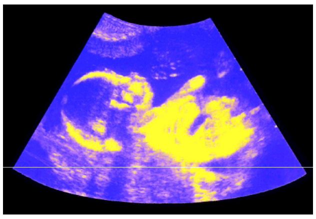
**BME2 – Biomedical Ultrasonics**

# *Lecture 5: Medical Ultrasound Imaging*



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Department of Engineering Science

## Contents

## References


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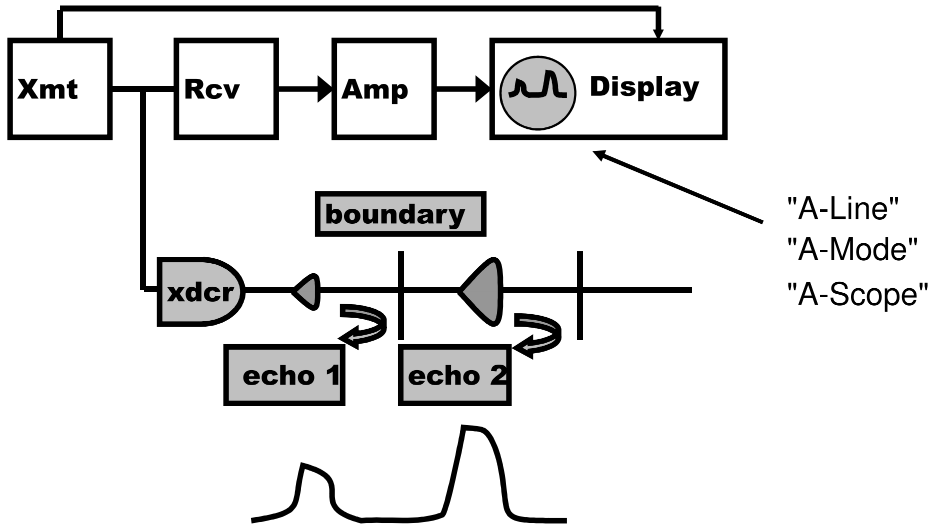
## First… a Little History About Imaging Ultrasound

Doc knows about as much anatomy as I do!

Adapted from Szabo (2004)

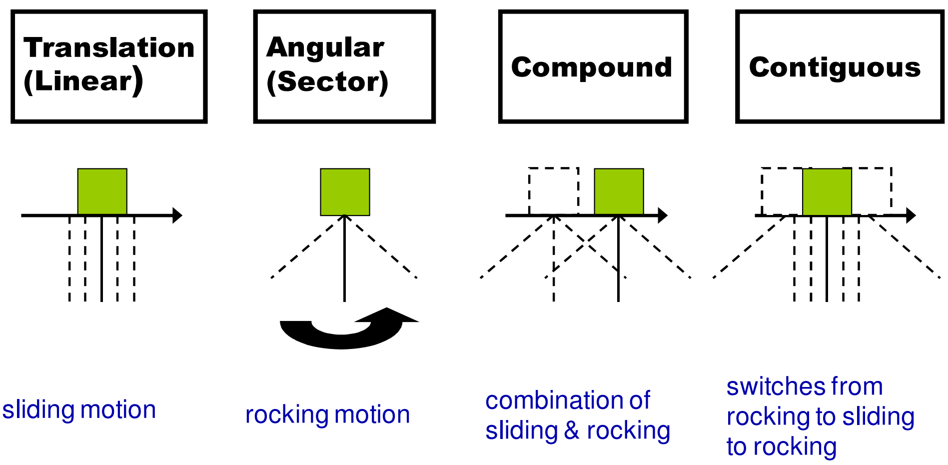
# Early Developments

- SONAR "Echo Ranging" at Ultrasound Frequencies
  - Firestone (1945) developed the "reflectoscope" and applied pulse ranging techniques to flaw detection




# Early Developments

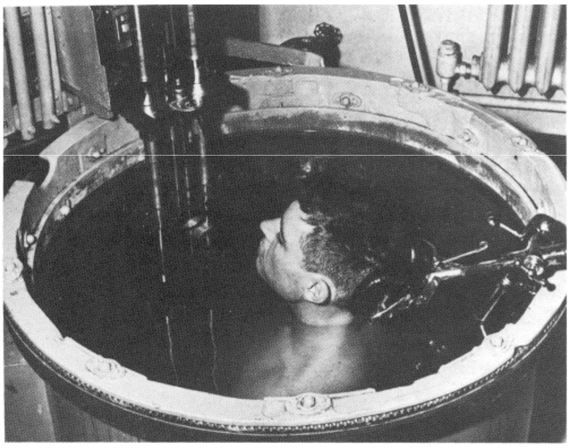
- **It didn't take long before someone thought to move the transducer -- the 2-D "B-Mode" scan was born**
  - **Howey fitted a pulse echo transducer to a B-29 gun turret (Holmes, 1980); scanned a patient's neck along a circular arc**
  - **Early systems employed water baths**
  - **Wild and Reid developed first hand-held contact scanners (Wells, 1969)**



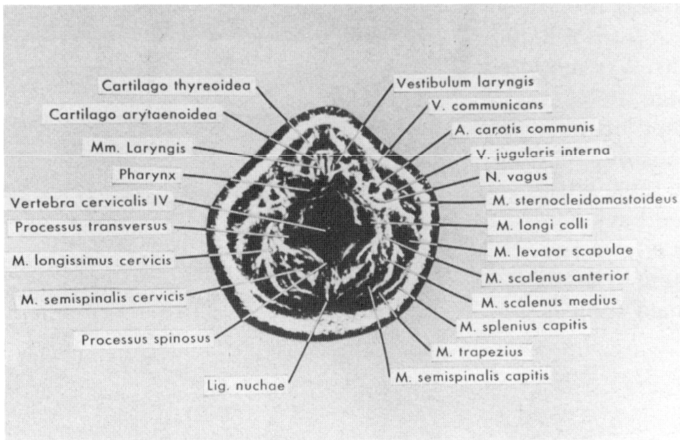
From Goldberg & Kimmelmann (1988)

# Early Developments

## Howery's B-29 Ultrasonic Tomographic System



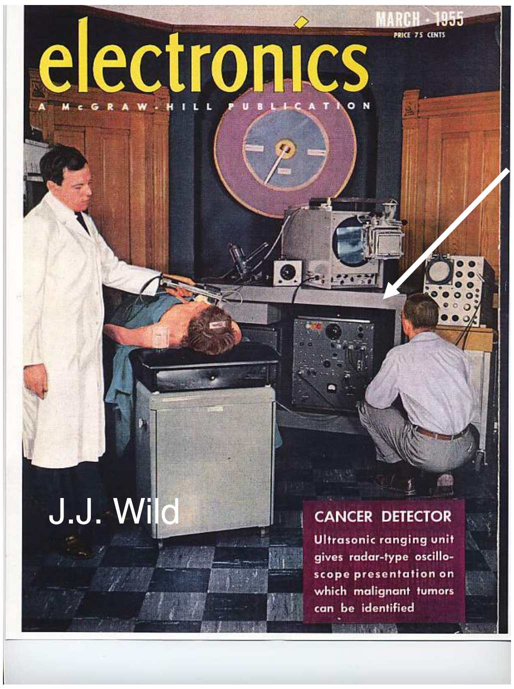
Lucky Patient




Annotated "Image" of the Neck

Adapted from Szabo (2004)

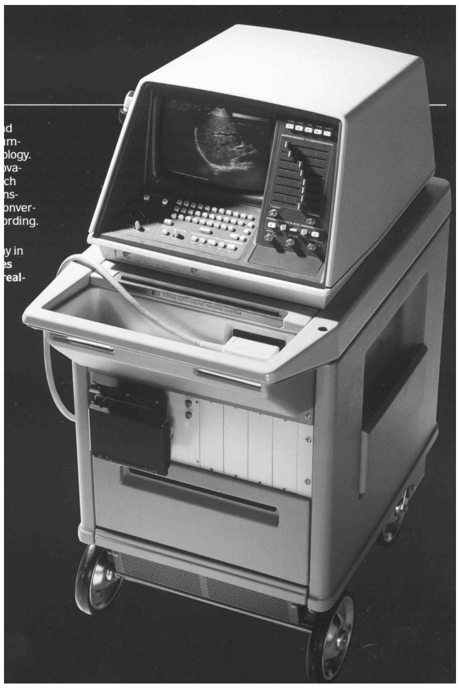
# Milestone Imaging Systems




Radar Equipment!

J. Reid

Early Mechanically Scanned System

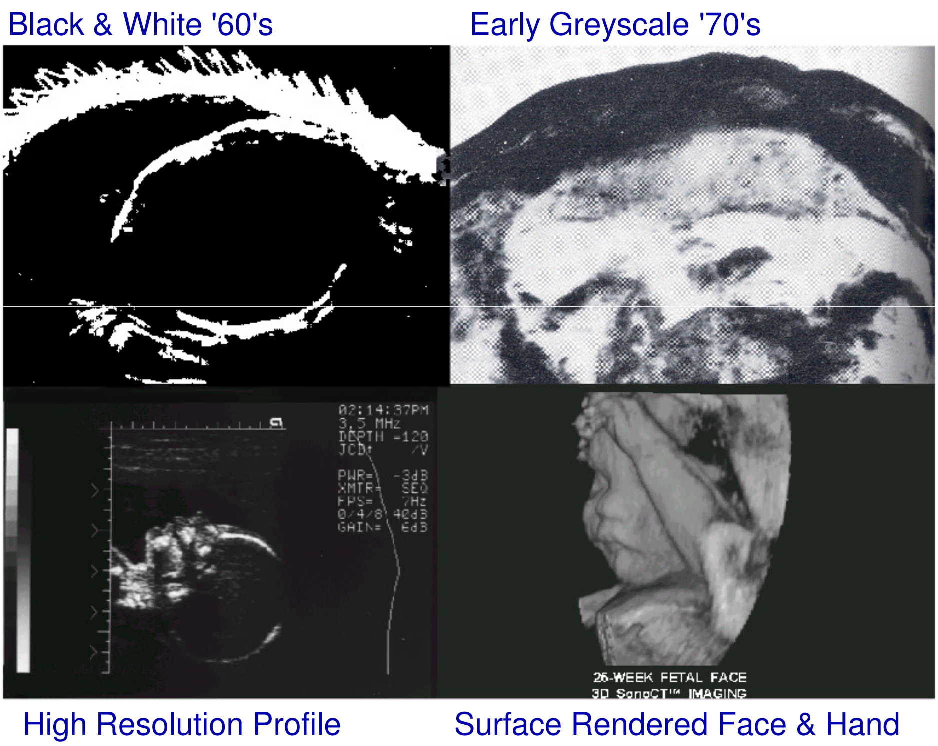


Early Phased Array System "HP 70020A"

