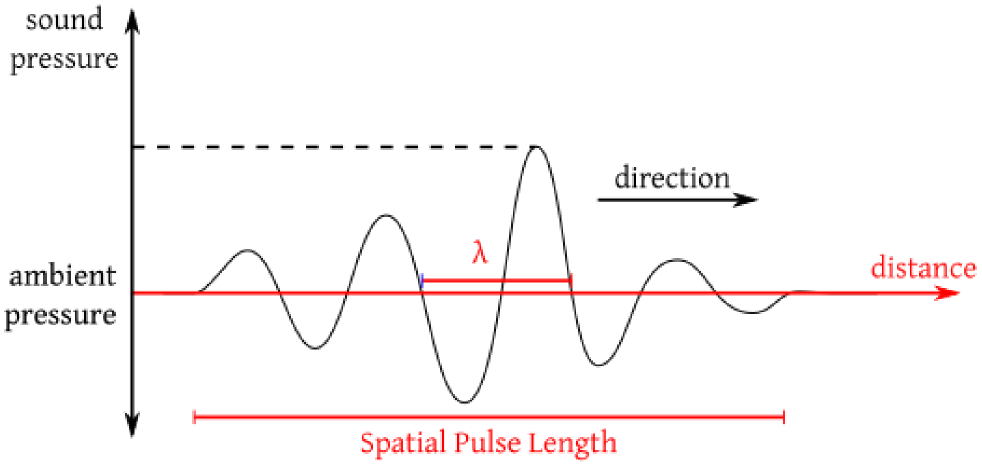


- SPL = 0.154 x ~4 = 0.624 mm
- AR = SPL / 2 = 0.312 mm

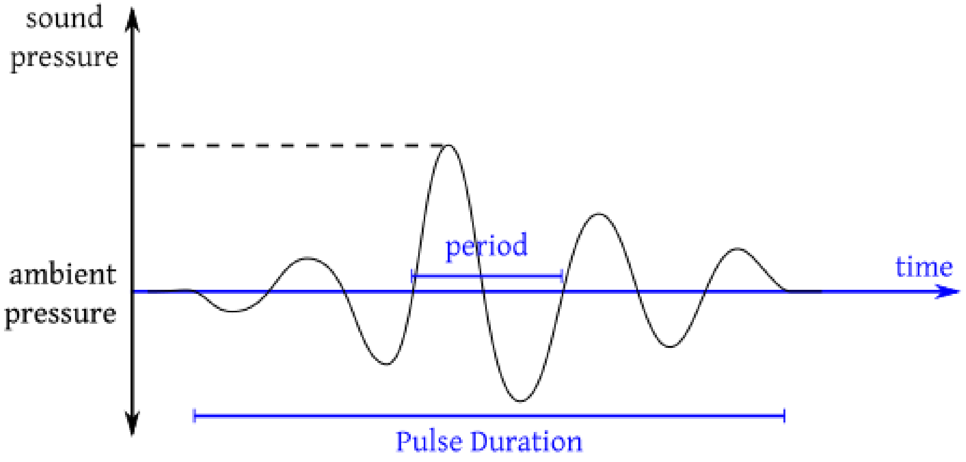
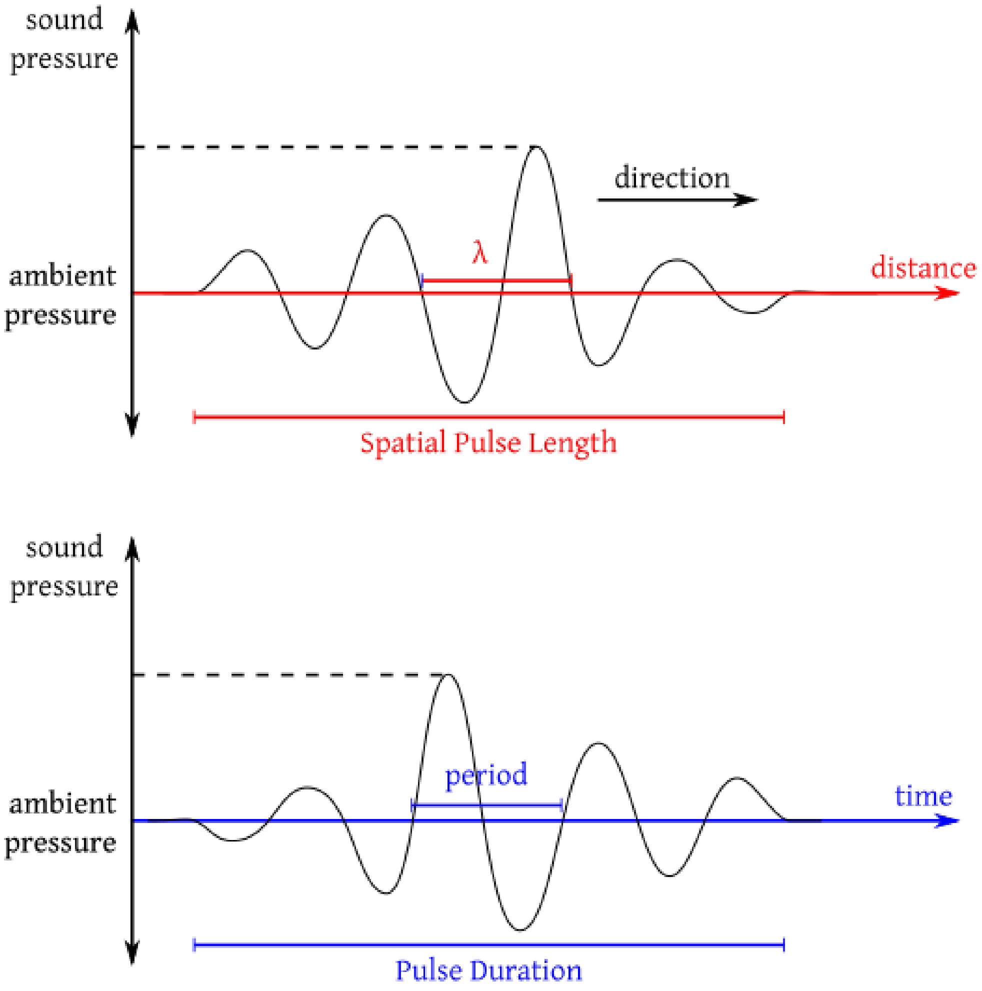


Photo Peter G Werner
https://commons.wikimedia.org/wiki/File:Homelard.jpg

The Pulse

If this pulse is generated by a 10 MHz transducer what is the pulse duration?



The Pulse

If this pulse is generated by a 4 MHz transducer what is the pulse duration?

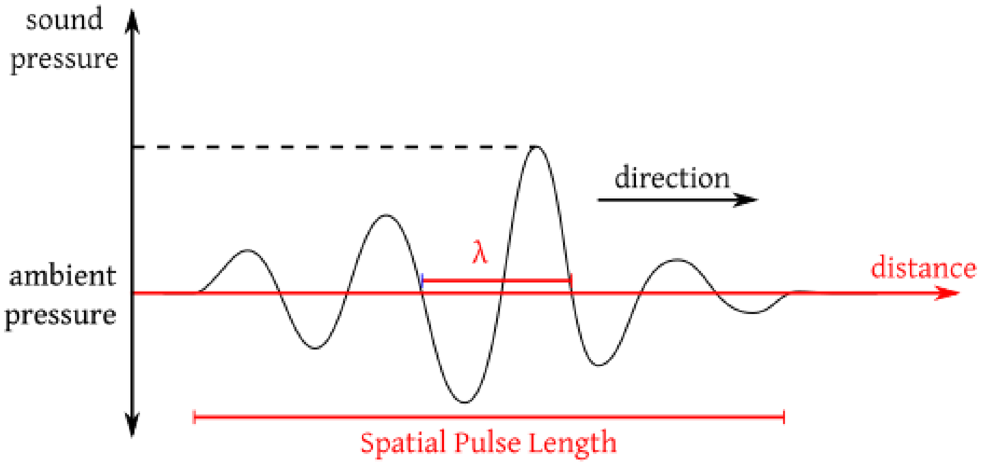
- Period x 4

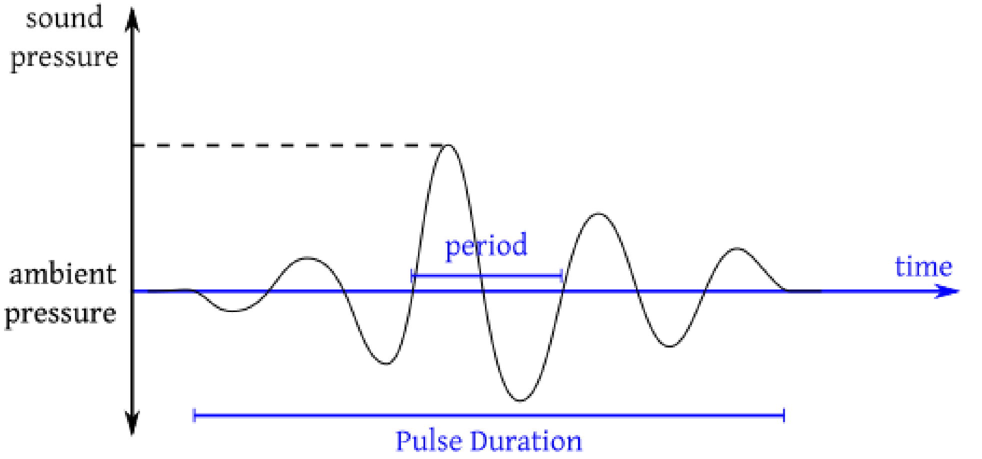
  = 4/f

  = 4 / 4,000,000 [1/s]

  = 0.000001 s

  = 0.1 μs





Various pulses for clinical applications

(a) Imaging
(b) Doppler
(c) Therapeutic

Fish P. Physics and Instrumentation of Diagnostic Medical Ultrasound. Wiley; 1990. 268 p.

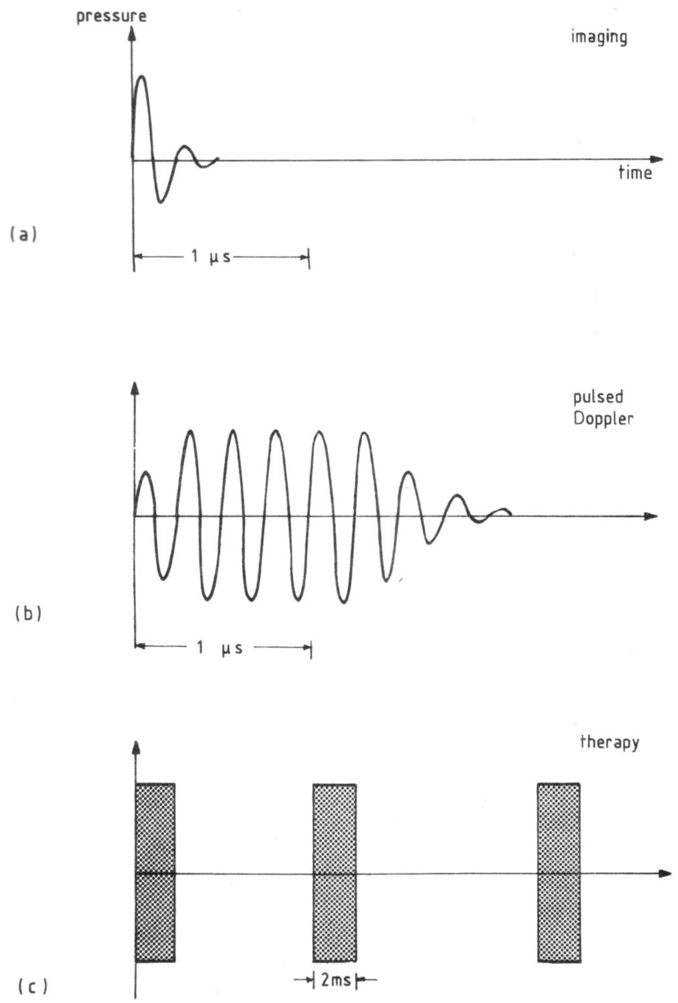


Figure 2.9 Typical pulses as used in ultrasound imaging (a), pulsed Doppler instruments (b) and therapy instruments (c).

Frequency representation (Fourier Transforms) of various pulses

Note that the shorter pulse has a _______ spectrum than the longer pulse.

Fish P. Physics and Instrumentation of Diagnostic Medical Ultrasound. Wiley; 1990. 268 p.