Adapted from Szabo (2004)

# Milestone Images

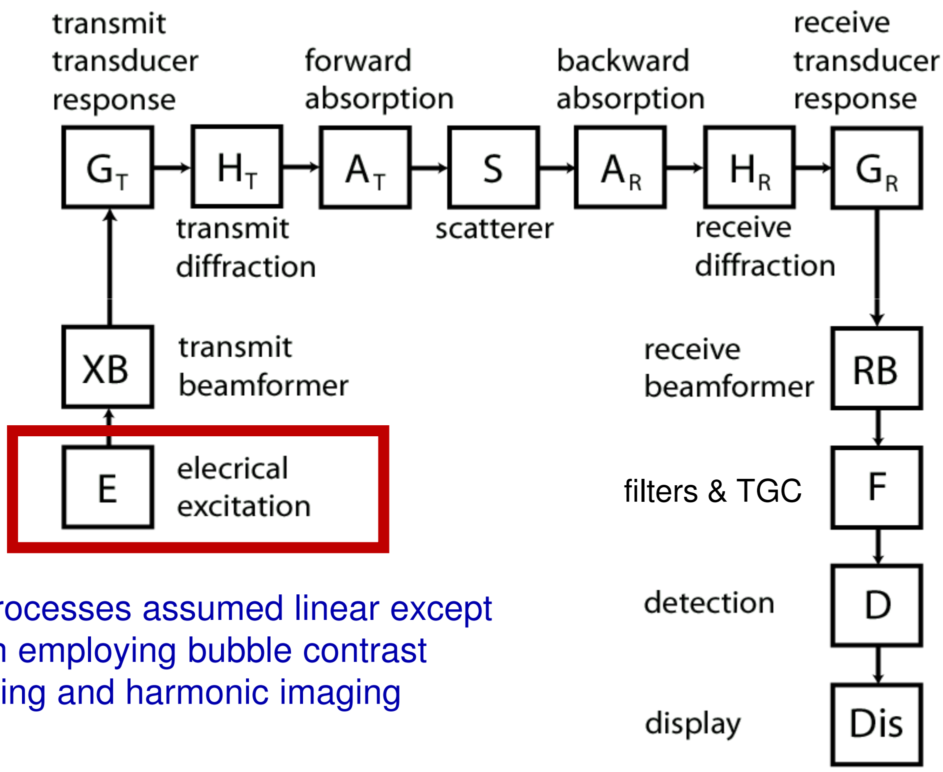
## Four Views of a Fetus




Adapted from Szabo (2004)

# The Imaging Roadmap

## The Diagnostic Imaging Signal Pathway



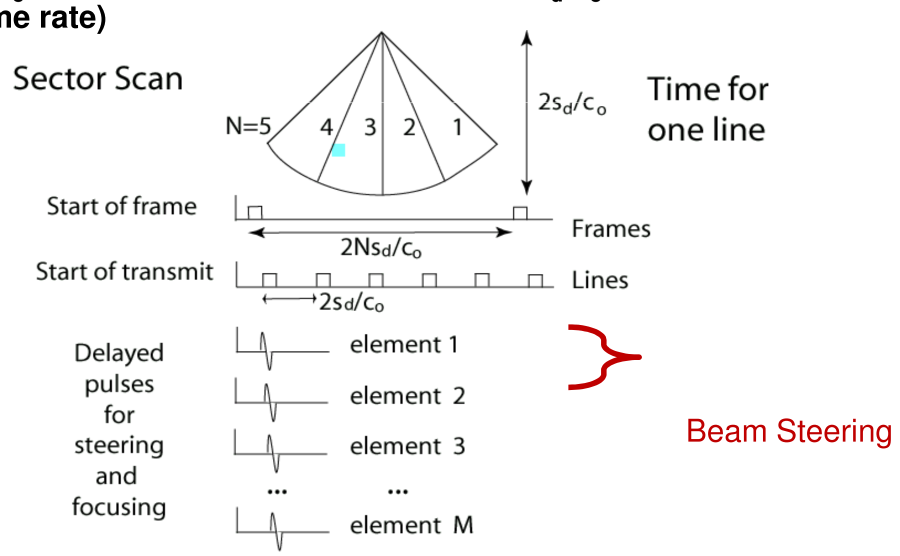

All processes assumed linear except when employing bubble contrast imaging and harmonic imaging

# Step 1: Electrical Excitation

- **Primitive Excitation Pulses Consist of Precisely Timed Single-Cycle Pulses or Multiple-Cycle Pulses**

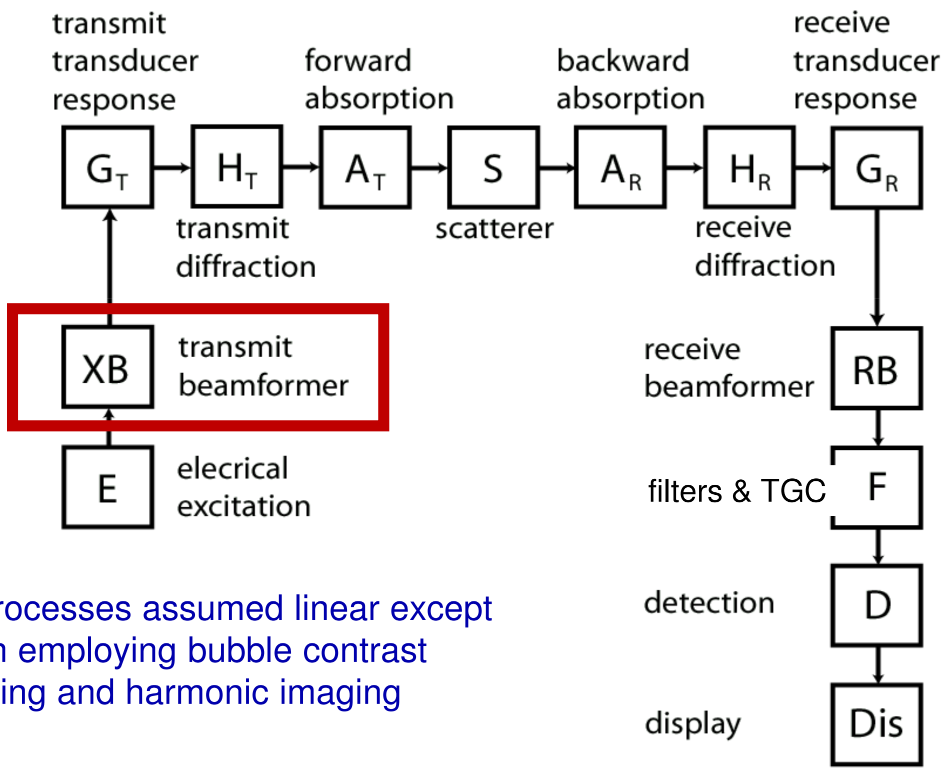
**N = Number of Scan Lines**
**$2S_d/c_o$ = time for one line (frame rate)**

**$S_d$ = desired scan depth**
**$2NS_d/c_o$ = Time for one scan**




Adapted from Szabo (2004)

# The Imaging Roadmap
## The Diagnostic Imaging Signal Pathway



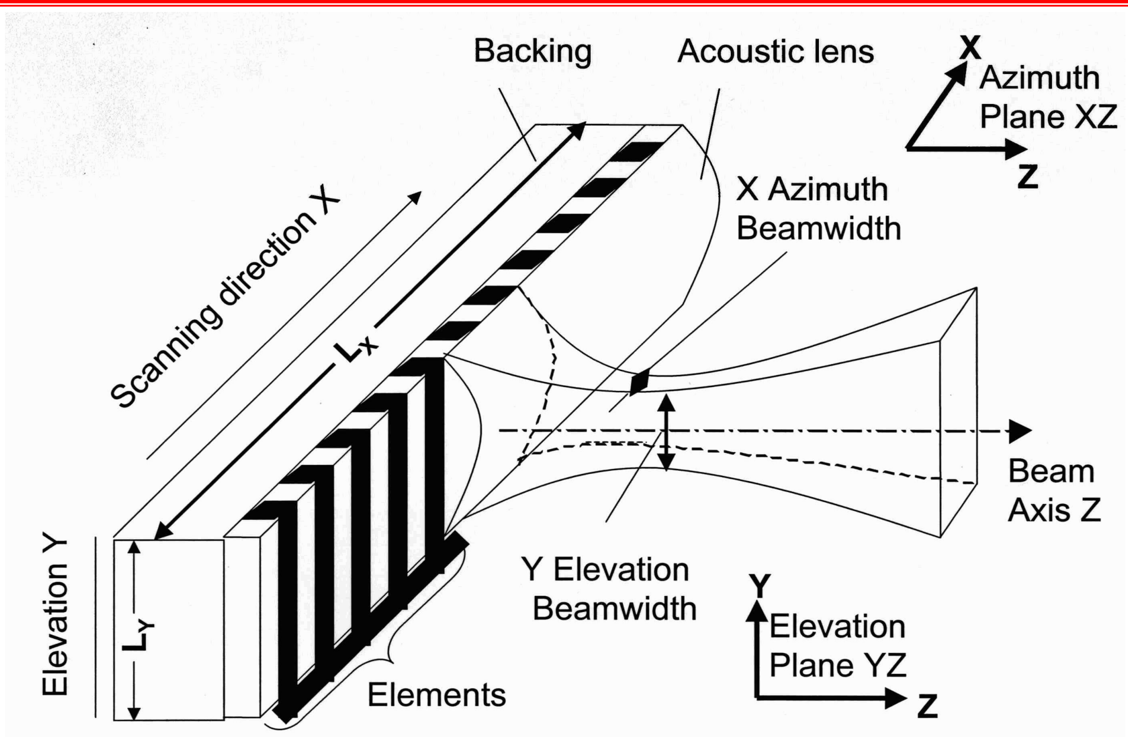

All processes assumed linear except when employing bubble contrast imaging and harmonic imaging

# Step 2: Transmit Beamformer

- Arrays consist of many small elements as opposed to large continuous apertures
- Each element is excited by signals delayed (phased) to steer and focus the beam electronically in the "scan" or "azimuth" plane
- A fixed focus lens provides focusing in the elevational plane
- By varying the delays to individual elements you can both focus the beam and direct its' axis.
- Beams can be radially scanned or linearly scanned
- Beamforming on receive proceeds in the same way as on transmit
  - You delay the received signals
  - You linearly sum the delayed signals

Adapted from Panda (1988) via Szabo (2004)

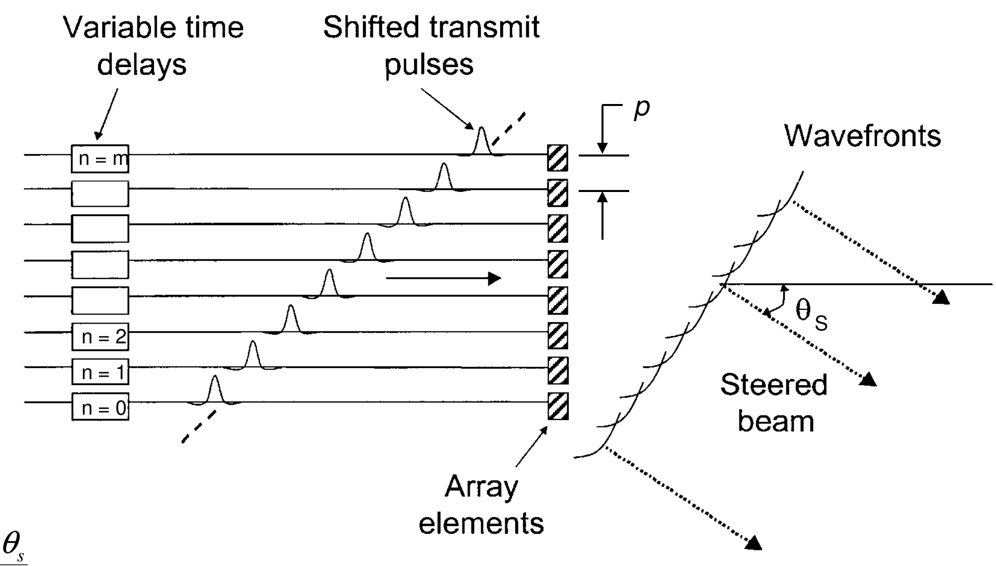
# Linear Array Geometry



Adapted from Szabo (2004)

# Phase Delay Beamsteering

- Introduce a linear time (phase) delay across the array elements corresponding to a wavefront at angle $\theta_s$ from the Z axis.




$$\Delta t_{sn} = \frac{(np)\sin\theta_s}{c}$$

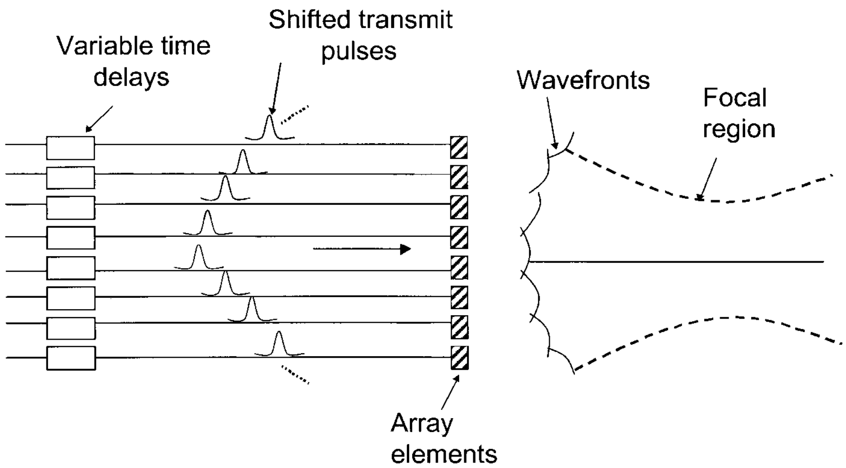
$$\omega_c \Delta t_{sn} = \frac{2\pi(np)\sin\theta_s}{\lambda_c}$$

From Szabo (2004)

# Phase Delay Focusing

- **Arrays can be focused by adding time delays that simulate the curved wavefront**
  - ***r*** **= distance from origin to focal point**
  - $x_n$ **= distance from origin to center of nth element (*np*)**
  - $t_o$ **= constant delay added to avoid negative delays**

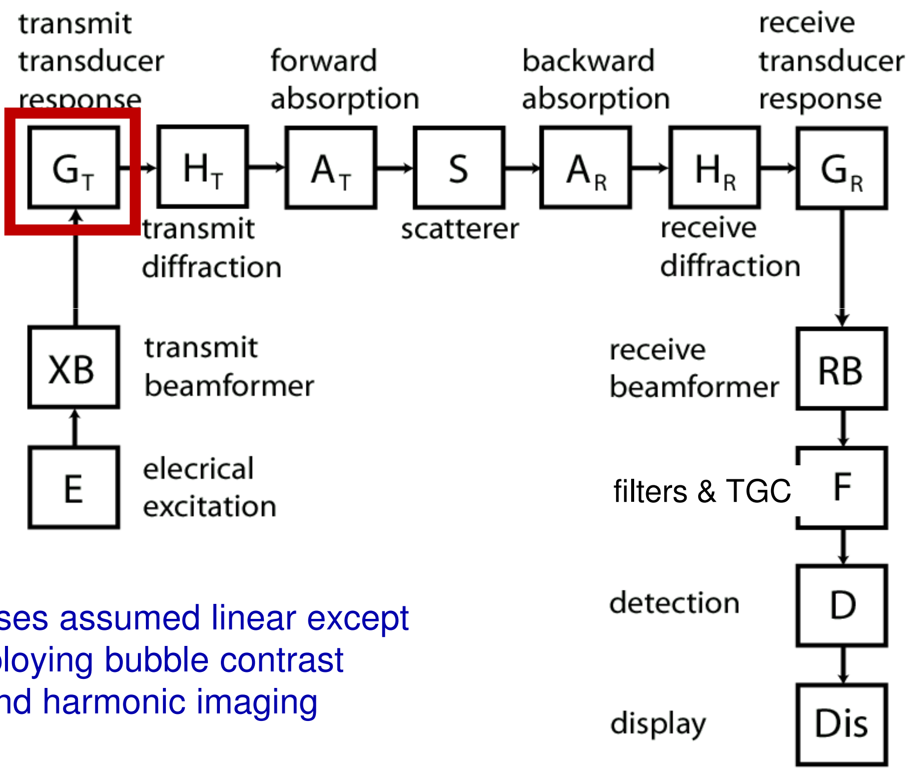
$$\tau_n = \frac{\left[r - \sqrt{(x_r - x_n)^2 + z_r^2}\right]}{c} + t_o$$



Adapted from Szabo (2004)

# The Imaging Roadmap

## The Diagnostic Imaging Signal Pathway



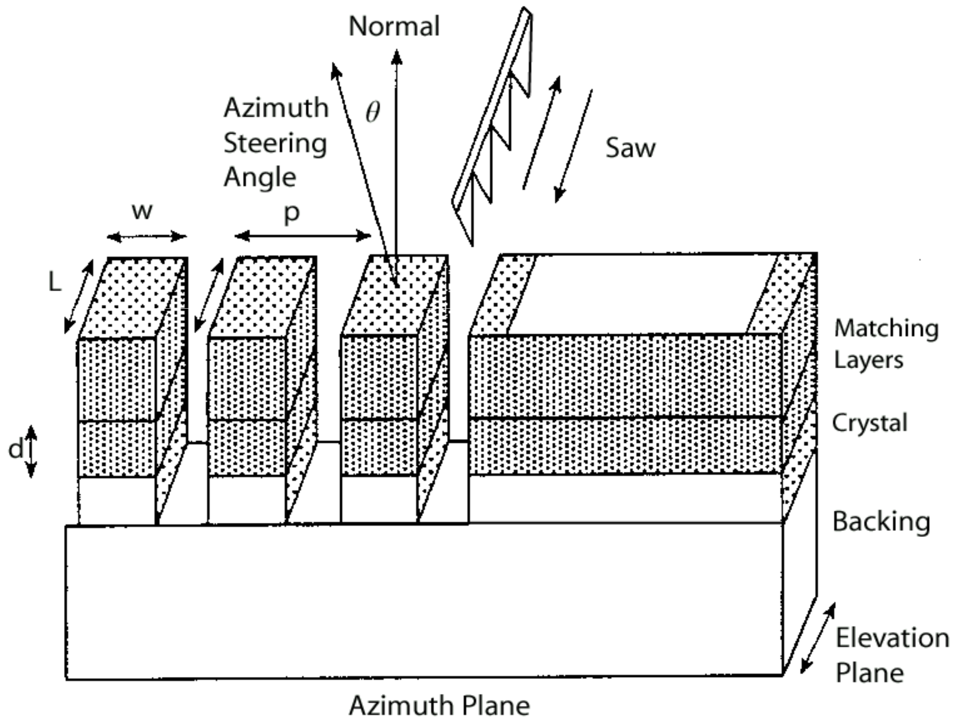

All processes assumed linear except when employing bubble contrast imaging and harmonic imaging