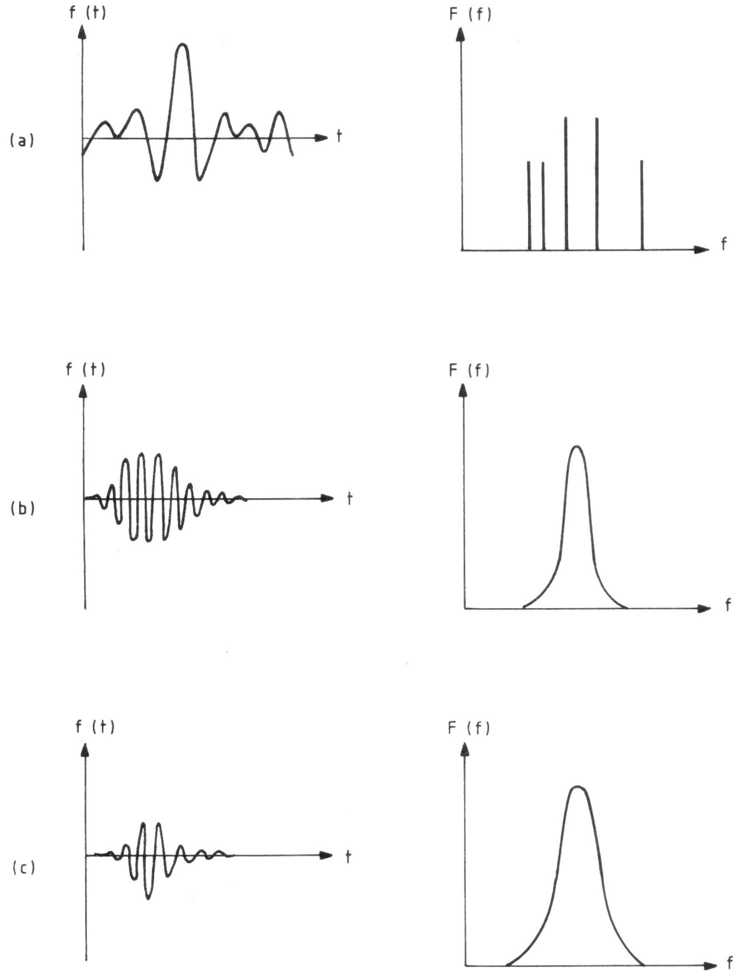


Figure 2.15 The frequency spectra corresponding to various pulse waveforms. (a) The case considered in Figure 2.14, (b) a long pulse and (c) a short pulse. The width of the spectrum (the range of frequencies needed to synthesise the pulse) is inversely proportional to the duration of the pulse.

Frequency representation (Fourier Transforms) of various pulses

Note that the shorter pulse has a WIDER spectrum than the longer pulse.

The Width of the frequency representation is the bandwidth.

The **shorter pulse** has a **wider bandwidth.**

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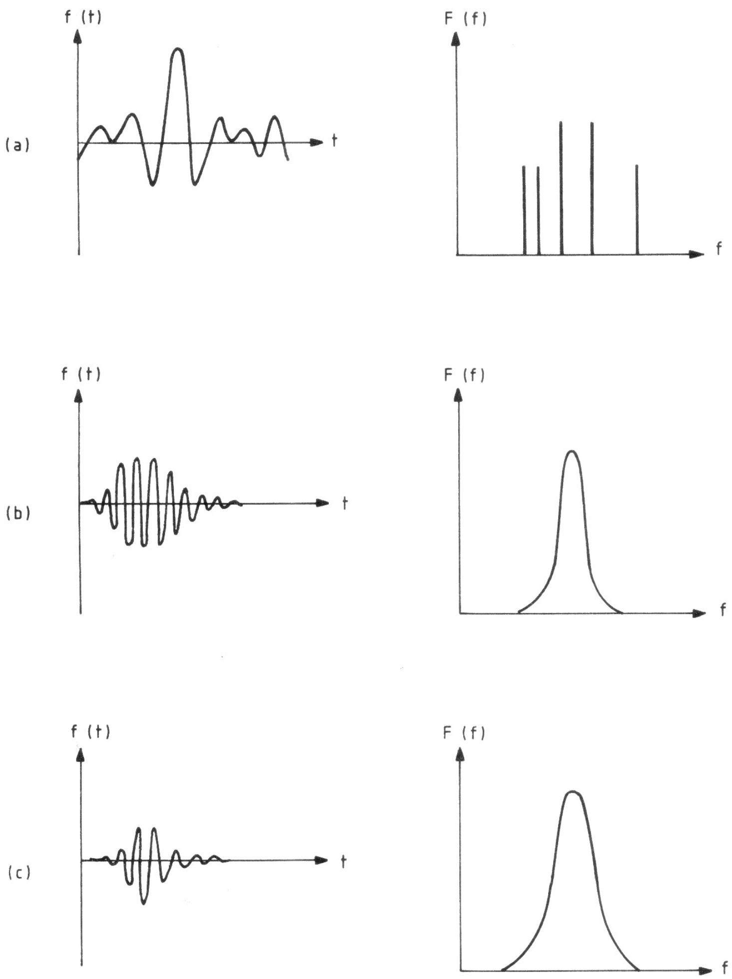

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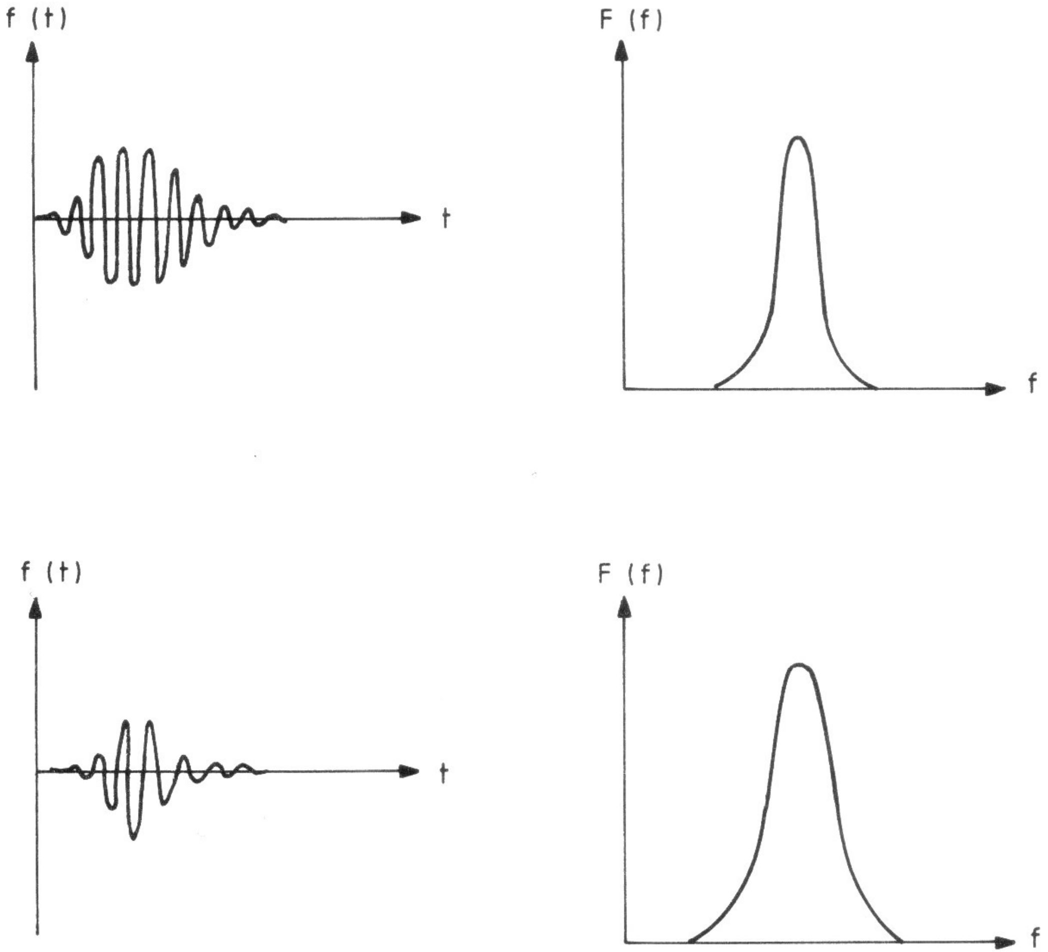
The quality factor (or Q characteristic) is defined as the central frequency divided by the bandwidth.

Which pulse has the higher Q factor value?

Which pulse yields the better axial resolution?



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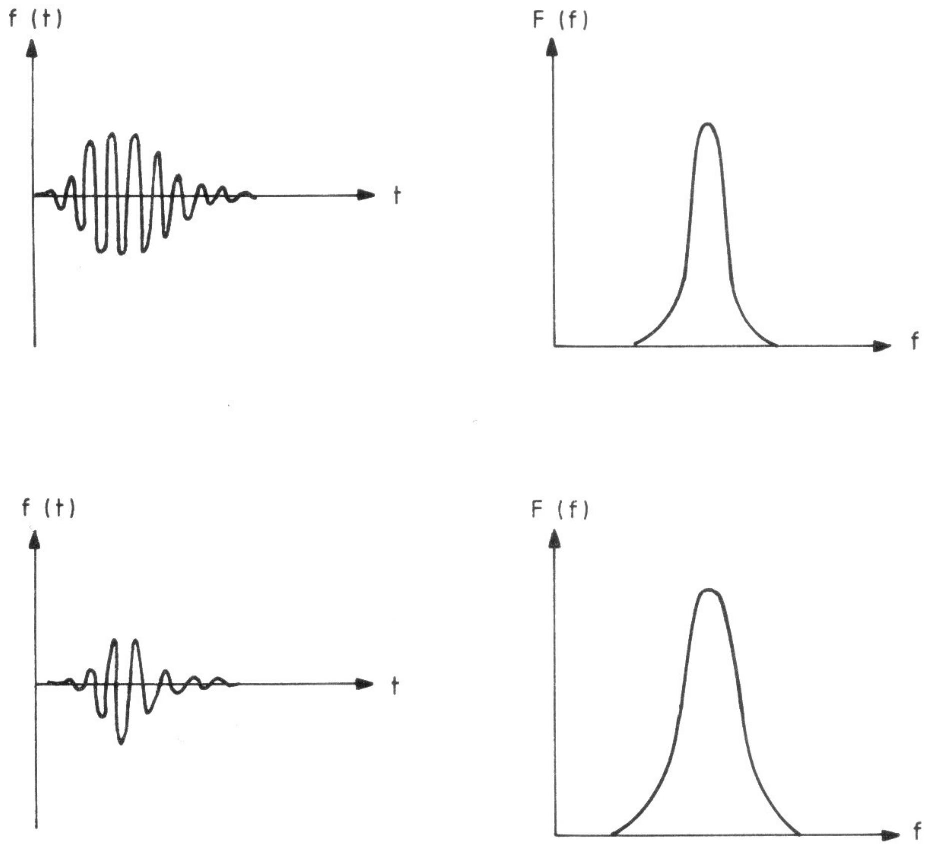


The wider pulse has the higher "Quality" value but the narrower pulse has the better AR.

Fish P. Physics and Instrumentation of Diagnostic Medical Ultrasound. Wiley; 1990. 268 p.

Which has the higher Q factor, a continuous wave at single frequency or a pulsed wave?

Which has the higher Q factor, a continuous wave at single frequency or a pulsed wave?

- The continuous wave has a miniscule bandwidth and a very high Q-factor value.

What does axial resolution have to do with pork fat?

Photo Peter G Werner https://commons.wikimedia.org/wiki/File:Homelard.jpg

What does axial resolution have to do with pork fat?

Also known as LARRD resolution

- Longitudinal
- Axial
- Range
- Radial
- Depth

Photo Peter G Werner https://commons.wikimedia.org/wiki/File:Homelard.jpg

What is azimuthal resolution?

How do you pronounce “azimuthal”?

What is azimuthal resolution?

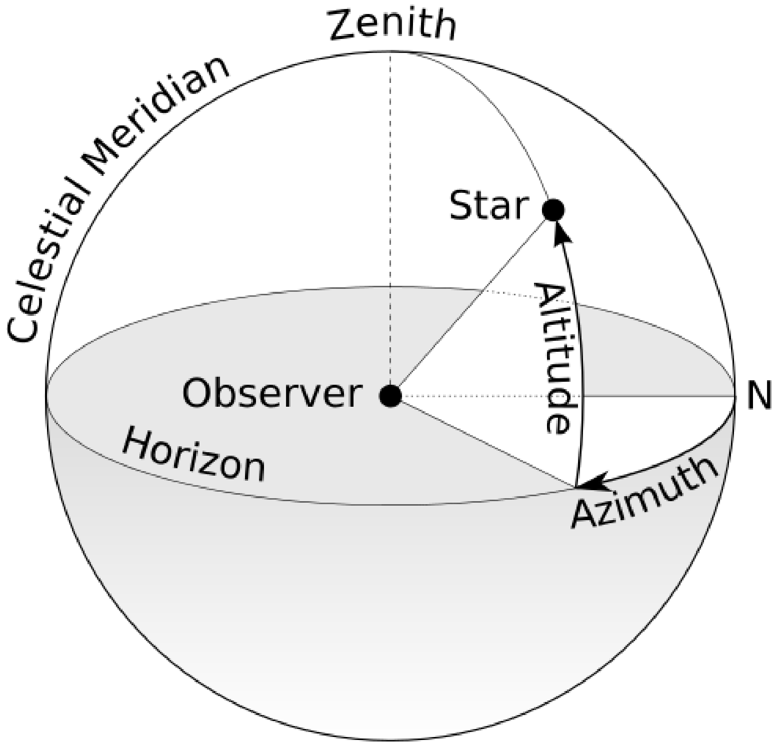
How do you pronounce “azimuthal”?

Is the resolution perpendicular to the axis of the beam and in the 2D imaging plane.

Also known as **LATA**

Lateral, Angular, Transverse, Azimuthal.

Ambiguous term in 3DE.



TWCarlson https://commons.wikimedia.org/wiki/File:Azimuth-Altitude_schematic.svg

What are the four components (types) of imaging resolution in echocardiography?