# Step 3: Transducer Considerations

- **Most arrays employ piezoelectric elements characterized by a resonance frequency and Q determined by material properties and construction.**
  - **Geometry and shape of piezoelectric material**
  - **Crystallographic orientation of PZT**
  - **Electrode placement**
- **Most arrays are stacked layers with large surface area bonded onto a backing pedestal**
- **The sandwich is cut into rows using a saw**
  - **Space between elements is the "kerf"**
  - **Width of the elements is given by "*w*"**
  - **Distance between element centers is the "pitch", *p* (typically 1/2 a wavelength)**
- **The cut elements are then covered by a cylindrical lens for elevational focusing**

From Szabo (2004)

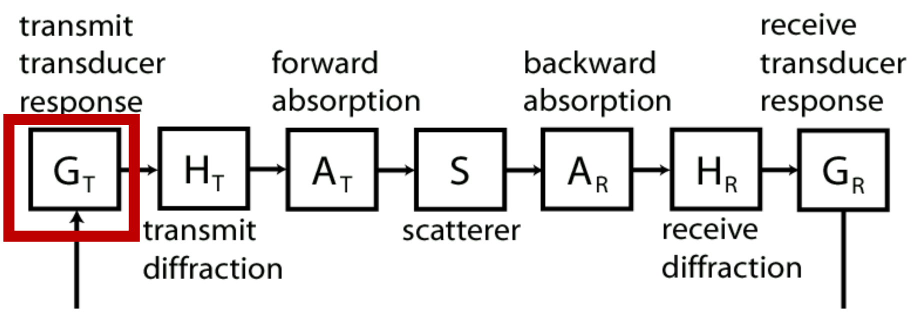
# Step 3: Transducer Considerations




Adapted from Szabo (2004)

# The Imaging Roadmap

## The Diagnostic Imaging Signal Pathway

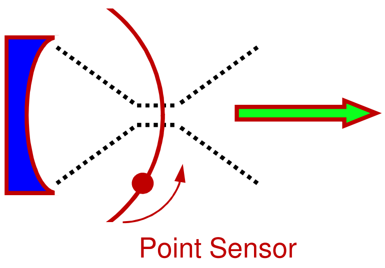


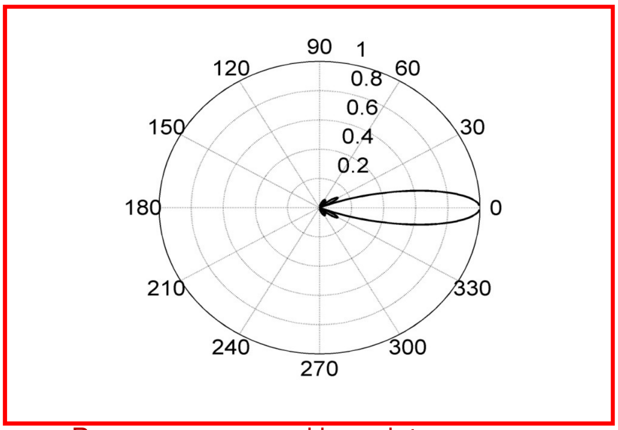

| Damping | Pulse Length | Band Width | Quality Factor | Efficiency | Best Used For… |
|---|---|---|---|---|---|
| Low | Long (20 cycles) | Narrow | High (order 20) | High | Therapy |
| High | Short (1.5 cycles) | Broad | Low (order 1) | Low | Imaging |

# An Important Principle: Reciprocity

- In its most elementary form the acoustic reciprocity principle states that an acoustic response remains the same when the source and receiver are interchanged

- A useful corollary: The **acoustic** response of a linear transducer is the same on receive as it is on transmit




Pressure measured by point sensor



# Competing Transducer Characteristics
## Imaging vs Therapy

- **Axial resolution is given by the spatial pulse length**
  - **B-mode imaging: 1-2 cycle pulse length**
  - **Doppler-mode imaging: 5-10 cycle pulse**
  - **Imaging transducers therefore possess a low quality factor**
    - **Lots of damping (inefficient)**
    - **Operate at low duty cycles to minimize heating and adverse bioeffects**

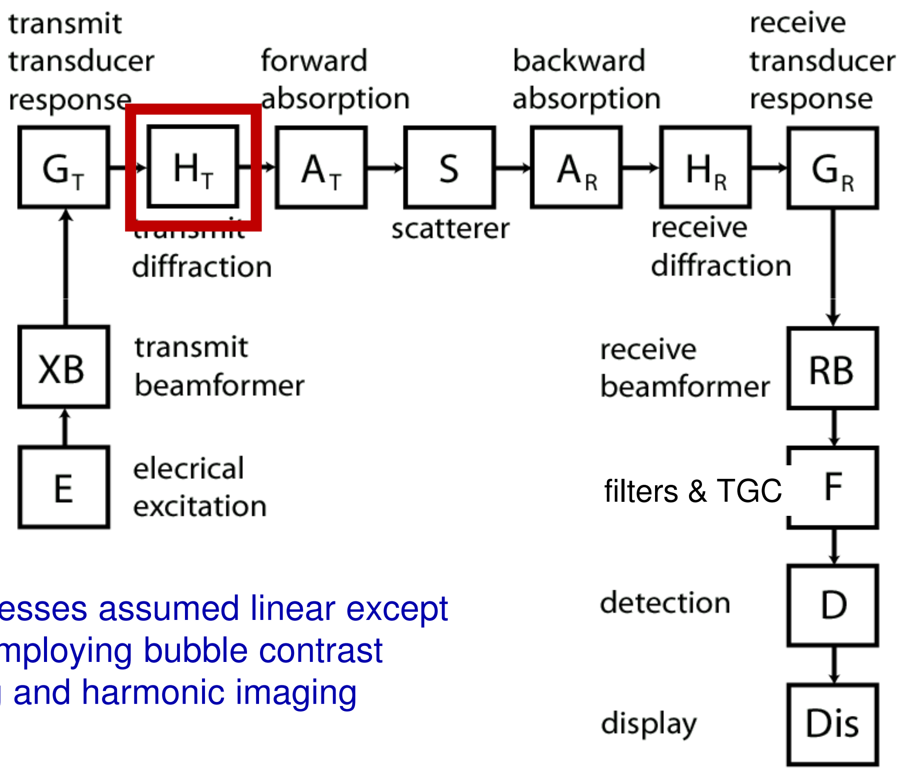
- **Therapy arrays must generate high peak acoustic intensities**
  - **Axial resolution given by focusing**
  - **CW or very long pulses**
  - **Tight focusing requires a large aperture**
  - **High efficiency requires low damping (high quality factor)**

- **A tradeoff exists**
  - **Good imaging transducers are poor therapy transducers, and vice versa**
  - **Image-guided therapy scan-heads usually employ separate transducers for imaging and therapy**

Adapted from Szabo (2004)

# The Imaging Roadmap

## The Diagnostic Imaging Signal Pathway




All processes assumed linear except when employing bubble contrast imaging and harmonic imaging

# Step 4: Transmit Diffraction

- **Radiating sources on the scale of a wavelength create a field described by the mutual interference of "wavelets" generated along the source surface.**
  - **Subdivide the continuous source into an array of point sources**
  - **Each point source is acoustically compact and generates spherical wave fronts**
  - **Sum these individual fields together to yield the radiated pressure field**

- **Rayleigh-Sommerfeld integral (Goodman, 1968)**

$$\phi(r,\omega,t) = \frac{-1}{2\pi} \int_S \frac{e^{i[\omega t - \vec{k}\bullet(\vec{r}-\vec{r}_o)]}}{|\vec{r}-\vec{r}_o|} v_n(r_o)\, dS$$

  - **Where $v_n(r_o)$ is the surface-normal component of the particle velocity and S is the radiating surface**

# Step 4: Transmit Diffraction

- Let $A_n(r_o)$ be the distribution of normal particle velocity across S, then

$$v_n(r_o) = VA_n(r_o)$$

- Rayleigh-Sommerfeld integral becomes

$$p(r,\omega,t) = \frac{i\rho ckV}{2\pi} \int_S \frac{e^{i[\omega t - \vec{k} \bullet (\vec{r} - \vec{r}_o)]}}{|\vec{r} - \vec{r}_o|} A_n(r_o) dS$$

- The Fresnel (or paraxial) approximation assumes that lateral dimensions are small compared with axial distances, thus

$$|\vec{r} - \vec{r}_o| \approx z$$

# Step 4: Transmit Diffraction

- Therefore:

$$p(r,\omega,t) = \frac{i\rho ckV}{2\pi z} e^{i\omega t} \int_S e^{i[-\vec{k} \bullet \vec{r}]} A_n(r_o) dS$$

- The far field radiation pattern for a transducer looks something like the spatial Fourier transform of $A_n(r_o)$ -- the "apodization" function.

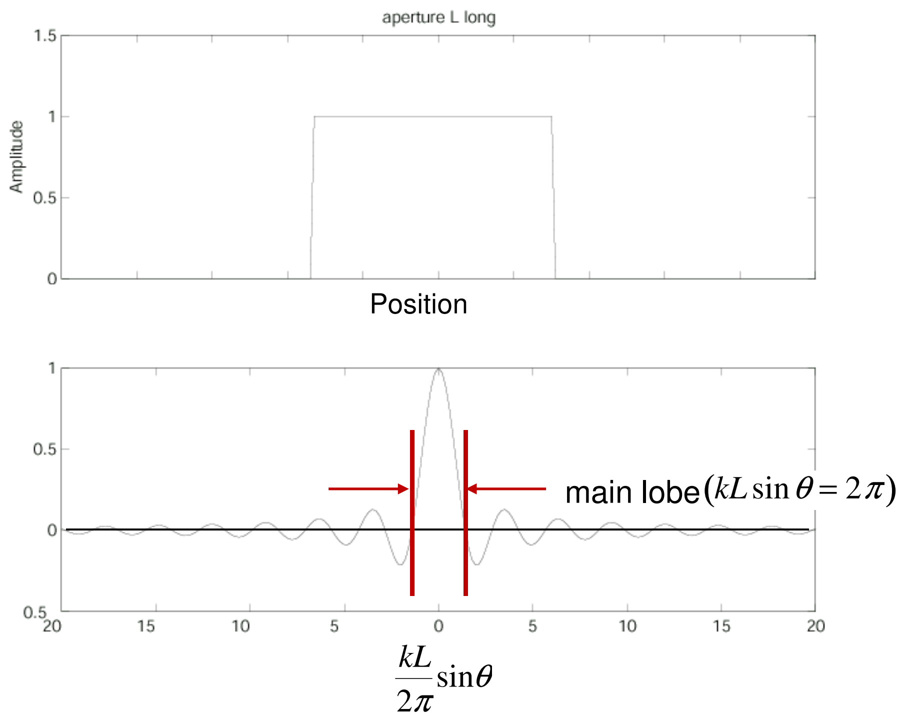
- For a uniform line source of length L, the apodization function is the rectangular function. The transform is a sinc function. Can show that

$$p(\theta) \propto \mathrm{sinc}\left(\frac{kL}{2\pi}\sin\theta\right) = \frac{\sin(\frac{1}{2}kL\sin\theta)}{\frac{1}{2}kL\sin\theta}$$

  - Beam possesses a main lobe plus side lobe structure
  - Acoustically small aperture -- small kL -- wide beam
  - Acoustically large aperture -- large kL -- narrow beam

Adapted from Szabo (2004)

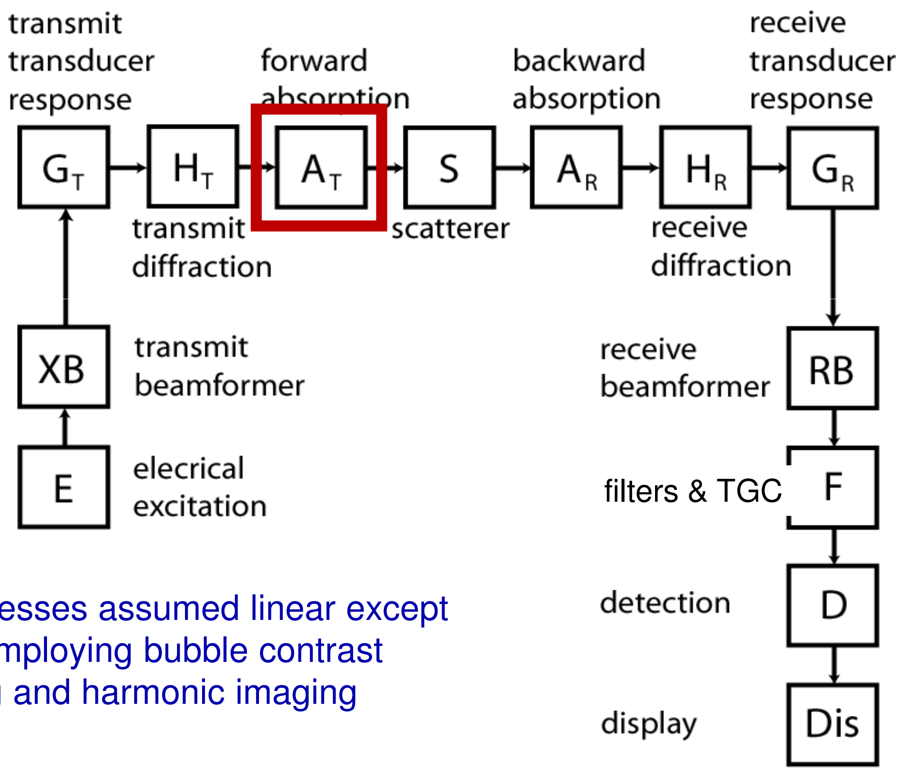
# Step 4: Transmit Diffraction




Adapted from Szabo (2004)

# The Imaging Roadmap

## The Diagnostic Imaging Signal Pathway




All processes assumed linear except when employing bubble contrast imaging and harmonic imaging

# Step 5: Propagation Losses in Tissue

- **Waves propagating in real media experience losses**
  - Thermal conductivity
  - Viscous losses
  - Molecular relaxation
- **These losses, along with scattering, remove energy from the propagating wave, a process known as attenuation.**
  - A time harmonic propagating plane wave is written as

$$P(z,t) = P_o e^{-\alpha z} e^{i(\omega t - kz)}$$

where alpha is the attenuation coefficient in nepers/cm. This is essentially a plane wave with a loss factor that increases exponentially with distance.

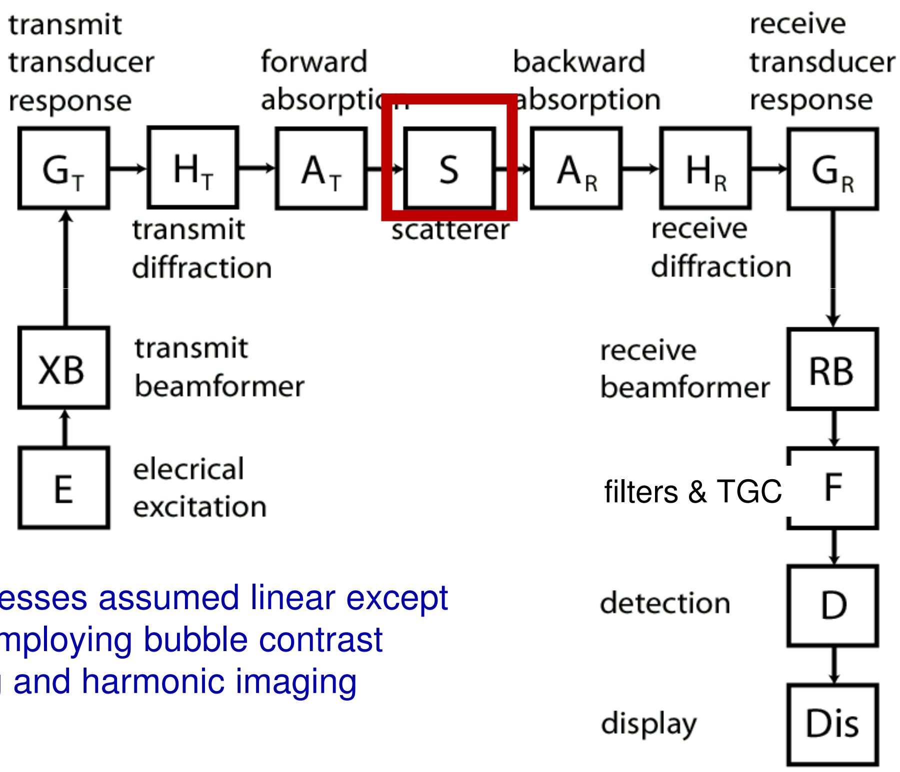
- **Because imaging is done with pulse echoes, it is useful to consider the effect of attenuation on pulse waveforms as well as intensities**
  - Understanding frequency-dependent attenuation is key

# Step 5: Propagation Losses in Tissue

- **Visco-thermal absorption has quadratic frequency dependence**
- **Not the case for propagation through tissues**
  - Power law attenuation model: $\alpha(f) = \alpha_o + \alpha_1 f^y$
  - Dispersion $c(f) = c_o + \Delta c(f)$
- **General rule of thumb for power law attenuation: y ≈ 1.1**
  - Duck (1990) has compiled data for a number of different tissues
  - Scattering contributes to measured attenuation
    - About 10-15% of total attenuation at low MHz frequencies
- **Deviation from viscothermal behavior is not fully understood**
  - Viscoelastic rheology, multiple relaxation times, etc
  - Beyond scope of lecture: See Szabo (2004) for a detailed discussion

Adapted from Szabo (2004)

# The Imaging Roadmap
## The Diagnostic Imaging Signal Pathway




All processes assumed linear except when employing bubble contrast imaging and harmonic imaging

# Step 6: The Scattering Medium

- **What information is contained in an ultrasound image?**
  - **Spatially dependent backscatter and transmission "properties" of the propagation medium**
    - **Interfaces**
    - **Volume scattering**
    - **Transmission and forward scatter impacts returns from objects "downstream"**
  - **This information is further "colored" by systemic characteristics**
    - **Transducer spatial and temporal response**
    - **Signal processing algorithms**
    - **Image processing algorithms**
    - **Frequency-dependent propagation losses**
    - **Nonlinearity**
- **Radiologists are needed to bridge the gap between what you see on the screen and the diagnosis of illness**