What are the four components (types) of imaging resolution in echocardiography?

1. Temporal resolution (frame rate in 2D, volume rate in 3D) in frames/second or Hz
2. Axial resolution (axis of LAARD)
3. Lateral resolution (LATA-ral) – clear in 2DE, ambiguous with BW in 3DE
4. Beam width (perpendicular to 2D imaging plane)

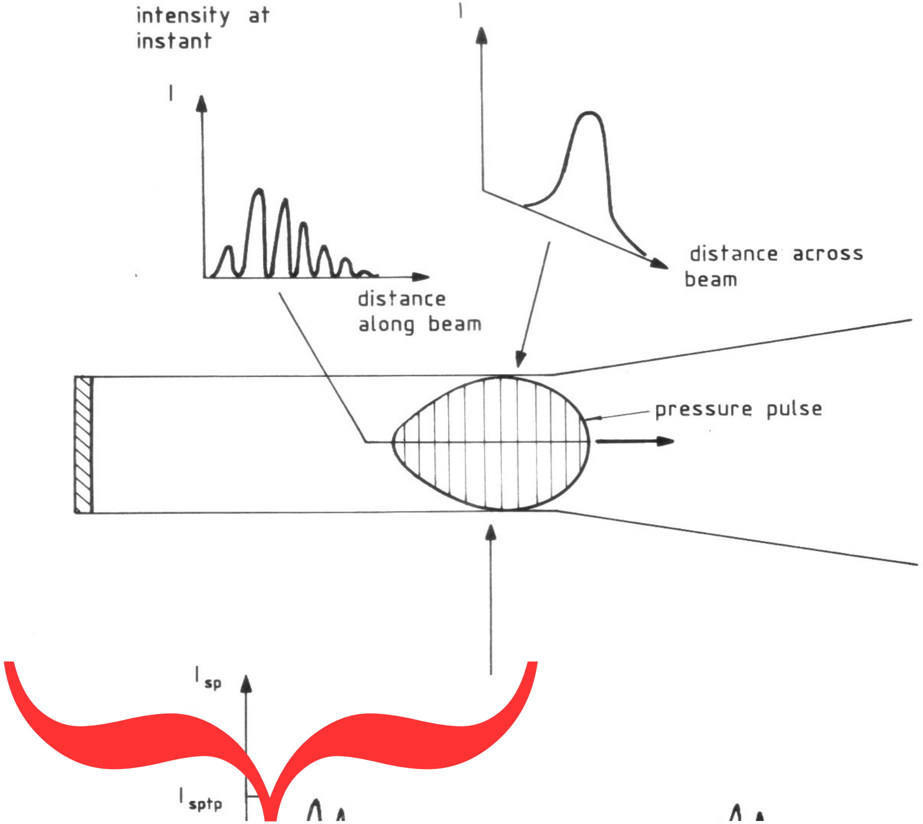
Aside from temporal resolution, which of the other 3 does not vary significantly with the location of the target?

Aside from temporal resolution, which of the other 3 does not vary significantly with the location of the target?

- Axial resolution depends only on the SPL which is more or less constant.
- LATA-ral and Beam width resolution are influenced by focusing and vary with distance.

This diagram represents the beam and pulse shape for a **single round crystal transducer**

What is the marked zone in the ultrasound beam called?



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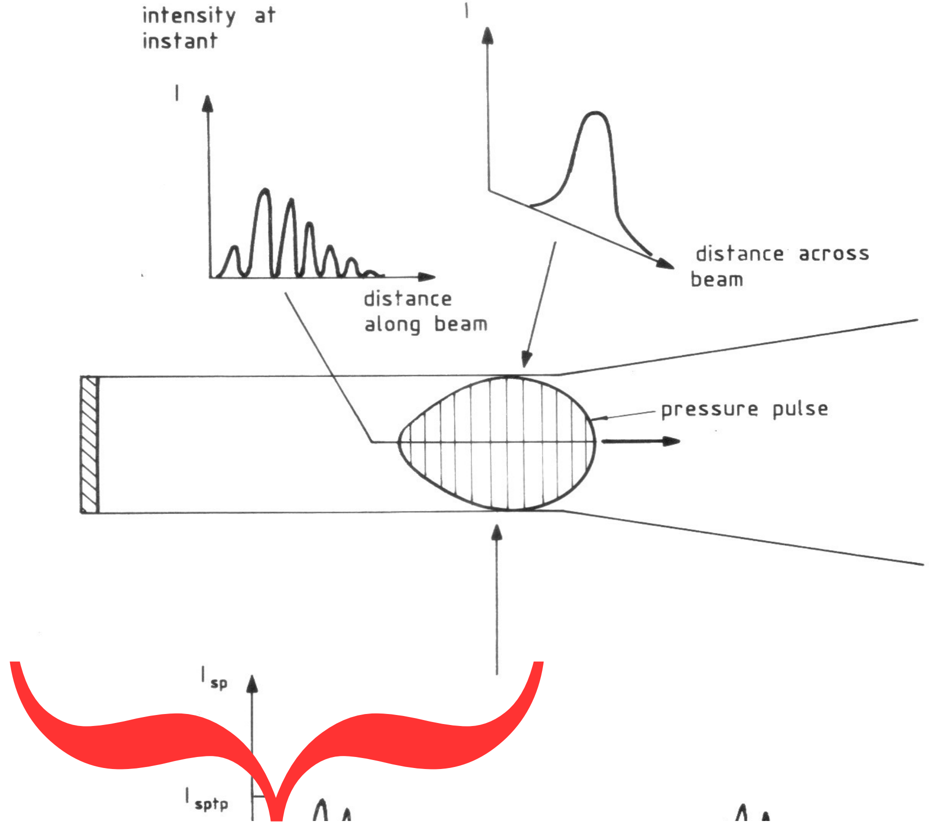

The near-field or Fresnel zone.

The region beyond is the far-field or Fraunhofer (Frown-how-FAR) zone

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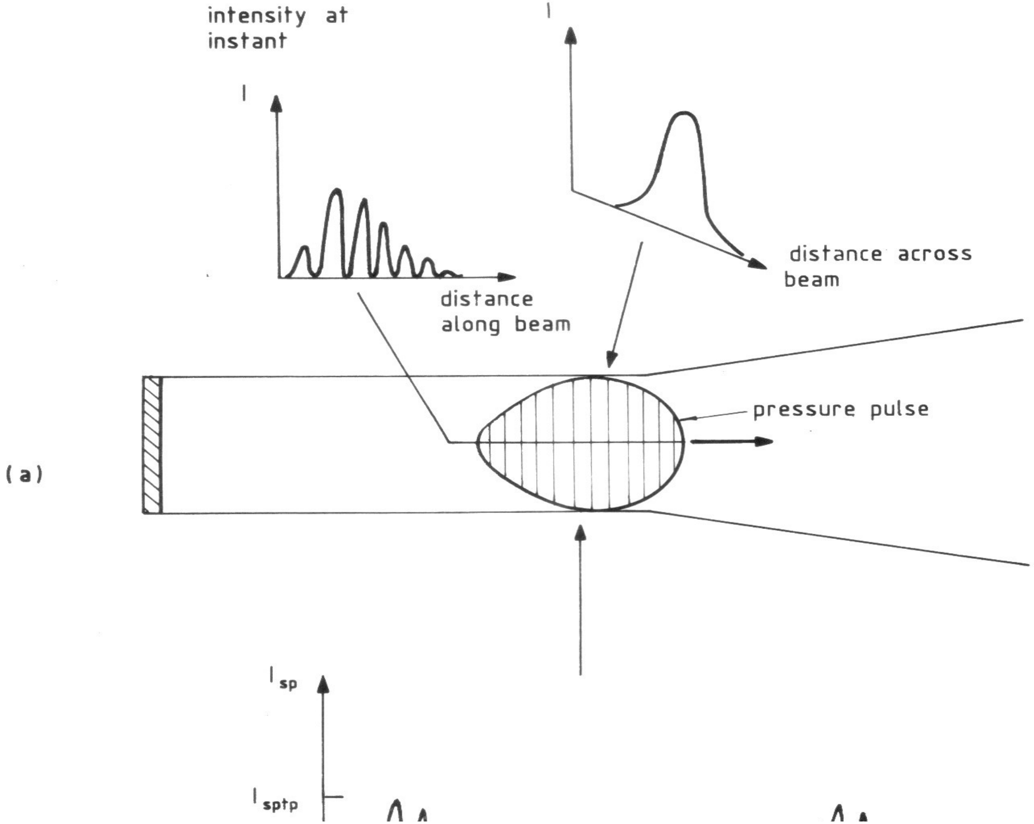
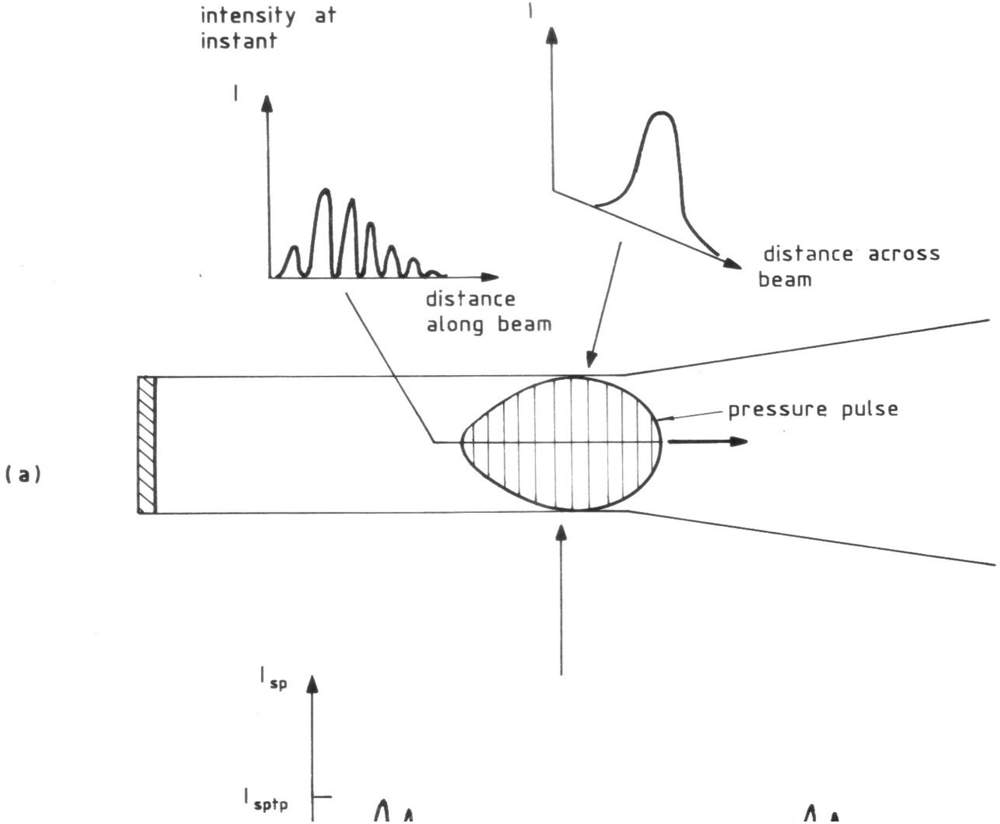
Which zone has the higher intensity? Why?



Fish P. Physics and Instrumentation of Diagnostic Medical Ultrasound. Wiley; 1990. 268 p.

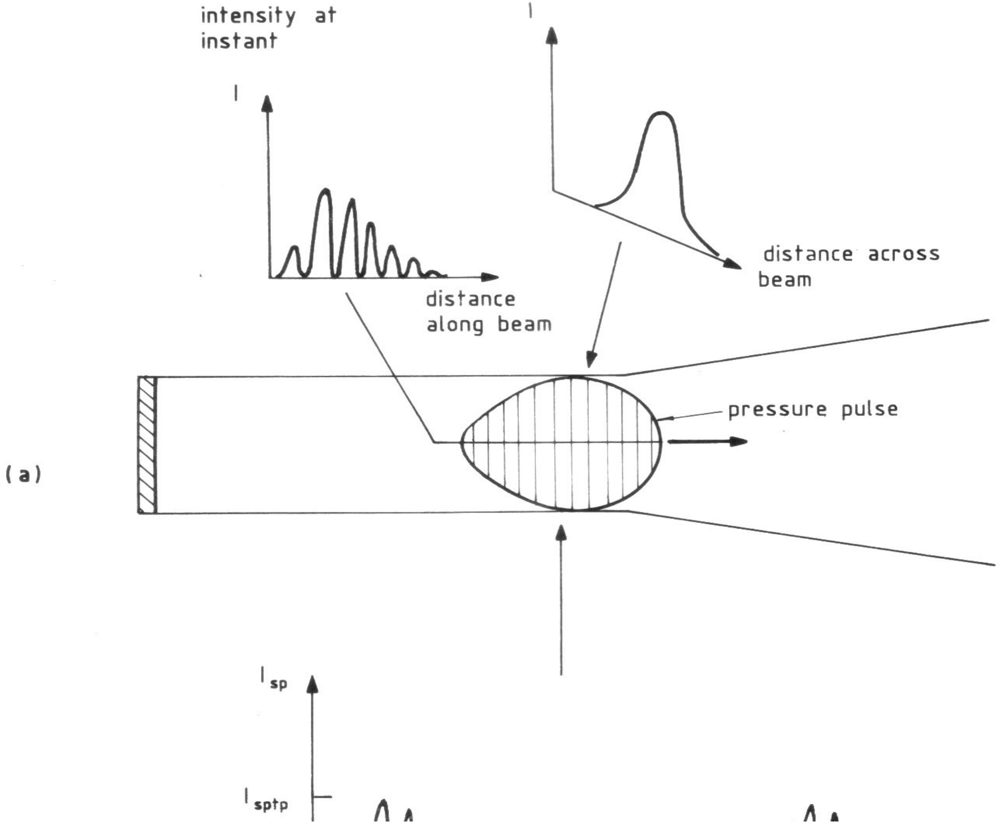
Which zone has the higher intensity? Why?



The near-field (Fresnel) since the cross sectional area is smaller.

Fish P. Physics and Instrumentation of Diagnostic Medical Ultrasound. Wiley; 1990. 268 p.

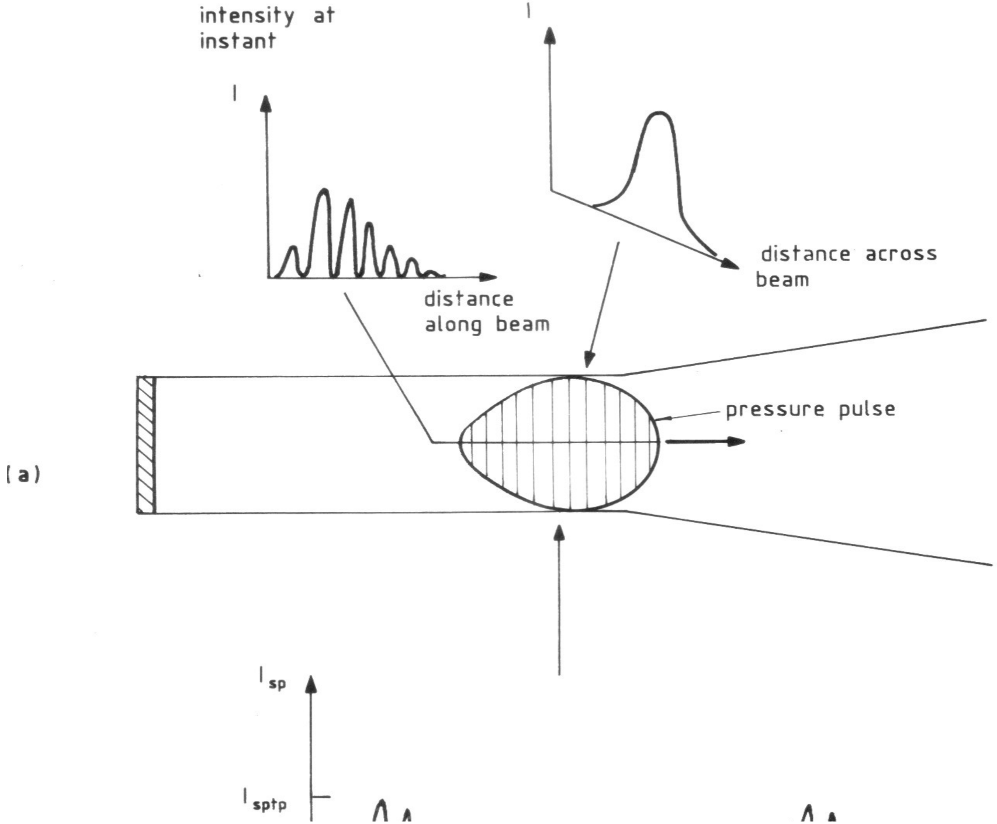
What does the beam out-line mean?



Fish P. Physics and Instrumentation of Diagnostic Medical Ultrasound. Wiley; 1990. 268 p.

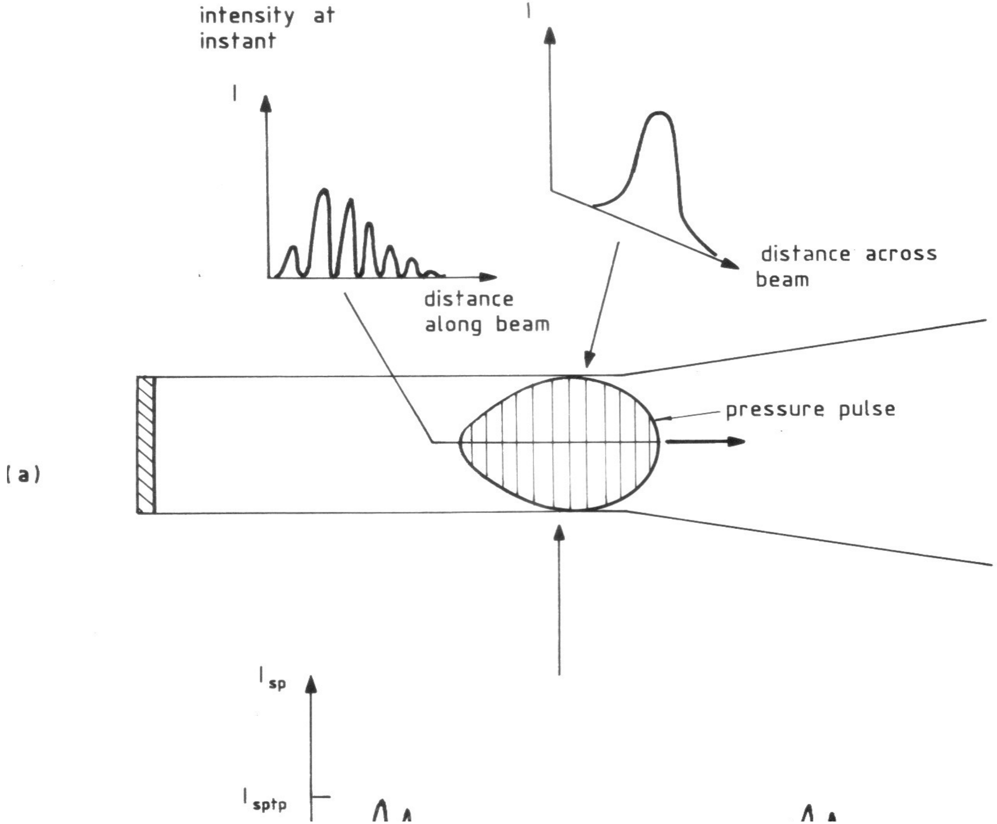
What does the beam out-line mean?

It representes the region where post of the Beam’s energy passes (highest power).



Fish P. Physics and Instrumentation of Diagnostic Medical Ultrasound. Wiley; 1990. 268 p.

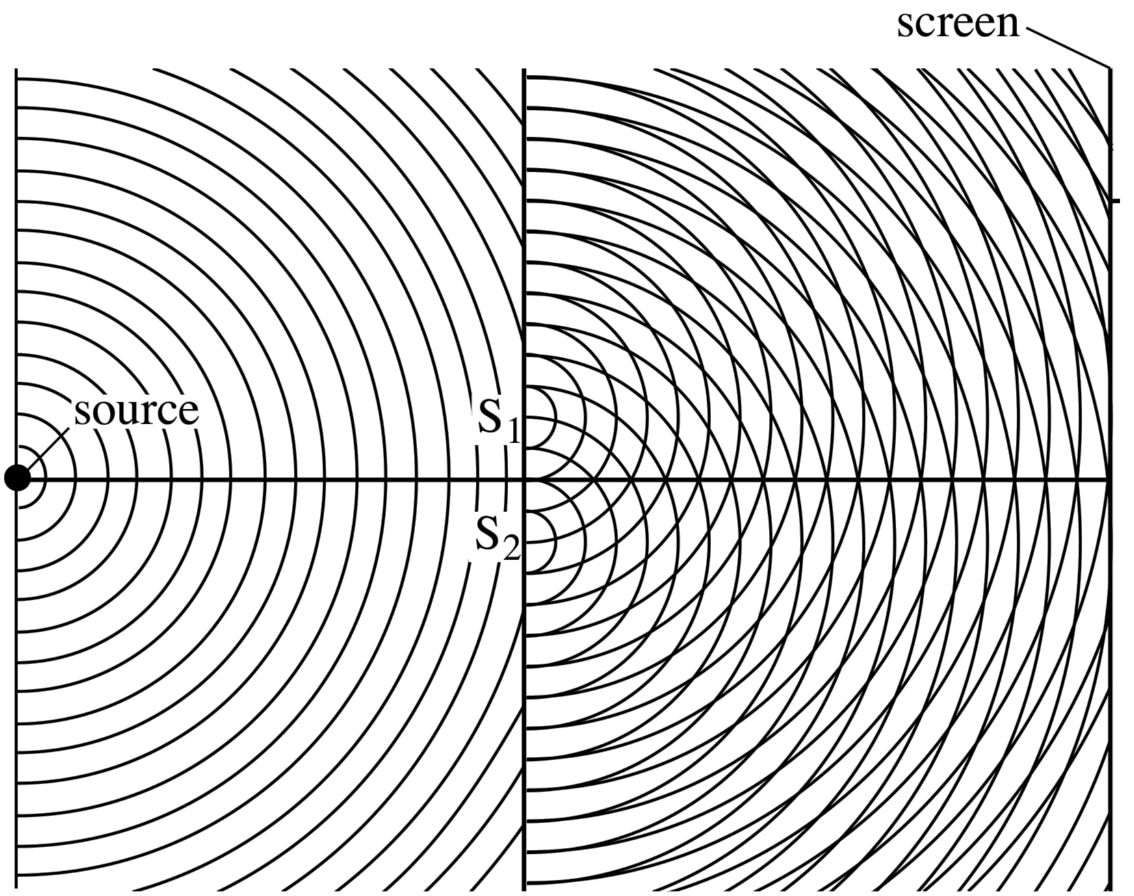
Why is the beam shaped like that?



Fish P. Physics and Instrumentation of Diagnostic Medical Ultrasound. Wiley; 1990. 268 p.

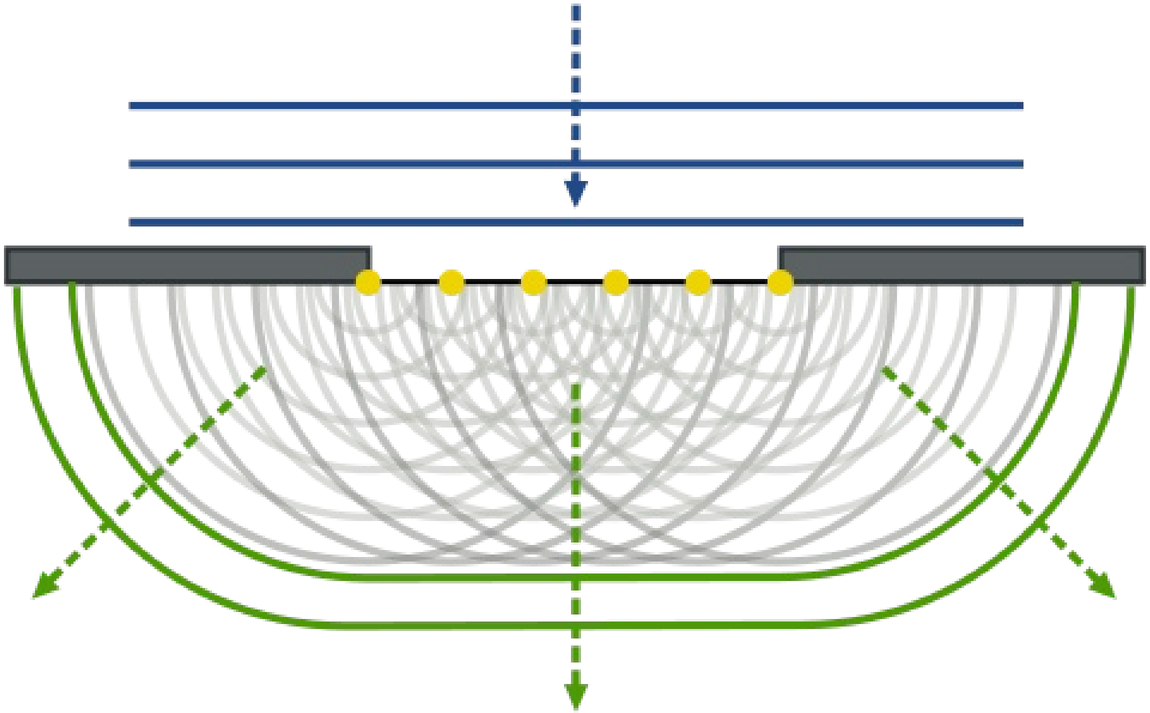
Why is the beam shaped like that?

The shape is created by interference of a large number of waves originating at the transducer surface.



What is the Huygens-Fresnel principle?

How do you pronounce “Huygens”?



Refraction on an aperture in the manner of Huygens. The yellow dots indicate notional origins of new waves.