## Step 6: The Scattering Medium
### Tissues present scatterers possessing several length scales

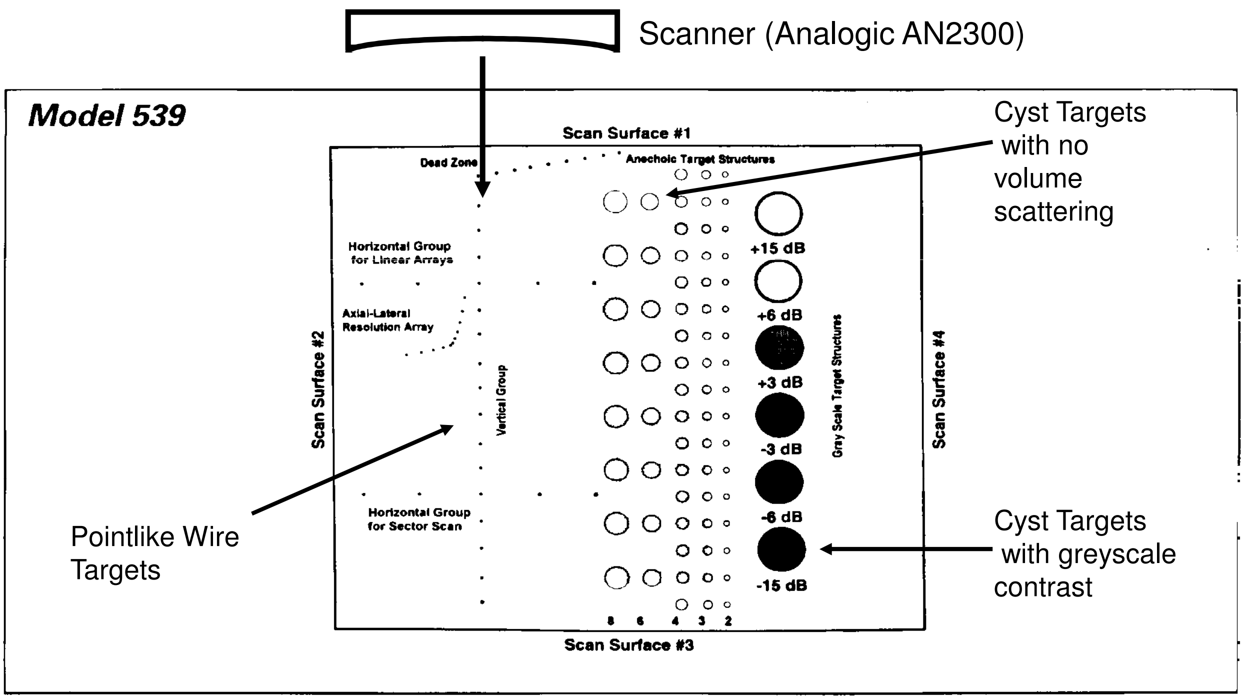
- Class 1: Objects much smaller than λ - diffusive scattering
  - Rayleigh scattering from individual particles (Morse & Ingard, 1968)
  - Pronounced frequency dependence ($I_s$ proportional to $f^4$)
  - Discrete returns are not resolved - you get volume scattering
  - Contrast based on compressibility and density of the particles and the number density of scattering particles -- not changes in bulk acoustic impedance

$$p_s = \frac{1}{3}\frac{p_i}{kr}(ka)^3\left[\left(\frac{\kappa-\kappa_s}{\kappa}\right)+\left(\frac{3(\rho-\rho_s)}{2(\rho+\rho_s)}\right)\cos\theta_s\right] \qquad ka << 1$$

- Class 2: Objects on the order of λ - diffractive scattering
  - Discrete returns with complicated angle and frequency dependence
  - Governed by matching boundary conditions -- continuity of normal stress and normal velocity -- at the surface of the scatterer (Morse & Ingard, 1968)
  - Invoke the Born approximation

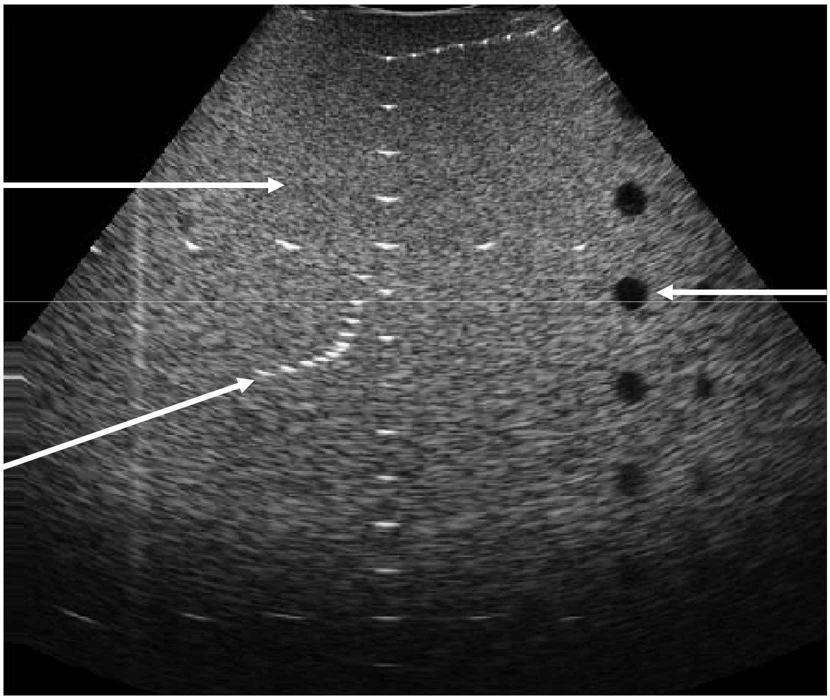
- Class 3: Objects and interfaces much larger than λ - specular reflection
  - Manifested as discrete returns that obey Snell's law
  - Contrast based primarily on the impedance mismatch at the boundary
  - Interfacial transmission loss matters too!

## Step 6: The Scattering Medium
### Geometry of A.T.S. Labs Calibration Phantom



## Step 6: The Scattering Medium

### B-Mode Image of A.T.S. Labs Calibration Phantom

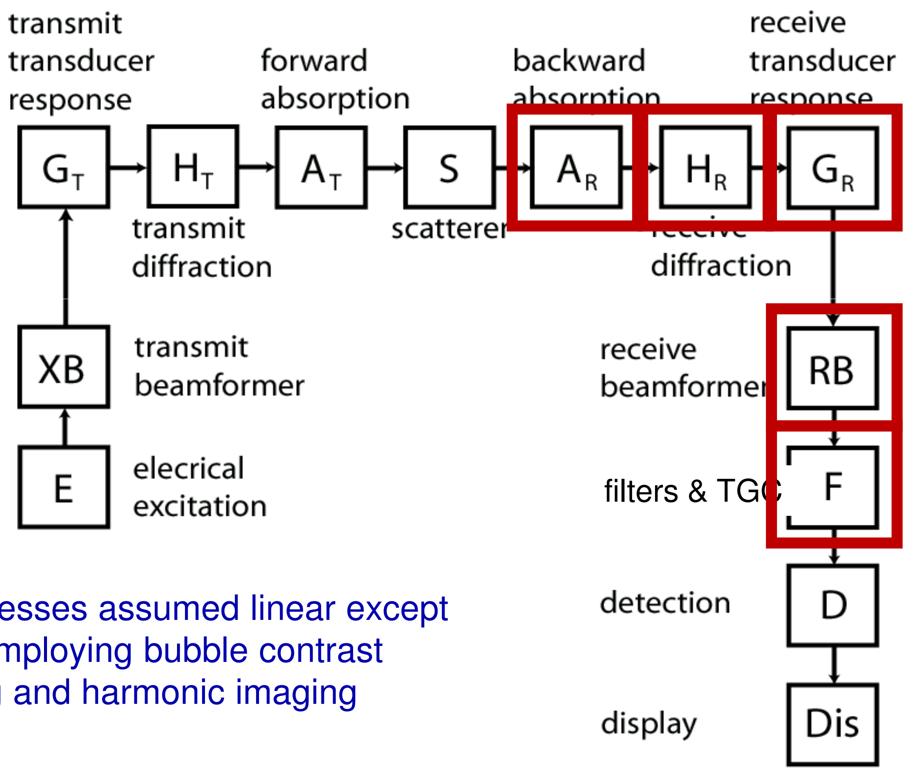



Analogic AN2300 equipped with a 5 MHz convex array scanhead

Adapted from Szabo (2004)

## The Imaging Roadmap

### The Diagnostic Imaging Signal Pathway

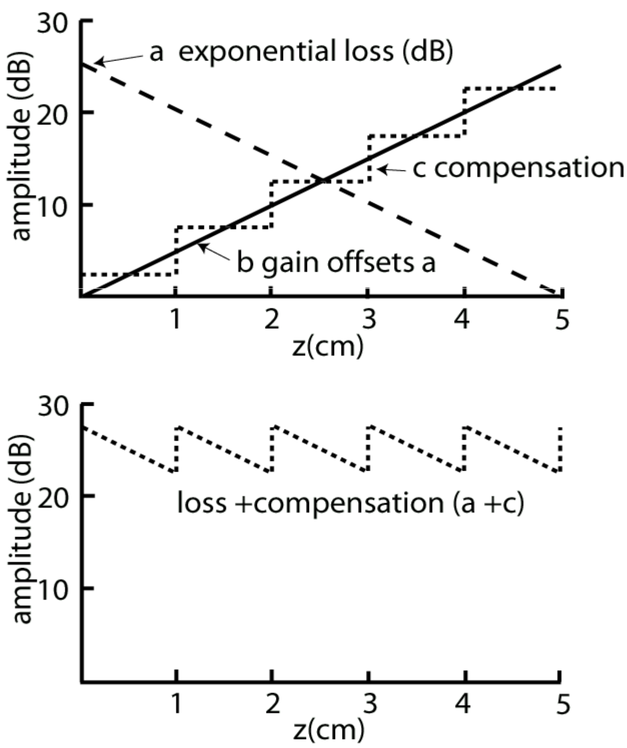



All processes assumed linear except when employing bubble contrast imaging and harmonic imaging

Adapted from Szabo (2004)

# Step 11: Correcting for Attenuation Loss
## Time Gain Compensation

- Divide the image into a stack of separate strips
  - Horizontal strips (linear scan format
  - Concentric arcs (sector scanned format)
- Data arriving in time windows corresponding to each strip is fed to a different receive preamplifier stage
- Set the TGC gains to offset average loss in each zone