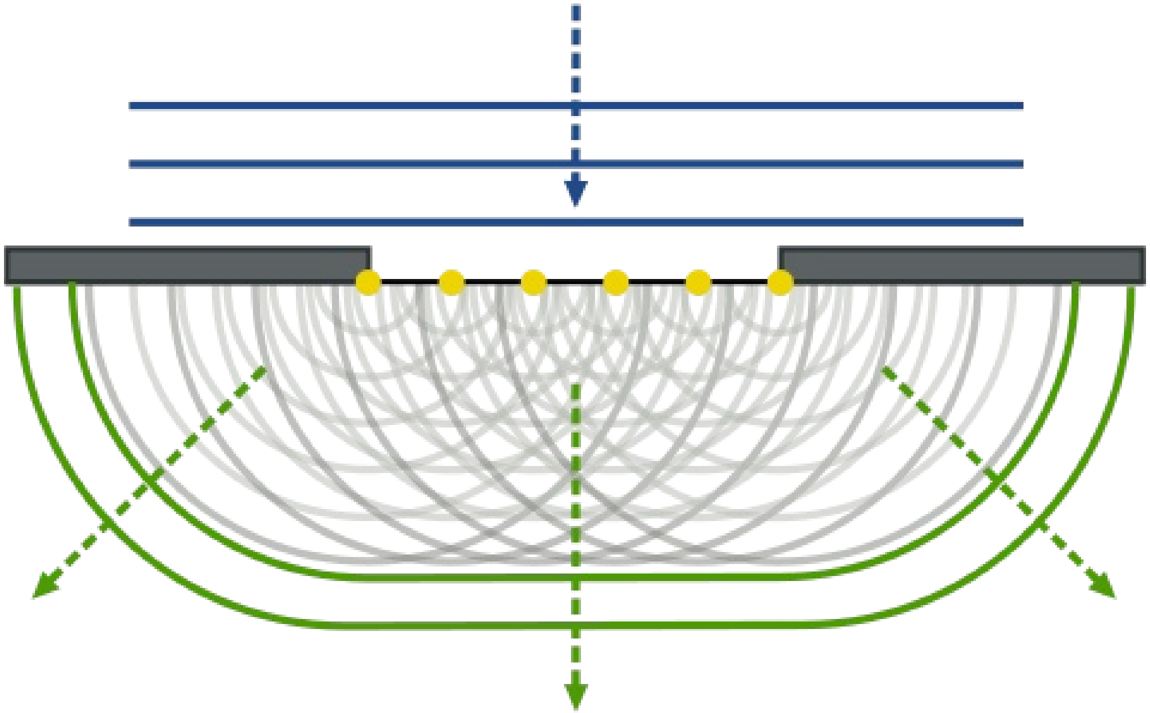
What is the Huygens-Fresnel principle?

How do you pronounce “Huygens”?

Everypoint on a wavefront acts as a point source emitting a spherical wave.

It is an empirical principles that accounts for **reflection** and **refraction** patterns.

https://en.wikipedia.org/wiki/Huygens%E2%80%93Fresnel_principle



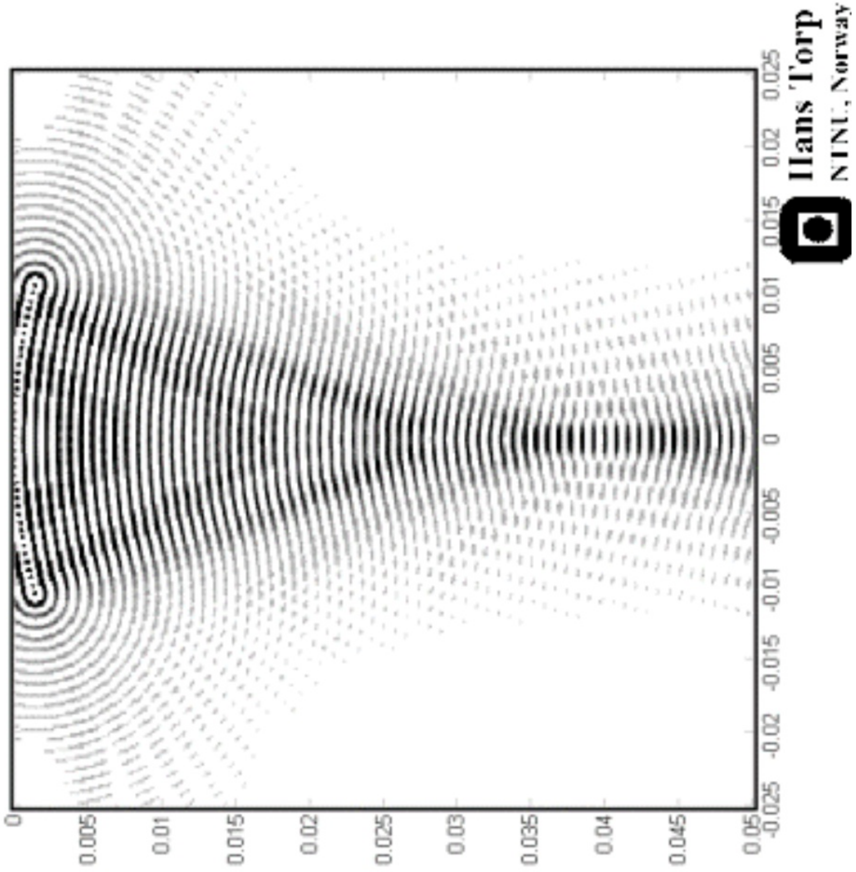
Refraction on an aperture in the manner of Huygens. The yellow dots indicate notional origins of new waves.

This is a simulation of the resulting interference pattern for a **curved crystal** (left) generating a **continuous wave**.

This is a snapshot in time.

The lines represent the peaks of the waves. The darker the higher the amplitude.

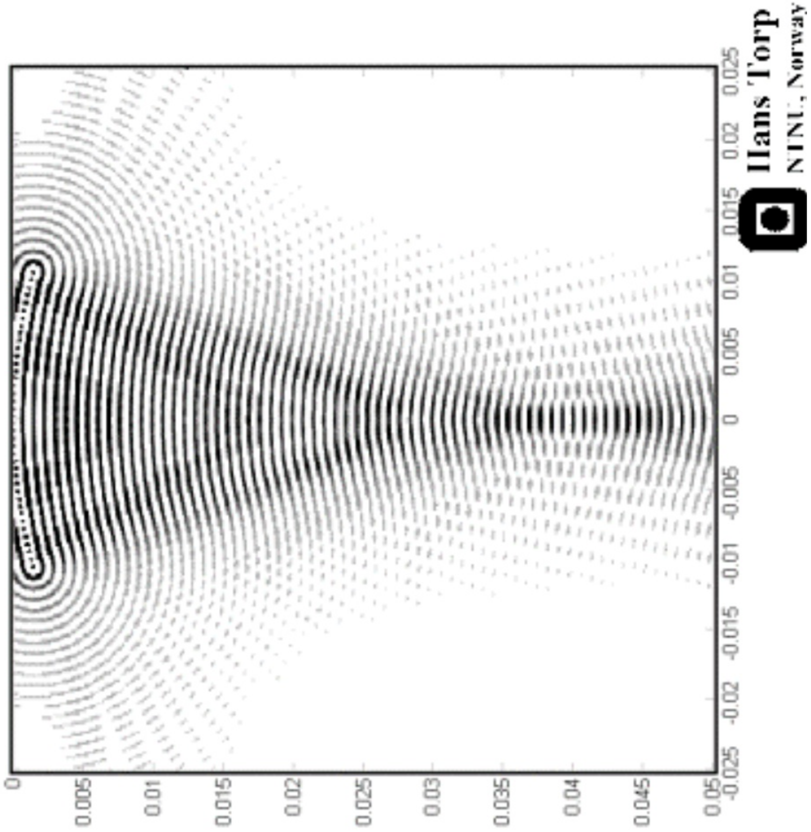
You can also think of them as representing the density of the particles in the medium, so darker areas represent high compression of the medium.



Simulated beam with focusing, showing interference pattern dispersing some of the beam to the sides. (image Hans Torp).

http://folk.ntnu.no/stoylen/strainrate/Basic_ultrasound#2D

Identify the Fresnel and Fraunhofer zones and the focal point.



Simulated beam with focusing, showing interference pattern dispersing some of the beam to the sides. (image Hans Torp).

http://folk.ntnu.no/stoylen/strainrate/Basic_ultrasound#2D

What is the length of the Fresnel zone (or the focal length) of a single cryztal transducer with diameter d and frequency f?

What is the length of the Fresnel zone (or the focal length) of a single cryztal transducer with diameter *d* and frequency *f* ?

Focal length = $radius^2 / \lambda$

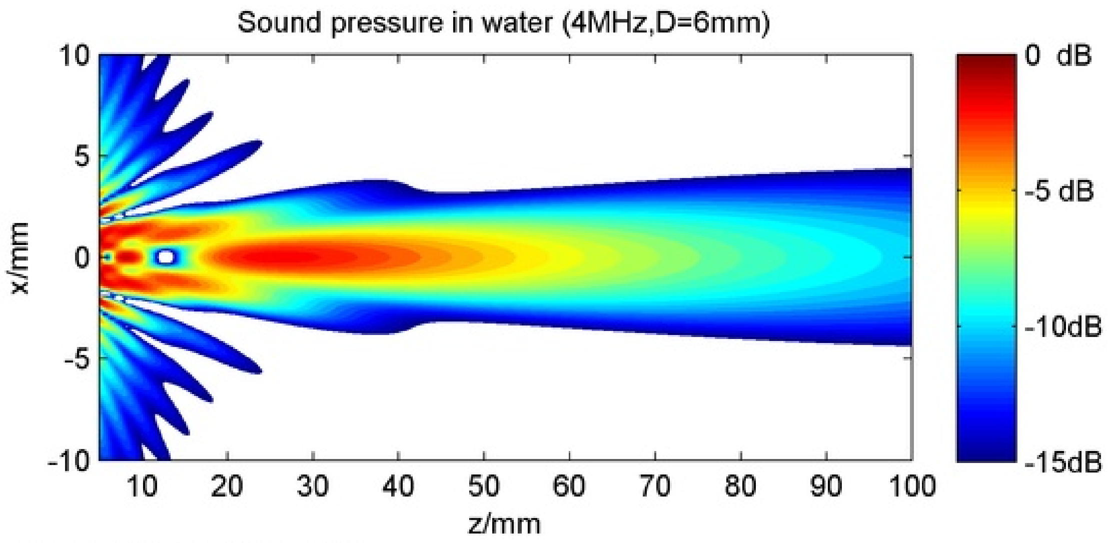
- $r = d/2$
- $\lambda = c/f$
- *Focal length* = $d^2 \times f / 4 \times c$

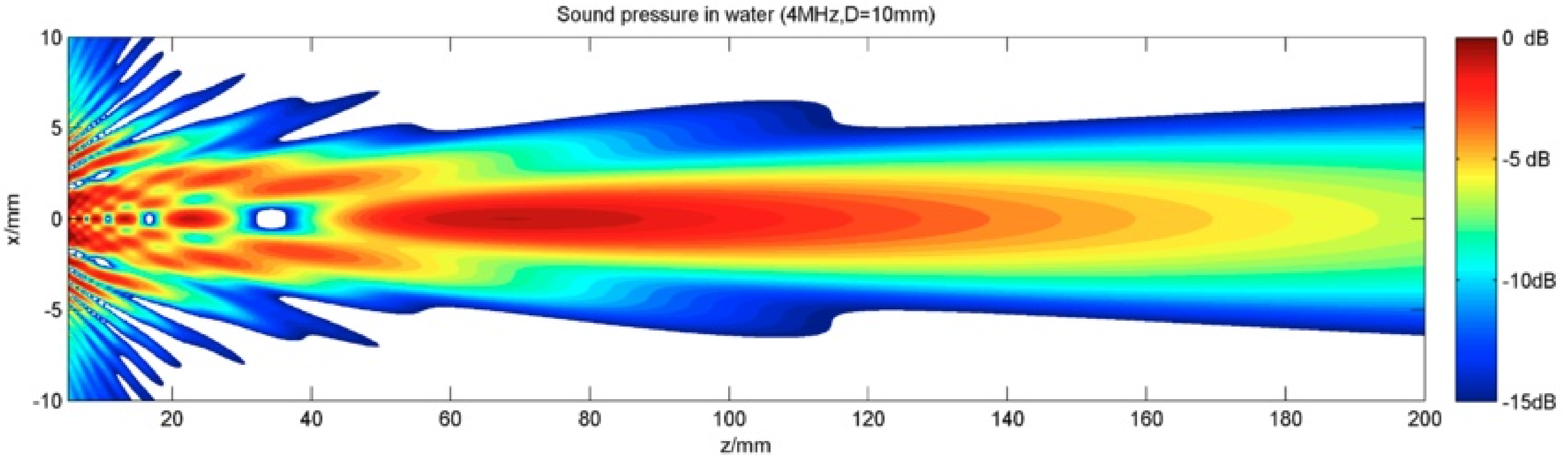
What is the focal length of a 4MHz disc transducer with diameter of 10mm in water (c=1500 m/s)?

What is the focal length of a 4MHz disc transducer with diameter of 10mm in water (c=1500 m/s)?

- *Focal length* = $d^2 \times f / 4 \times c$
- = (0.01 [m])2 x 4000000 [1/s] / 4 x 1500[m/s] = 0.075 m = 75 mm

Soundfields in water for 4MHz flat crystals, radius 3mm (right) and 5 mm (below). Intensity is colour coded.





Michael Lenz. https://commons.wikimedia.org/wiki/File:Soundfield_Water_4MHz_TransducerRadius5mm.png and https://commons.wikimedia.org/wiki/File:Soundfield_Water_4MHz_TransducerRadius3mm.png Public Domain.