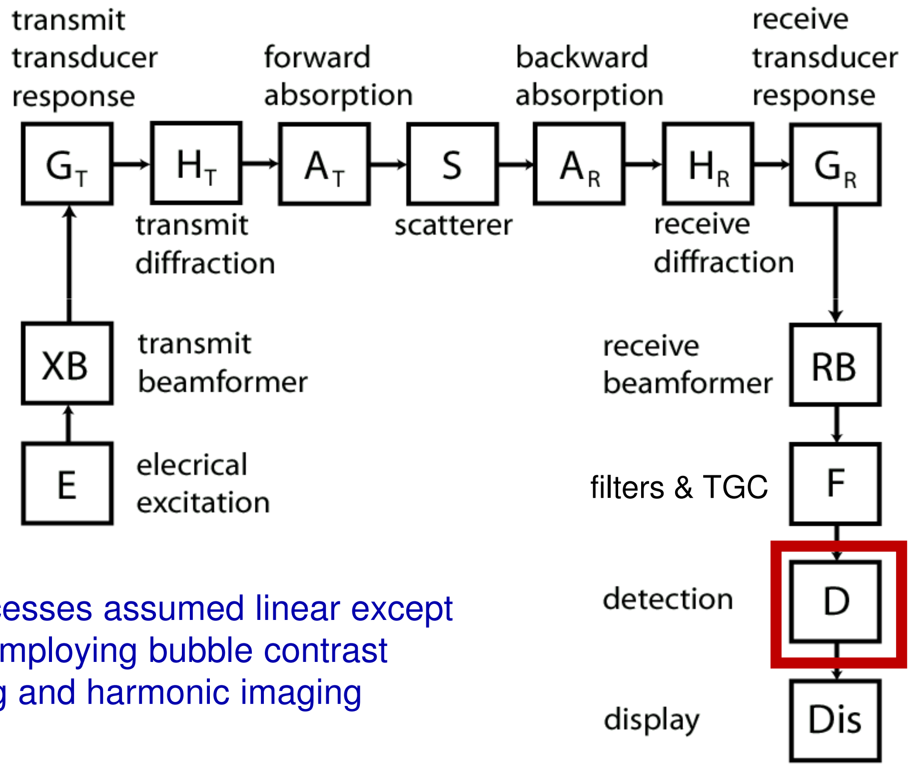



# Step 11: Filtering

- Low-pass anti-aliasing filter
- Bandpass filter centered at $\omega_o$ for conventional B-Mode imaging
- Bandpass filter filter centered at $2\omega_o$ for harmonic imaging

Adapted from Szabo (2004)

# The Imaging Roadmap
## The Diagnostic Imaging Signal Pathway

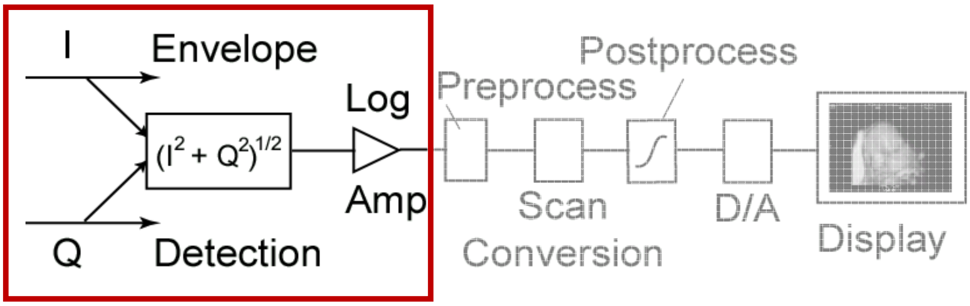



All processes assumed linear except when employing bubble contrast imaging and harmonic imaging

Adapted from Szabo (2004)

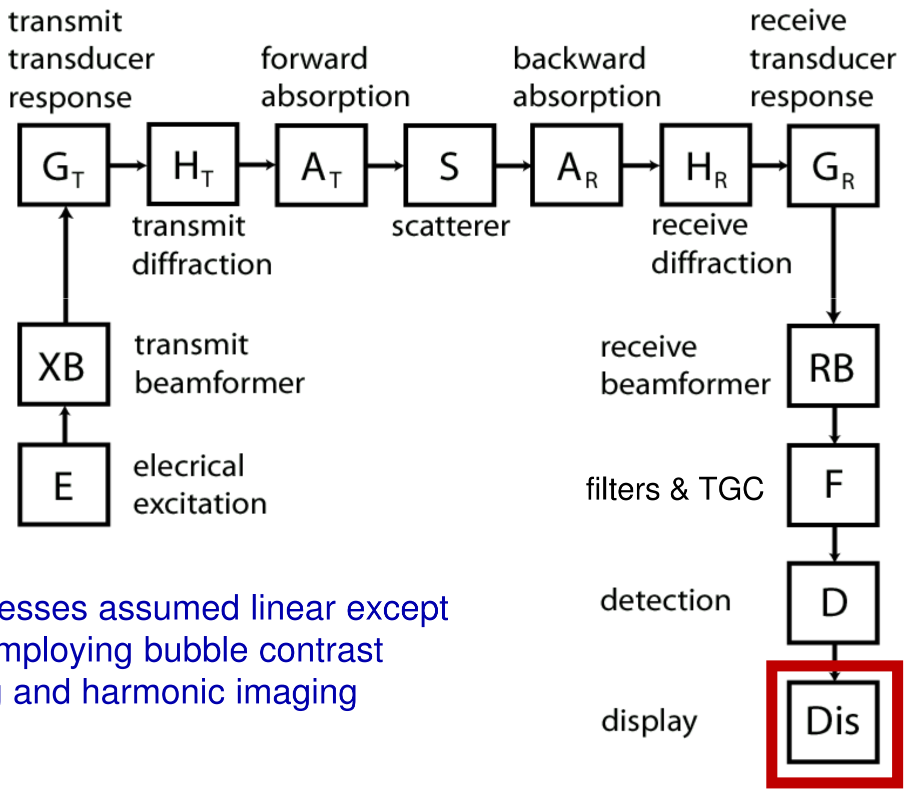
# Step 12: Detection

- **Filtered beamformed signal is envelope detected**
  - **Done in analog using diode bridges (lose phase information)**
  - **Done in analog using a quadrature demodulator (preserves phase information -- good for Doppler)**
  - **Done digitally using a variety of techniques**
- **Result is logarithmically compressed**
- **End up with an "A-line" in a known scan vector direction**



Adapted from Szabo (2004)

# The Imaging Roadmap
## The Diagnostic Imaging Signal Pathway

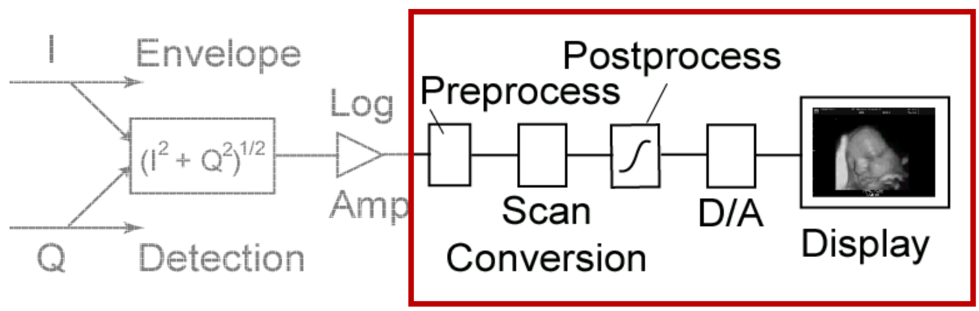



All processes assumed linear except when employing bubble contrast imaging and harmonic imaging

Adapted from Szabo (2004)

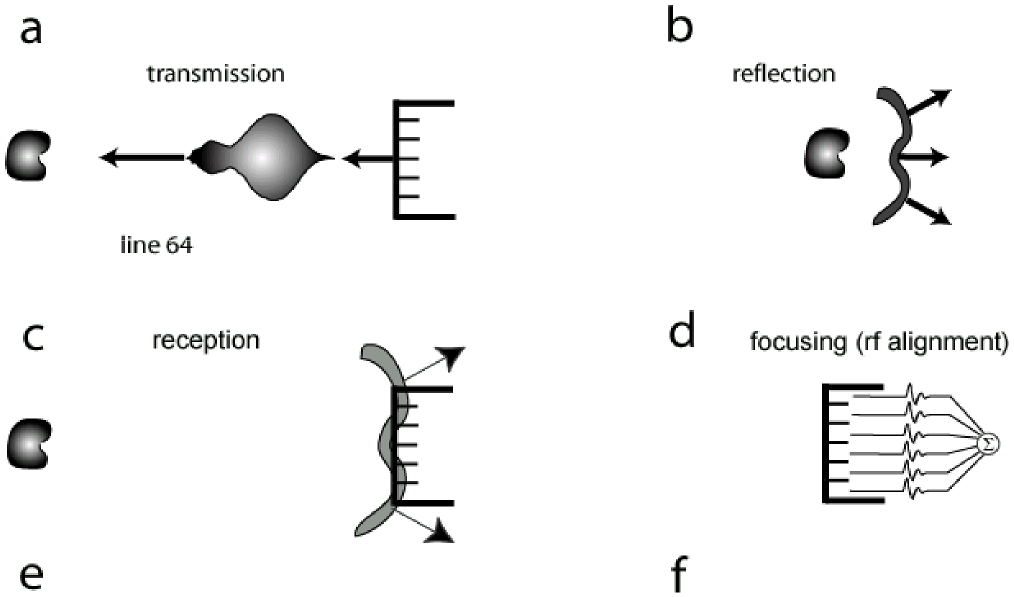
# Step 13: Display

- **Subsequent scan vectors are obtained and stored in memory**
- **All the lines are interpolated or "scan converted", forming a pulse-echo image where the lines are arranged in their proper geometrical orientation**
- **The image is converted to grey scale (represented compressed echo amplitude information) and displayed**