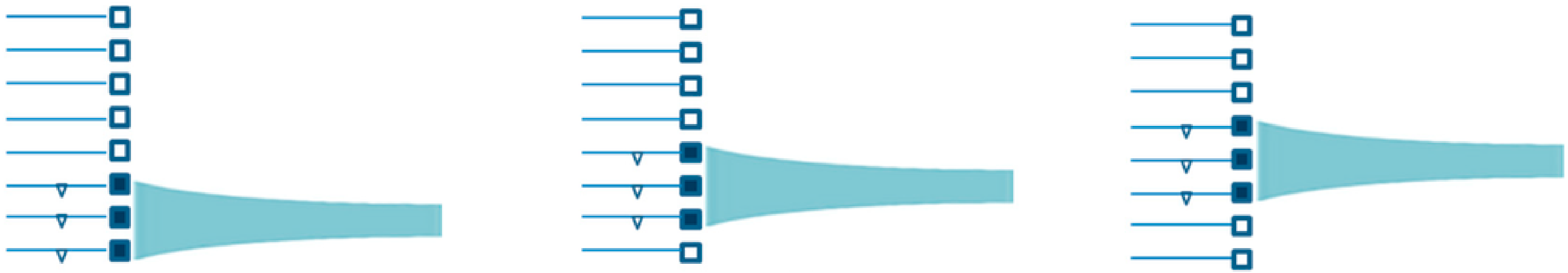
What are the three most common ways of focusing ultrasound beams?

What are the three most common ways of focusing ultrasound beams?

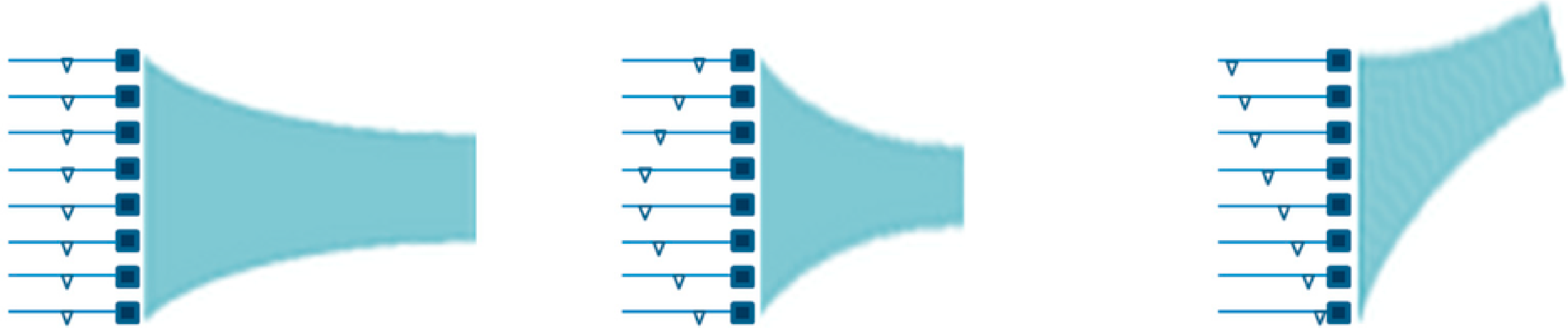
- Curvature of crystal or array (for single crystal transducers)
- Lense
- Electronic focusing (method used in virutally all modern, mutil-crystal systems imaging systems)

What is electronic focusing?

What is electronic focusing?



(a)



(b)

Qiu Y, Gigliotti JV, Wallace M, Griggio F, Demore CEM, Cochran S, et al. Piezoelectric Micromachined Ultrasound Transducer (PMUT) Arrays for Integrated Sensing, Actuation and Imaging. Sensors. 2015 Apr 3;15(4):8020–41.

What is the effect of the density of the medium on the speed of sound?

What is the SI units of density?

What is the effect of the density of the medium on the speed of sound?

What is the SI units of density?

- More density, slower speed. i.e. inversly proportional
- Kg/m^3

Besides density what physical property determines sound velocity through a medium?

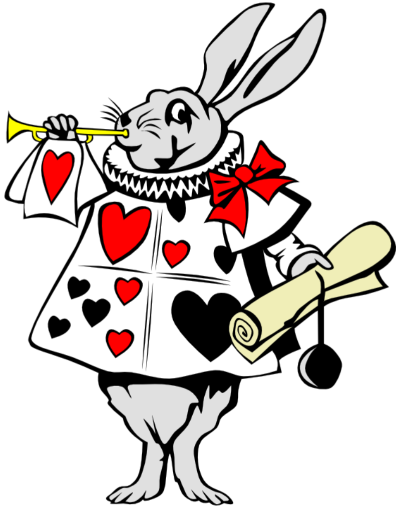
Besides density what physical property determines sound velocity through a medium?

- Stiffness or Compressibility or Elasticity

What is the relationship between stiffness and compressibility?

Which one is directly related to the value of Young Modulus (also known as elastic modulus)?

What is the relationship between stiffness and elastance?
Which one is directly related to the value of Young Modulus (also known as elastic modulus)?



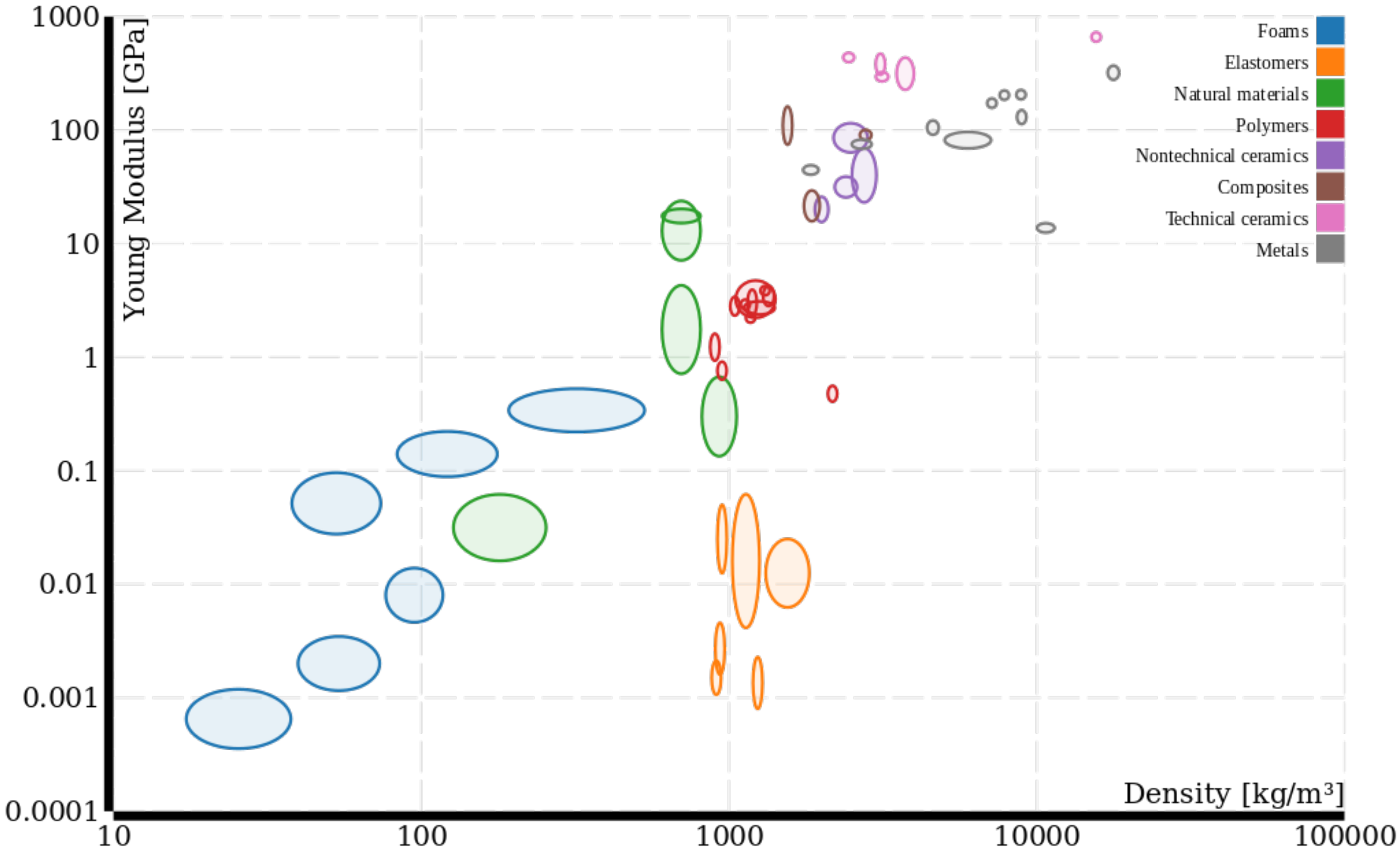
- Reciprocals
- Despite the name the value of the Young Modulus is directly related to stiffness not elasticity.
- Measure of Stress Force / Deformation. More stiff materials require more force to achieve the same deformation, hence higher values.
- Aside from empirical measurement, can also be calculated from the speed of sound and density of the medium as

$$\text{YM} = \text{velocity}^2 \times \text{density}$$

Young modulus (aka. elastic modulus) vs density for a sample of 50 materials. The colors represent families of materials. The scales are logarithmic and the semi-axes of the ellipses represent the variation of the material property for each group.

Despite its name the Young Modulus is a measure of stiffness and its **value increases with stiffness**.

See also:
https://en.wikipedia.org/wiki/Young's_modulus



Why does the speed of sound SEEM to increase with density (when it actually doesn't)?

Why does the speed of sound SEEM to increase with density (sound moves faster through metal than air)?

- Because in most but not all cases density and stiffness are correlated and stiffness does lead to faster sound transmission.
- But consider what happens to the speed of sound in a gas as the gas cools at constant pressure (speed drops)

	Sound Velocity (m/s)	Density (g/cm^3)
Lead	1 322	11
Stainless steel	5 790	~8
Diamond	12 000	3.5

What is the forumula for the speed of sound in a medium as a function of density and elastic modulus?

What is the forumula for the speed of sound in a medium as a function of density and elastic modulus?

$$c = \sqrt{\frac{elastic\ modulus}{density}}$$

Impedance (Z) relates excess pressure to the velocity of the particles in the medium.

The higher the impedence the slower the particles will move in response to a given excess pressure.

What is the SI unit for impedance?

$$Z = density\ x\ velocity = density\ x \sqrt{\frac{stiffness}{density}} = \sqrt{stiffness\ x\ density} = \sqrt{K\rho}$$

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- kg / m^3 x m/s = **kg / m^2s** = rayl

Two substance of equal density, one has a higher impedance than the other. In which substance does the sound travel faster?

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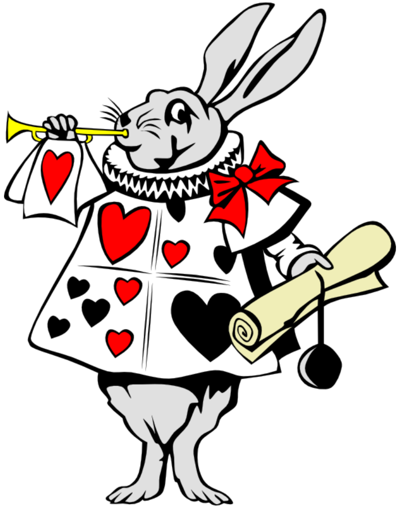


$$Z = density \; x \; velocity$$

The one with **higher impedance** has the **higher velocity**.

This is a bit counter intuitive. Impedance is related to the resistance of the particles in the medium to move in response to an applied pressure. *This is not the same as resistance to wave propagation.*

It is similar intuitively to stiffness.

Gerald G Rabbit From Alice In wonderland. Open Clip Art Library. (Public Domain).

Which of these substances has the highest impedance?

	Sound Velocity (m/s)	Density (g/cm^3)
Lead	1 322	11
Stainless steel	5 790	~8
Diamond	12 000	3.5

Which of these substances has the highest impedance?

	Sound Velocity (m/s)	Young Modulus (Pa)	Density (g/cm^3)	Density (kg/m^3)	Impedance (Rayl)
Lead	1 300	16 E+9	11	11 000	**14.5 E+6**
Stainless steel	5 500	150 E+9	~8	8 000	**46.3 E+6**
Diamond	12 000	1200 E+9	3.5	35 00	**42.0 E+6**

What is the application of continuous wave ultrasound in echocardiography?

What is the application of continuous wave ultrasound in echocardiography?

- Continuous wave doppler (CWD) measurements

Why is continuous wave ultrasound not used for imaging?

Why is continuous wave ultrasound not used for imaging?

- Because it cannot be used to determine the distance of a target from the transducer (range ambiguity)

What is the difference between **energy** & **power**?

What are the SI units for each?

What is the difference between **energy** & **power**?

What are the SI units for each?

- Power is a measure of **energy flow**. Though a given surface (analogous to the flow of sewage through the cross section of a pipe)
- SI units for energy is the Joule, which is equivalent to $kg.m^2/s^2$ (remember the formula for kinetic energy = (½) mass x velocity^2 or the famous $e=mc^2$)
- SI units for power is J/s (since it measure the rate of flow) or Watt.

What does the transmission power of a transducer refer to?

What does the transmission power of a transducer refer to?

- The rate at which mechanical energy, in the form ultrasound waves, is leaving the surface of the transducer.

What is the difference between the sun power passing the lense surface and that impacting the ignition point?

Photo: Dave Gough https://www.flickr.com/photos/spacepleb/1505372433

What is the difference between the sun power passing the lense surface and that impacting the ignition point?

Photo: Dave Gough https://www.flickr.com/photos/spacepleb/1505372433

- There is no difference. The same amount of power is passing through both areas.

Then why would an insect sitting on the lense surface likely be safe (at least from fire)?

What is the difference between **power** and **intensity**?

What is the SI unit of intensity?

What is the difference between **power** and **intensity**?

What is the SI unit of intensity?

- Power is the rate of energy flow through a surface.
- Intensity is the concentration of power per unit area and is measured as W / m^2
- The same power goes through the lense and the insect, but at the insect the instensity is much higher.

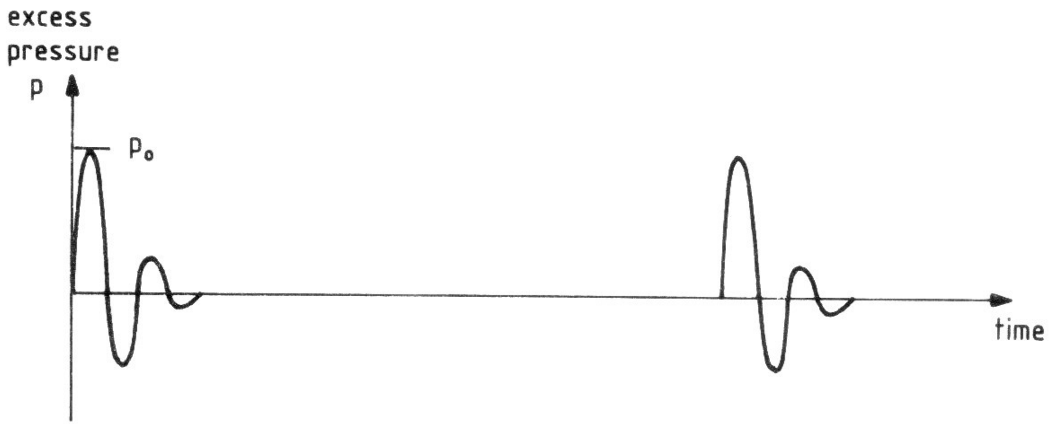
What 2 pieces of information do you need to calcluate the proportion of the Sun's total power that is impacting the insect?

What 2 pieces of information do you need to calcluate the proportion of the Sun's total power that is impacting the insect?

1. The distance of the lense from the sun.
2. The radius or surface area of the lense.

What is the relationship between wave pressure and wave **intensity**?

Draw an intensity vs. time representation of this repeating pulsewave signal.



Fish P. Physics and Instrumentation of Diagnostic Medical Ultrasound. Wiley; 1990. 268 p.

What is the relationship between wave pressure and wave **intensity**?

Draw an intensity vs. time representation of this repeating pulsewave signal.

Intensity and power are proportional to pressure²

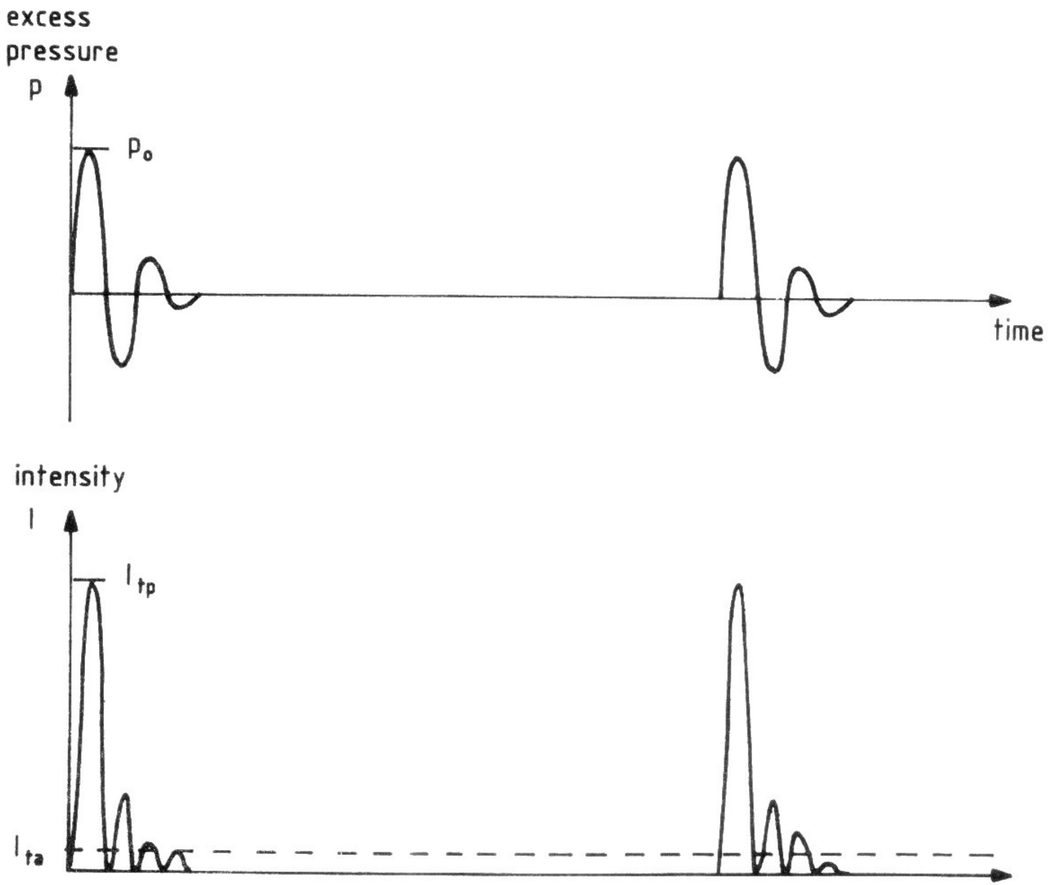


Figure 2-11 The excess pressure and intensity variation with time at a point in the field of a repetitively pulsed ultrasound source showing the temporal peak (Itp) and the temporal average (Ita) intensities.

Fish P. Physics and Instrumentation of Diagnostic Medical Ultrasound. Wiley; 1990. 268 p.

The 3D shape of the pulse

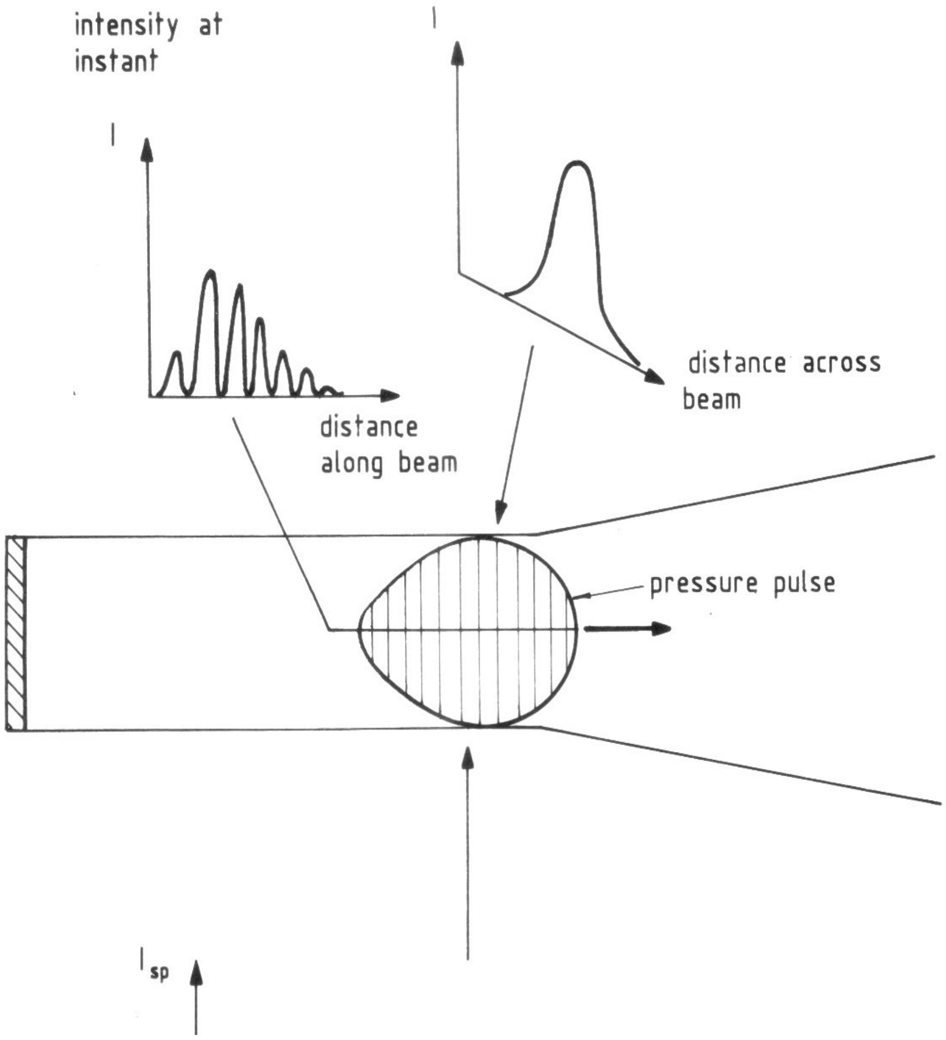
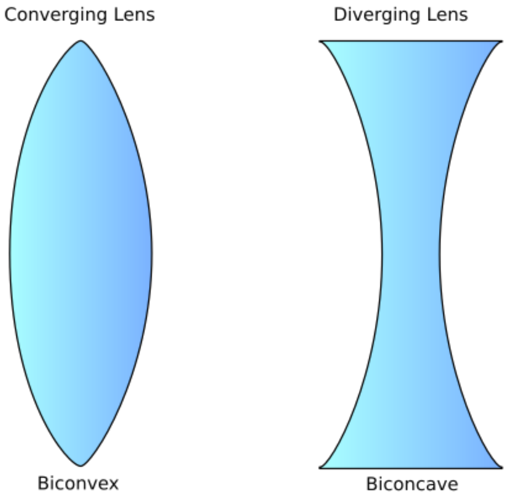


Figure 2-12 (a) The wavefronts of a pressure pulse in the field of a plane ultrasound transducer at an instant in time, together with the intensity variation along the beam axis and across the beam.

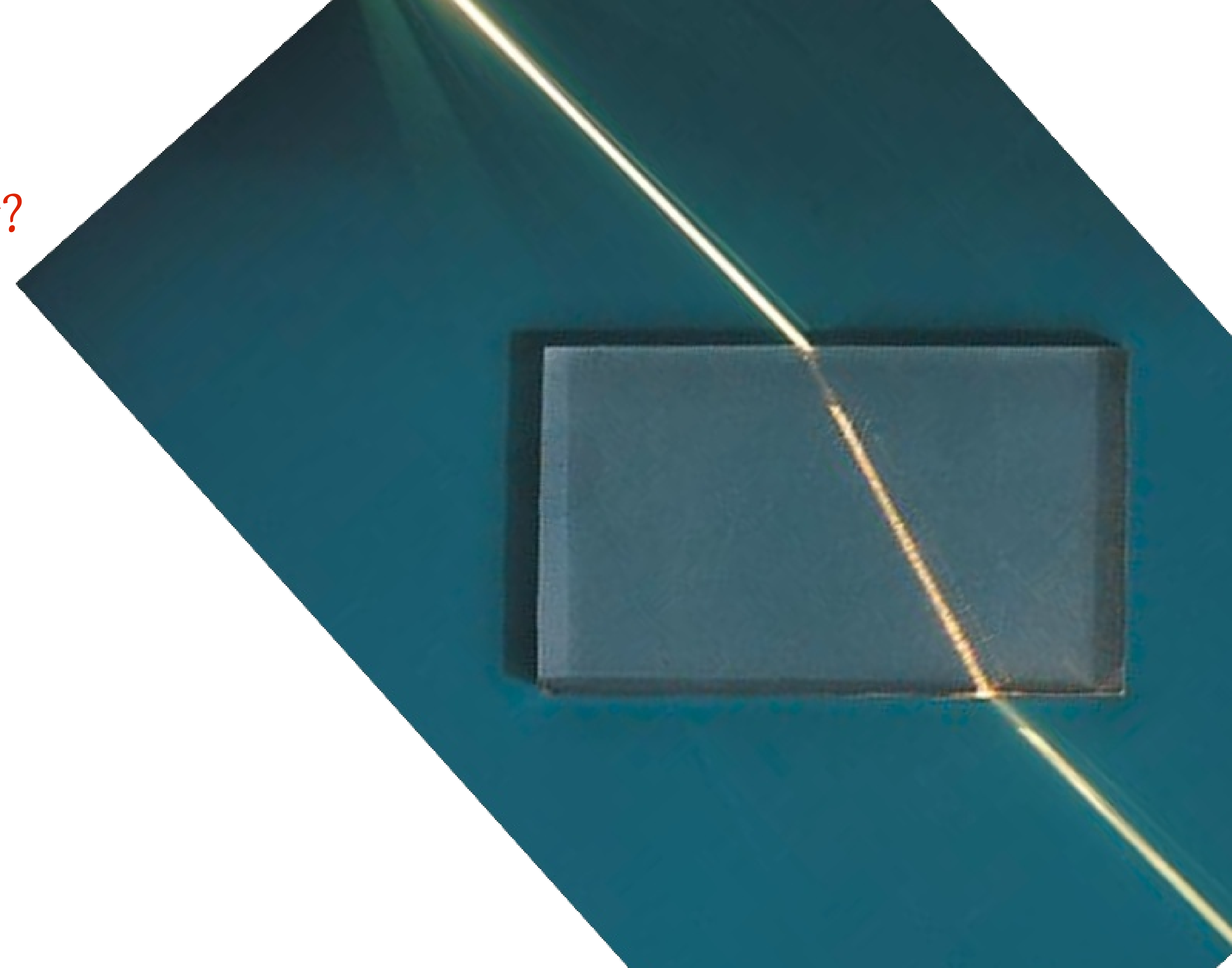
Fish P. Physics and Instrumentation of Diagnostic Medical Ultrasound. Wiley; 1990. 268 p.