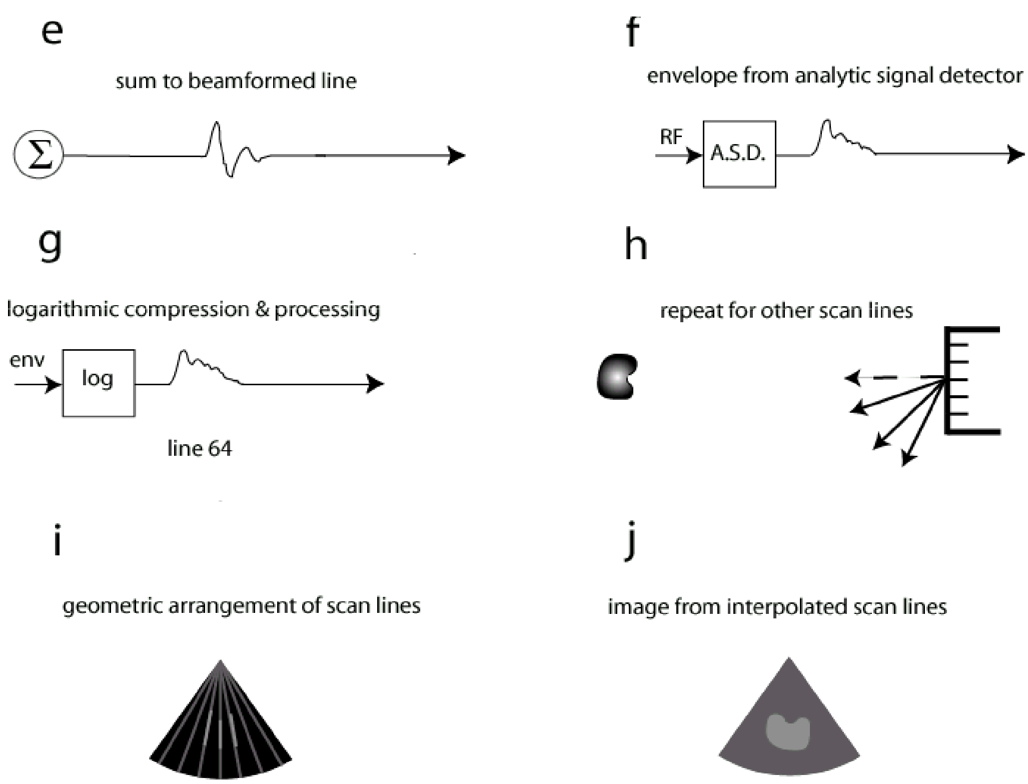
Adapted from Szabo (2004)

# Recapitulation




Adapted from Szabo (2004)

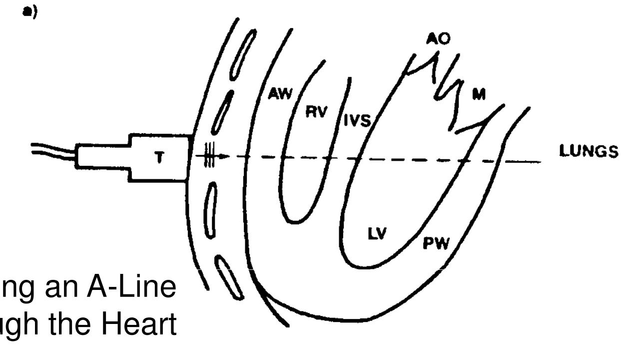
# Recapitulation



Shoup and Hart (1988)

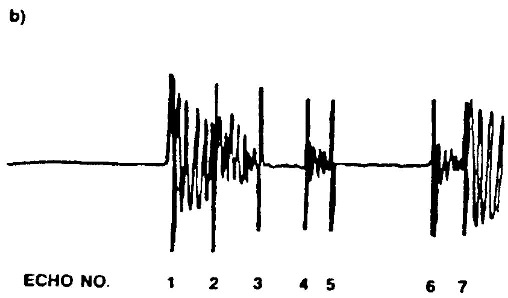
# Popular Imaging Modalities

- **A-Mode**
  - **Shoot a single line and view the depth (time) dependent returns.**
  - **Similar to what you might see on an oscilloscope display, where time is converted to distance: $\Delta z = c\Delta t$**




Shooting an A-Line Through the Heart

Resulting A-Mode Display

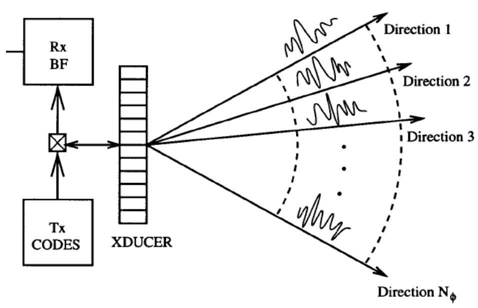


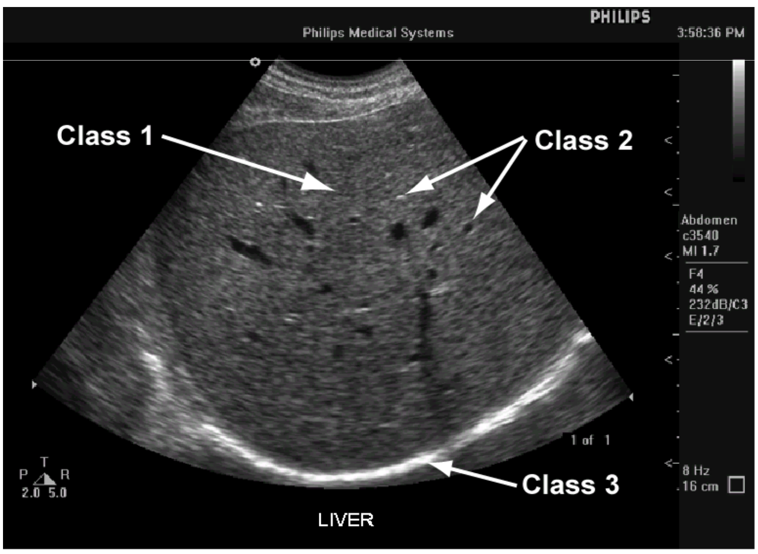



Phillips Medical Systems

# Popular Imaging Modalities

- **B-Mode**
  - **Generate a series of scan lines in a plane (the imaging plane)**
  - **The lines can be scanned linearly (linear scan) or angularly (sector scan).**
  - **Propagation time is converted to distance: $\Delta z = c\Delta t$**
  - **Combine the scans to form a 2-D image.**



# Popular Imaging Modalities

- **M-Mode**
  - **x-y display where depth is y and x is a running display of the same imaging line shot over and over, and return amplitudes are encoded as brightness**
  - **Displays a time history of activity (interface motion) for a given line**
  - **Duplex M-Mode: displayed in conjunction with B scan**

Duplex B-mode image and M-mode display of a mitral valve in the heart

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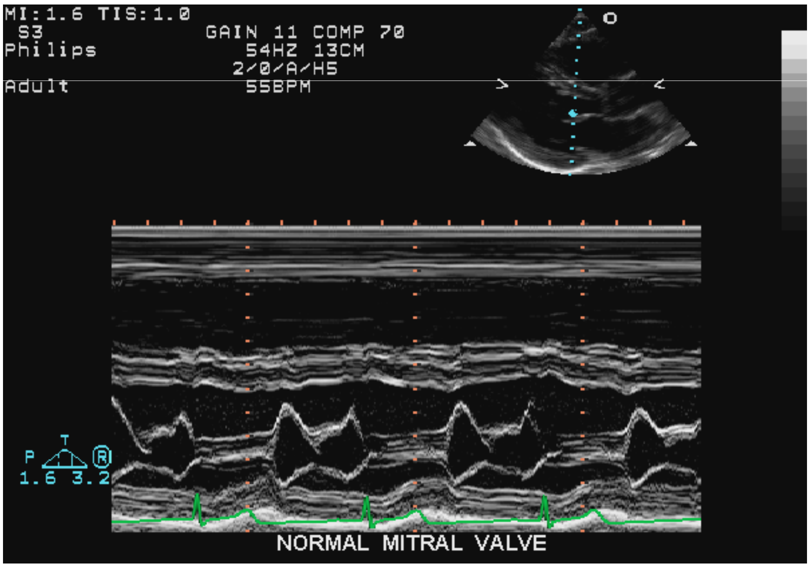
The cardiac cycle is clearly evident in the M-mode display






# Popular Imaging Modalities

- **Color Flow Doppler**
  - **A spatial map that depicts blood flow mean velocity with direction given by color**
  - **The map is overlayed on a B-Mode image**

Linear B-mode image with color Dopper overlayed

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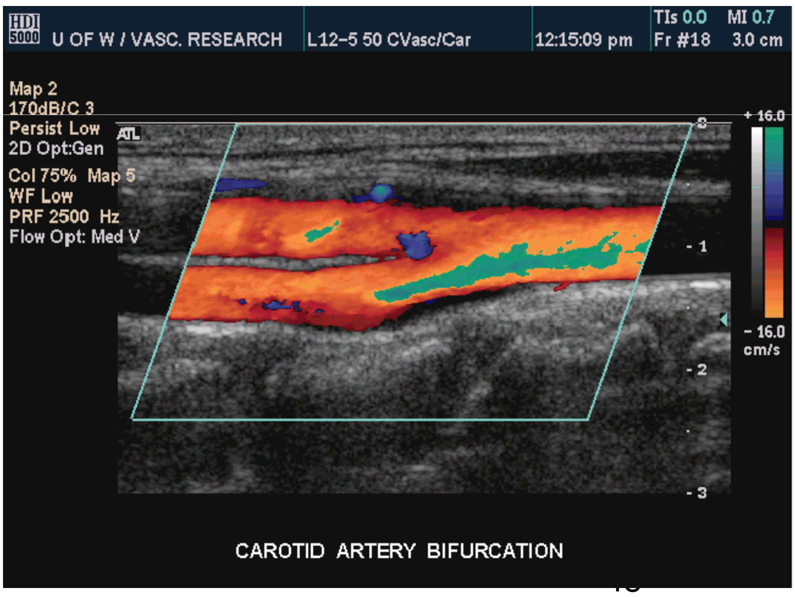
Contiguous imaging format (sector steering plus translation)



# Popular Imaging Modalities

- **Color M-Mode**
  - **Standard M mode plus a color flow depiction of flow**
  - **Displays a time history of a single color flow line**

Color Flow Doppler Image (top)

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Color M-Mode display (bottom)