To focus the a straight beam of light travelling through air onto a point a **convex** optical lense is used.
To do the same for a sound wave a **concave** acoustic lense is needed.
Why?



Refraction

What is Snell’s Law?



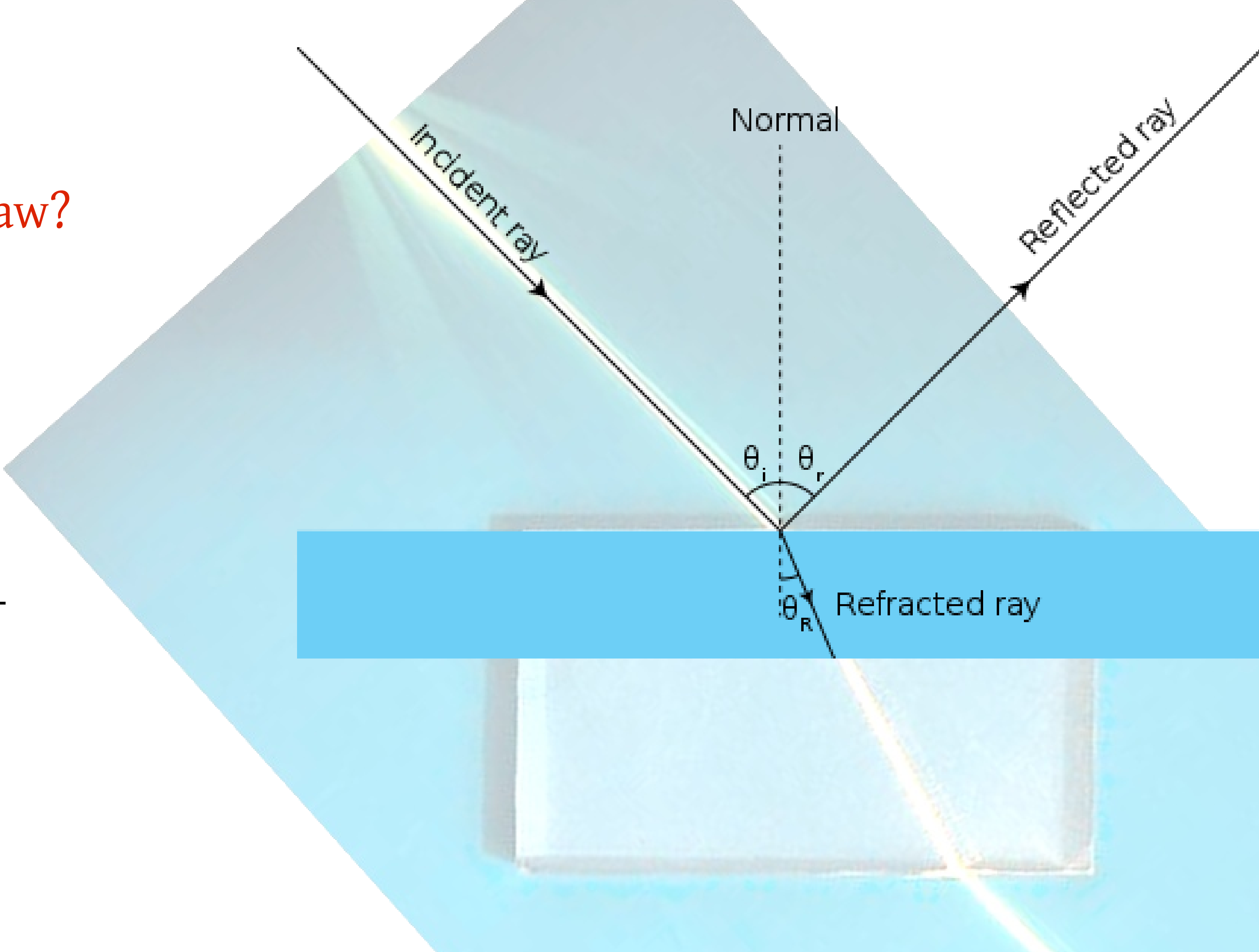
Refraction

What is Snell's Law?

Snell's Law:

$$\frac{\sin\theta_i}{c_i}=\frac{\sin\theta_R}{c_R}$$

$$\frac{\sin\theta_i}{\sin\theta_R}=\frac{c_i}{c_R}$$



$$\frac{\sin \theta_i}{\sin \theta_R} = \frac{c_i}{c_R}$$

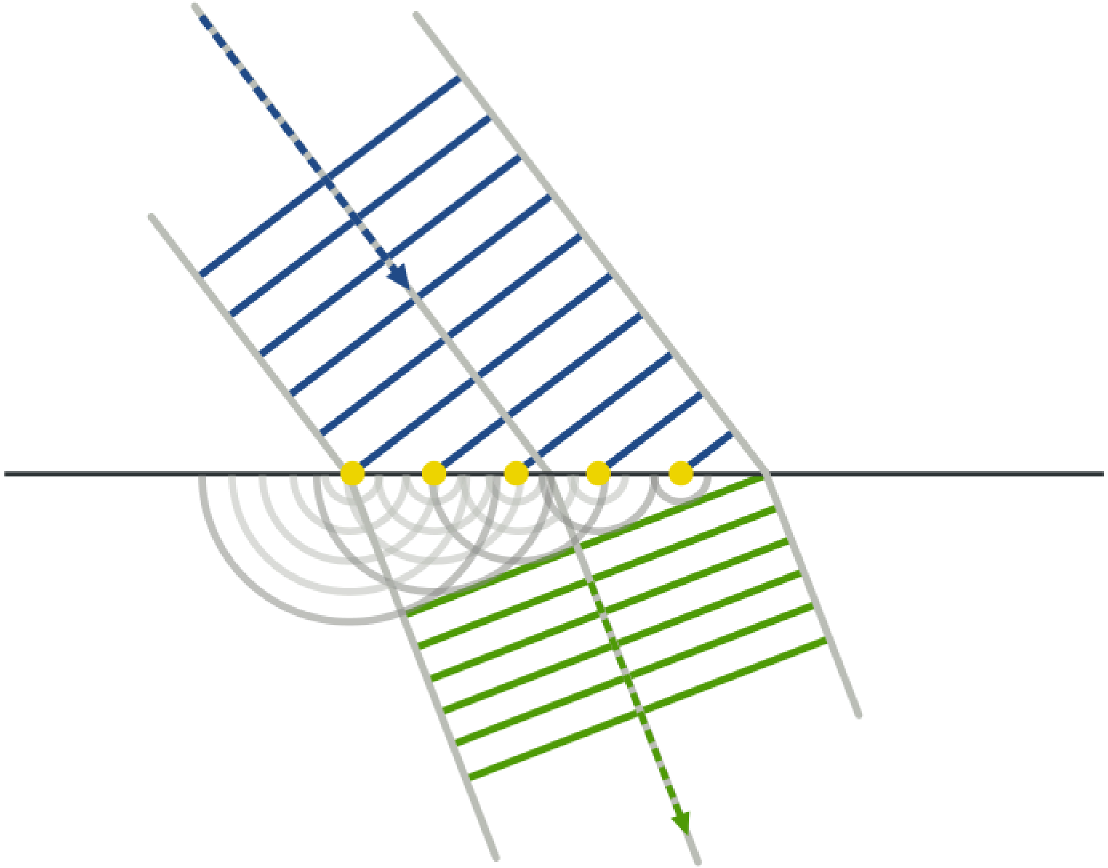
If the second medium has **lower** sound velocity than the first, the axis of the wave will bend **[towards? / away?]** from the normal.

$$\frac{\sin \theta_i}{\sin \theta_R} = \frac{c_i}{c_R}$$

If the second medium has **lower** sound velocity than the first, the axis of the wave will bend **towards** from the normal.

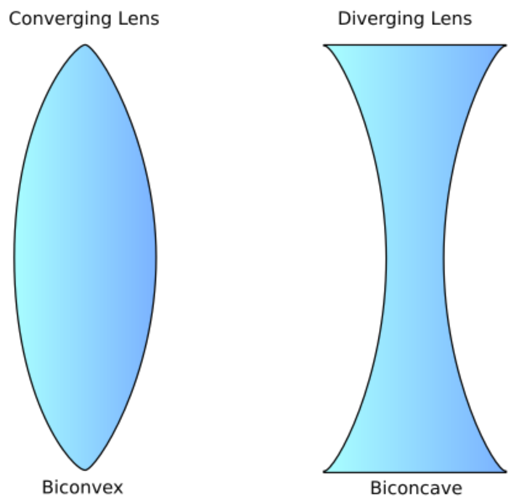
Snell's Law Derivation from Huygens Fresnel Principle

- Note that the wavefronts in the second medium are closer together since the the wave has slowed down.
- The wave has bent towards the normal.



Refraction at an interface based on Huygens-Fresnel principle

To focus the a straight beam of light travelling through air onto a point a **convex** optical lense is used.
To do the same for a sound wave a **concave** acoustic lense is needed.
Why?



Because light travels more slowly in the lense than in air but sound travels faster in the lense than in air

Attenuation

Attenuation of a signal is quoted as 5 dB/m. What does that mean?

Attenuation

Attenuation of a signal is quoted as 50 dB/m. What does that mean?

- dB is a means of expressing ratios. It is not technically a unit.
- It is 10 times the log (base 10) of the ratio of the power or intensity of two signals. i.e.

$$Signal\,Change\;as\;dB = 10 \cdot \log\left(\frac{Power_1}{Power_0}\right)$$

- 50 dB change means that the **ratio of the powers is 10^5**
- i.e. the signal power decreases by 10^5 every meter.

Attenuation

If the signal power is decreasing by 10^5 every meter, what is happing to the pressure amplitude of the signal?

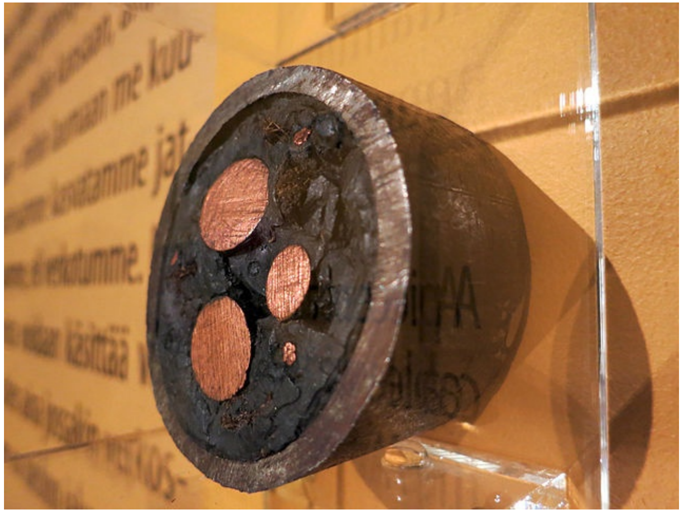
What about the intensity of the signal?

- Since power is proportional to the square of the pressure amplitude the power ratio is equal to the square of the pressure amplitude.
- So the ratio of the pressure amplitudes the square root of 10^5 or $10^{2.5}$
- Since intensity, like power, is also proportional to the pressure amplitude squared, the intensity relationship is the same as the power relationship

Attenuation

If the signal power is decreasing by 10^5 every meter, what is happing to the pressure amplitude of the signal?

Why is the decible defined as it is?



- Logarithmic since attentuation is a log function of distance.
- The factor of 10 was chosen historically in order to have 1dB come out close to an older unit for measuring attentuation of telegraph signal knows as MSC (miles of standard cable).

Trogain, Piece of first transatlantic telegraph cable.
https://commons.wikimedia.org/wiki/File:Piece_of_first_transatlantic_telegraph_cable_at_the_Rupriikki_Media_Museum.jpg CC-BY-SA

Piezoelectricity

- Historical film of crystal manufacturing from quartz https://youtu.be/b--FKHCFjOM
  - https://youtu.be/b--FKHCFjOM?t=1m30s - introduction
  - https://youtu.be/b--FKHCFjOM?t=3m19s - sorting
  - https://youtu.be/b--FKHCFjOM?t=23m30s - thickness classification
  - https://youtu.be/b--FKHCFjOM?t=26m58s - frequency classification
  - https://youtu.be/b--FKHCFjOM?t=30m7s - frequency adjustment
- Home made Piezoelectric crystal: https://www.youtube.com/watch?v=K3G2QM5a-9U
- Modern systems use PZT, lead zirconate titanate.