“Wavefront synthesis” is not a used technical term, but is rather a suitable description of the application of a phased array when used for, aperture synthesis, focusing and depth selection

Why ultrasound?

- Non-invasive
  - Less hygiene risk
  - No need to cut the patient open
- Non-ionising
  - Xray / CR / CT / nuclear is generally not very portable and exposes the patient to ionising radiation
- Portable, minimal preparation
  - MRI generally requires a CT beforehand to check for implants that could heat in a magnetic field, or be moved, tearing tissue
- Lots of money was put into sonic imaging during WW2 (Sonar), concepts from other military imaging technologies (notably: radar) have migrated over, so ultrasonography is versatile.

While recording images by eye may probably be traced back to cave paintings, scientific recording of images (prior: measurement of details within an image) dates back to what is essentially a pinhole camera.

Aristotle noticed that during a partial solar eclipse, the crescent of the sun appeared on the ground, underneath a canopy of interlocking leaves

He also noticed that while the shapes of the holes between leaves varied, this had no effect on the projected shape of the Sun.

Additionally, he later found that the size of the projected image varies with the distance between the “aperture” (hole) and the screen onto which the image is projected – the first “Zoom” optic?

Simulacrum

"An image or representation of someone or something."

- Camera Obscura:
  - Mo-Ti (Chinese, ~400 BCE)
  - Essentially, a pinhole camera.
  - Image of an object is projected onto paper (through a small hole), and can then be traced.
- Aristotle *[right]*
  - Observed a partial solar-eclipse, projected through a gap between leaves.
  - Created the first "zoom" optic: Image from a distant object grows with the distance between pinhole and screen.
- Euclid: *Optics*
  - Used the *Camera Obscura* as evidence that light travels in straight lines.

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Simulacrum

- Alhazen (10-11th Century) *[right]*
  - Proved Aristotle's theory of vision: rays entering the eye
  - Disproving Ptolemy: rays emitted from within the eye
  - Credited with building the first *Camera Obscura*
- Leonardo da Vinci (16th Century)
  - The camera had primarily been used for astronomy prior to da Vinci
  - He wrote about using a *camera obscura* to project a hand-traceable image
  - Probably the first concept of image recording with optics.

Another notable camera from ~1800 is the *Camera Lucida*, where the artist views a page through a prism, which superimposes an image of the object onto the page (from the artist's view). This allows an object or scene to be traced onto paper without the need for a darkroom.

Iraqi scientist, proved that we see by light entering the eye – not by rays leaving the eye.

Developed refraction theory, although not quite up to Snell's law

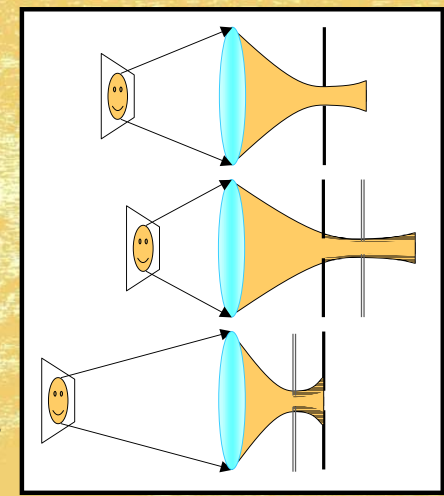
Explained the workings of the *camera obscura*

Da vinci: Wrote about using the *camera obscura* to project an image onto a page, where it could then be traced accurately by hand – the first photograph?

Aperture

Distance-varying lowpass filter

- Aristotle noticed that the shape of the aperture (pinhole) did not affect the shape of the image
- The size does however affect the sharpness of the image, a non-circular shape causes uneven sharpness across the image.
- Place a lens between an aperture and an observer, the aperture size appears to vary with the distance between the observer and the lens.
- The lens/aperture system forms a Fourier optic: a lowpass filter, with cutoff that varies with object depth. Cross-sections of the light-field originating from outside the focal plane experience a smaller aperture and are blurred by the lowpass effect



Top: in focus - rays pass through the aperture
Middle, bottom: out of focus - the effective aperture in back focal plane blocks higher harmonics

Partial solar eclipse; crescent remains a crescent

Consider a 100% transmissive hole in an opaque sheet, in front of a diffusely reflecting surface (i.e. not a mirror):

Infinitely large hole → No sheet! → No camera → No image

Infinitesimally small hole → No hole → No light enters camera → No image

Depth selection - example

Long focal length (focused on camera):

- Lens surfaces are out of focus, blurred to the point that they are not noticeable*

*excluding a specular reflection at the top-right

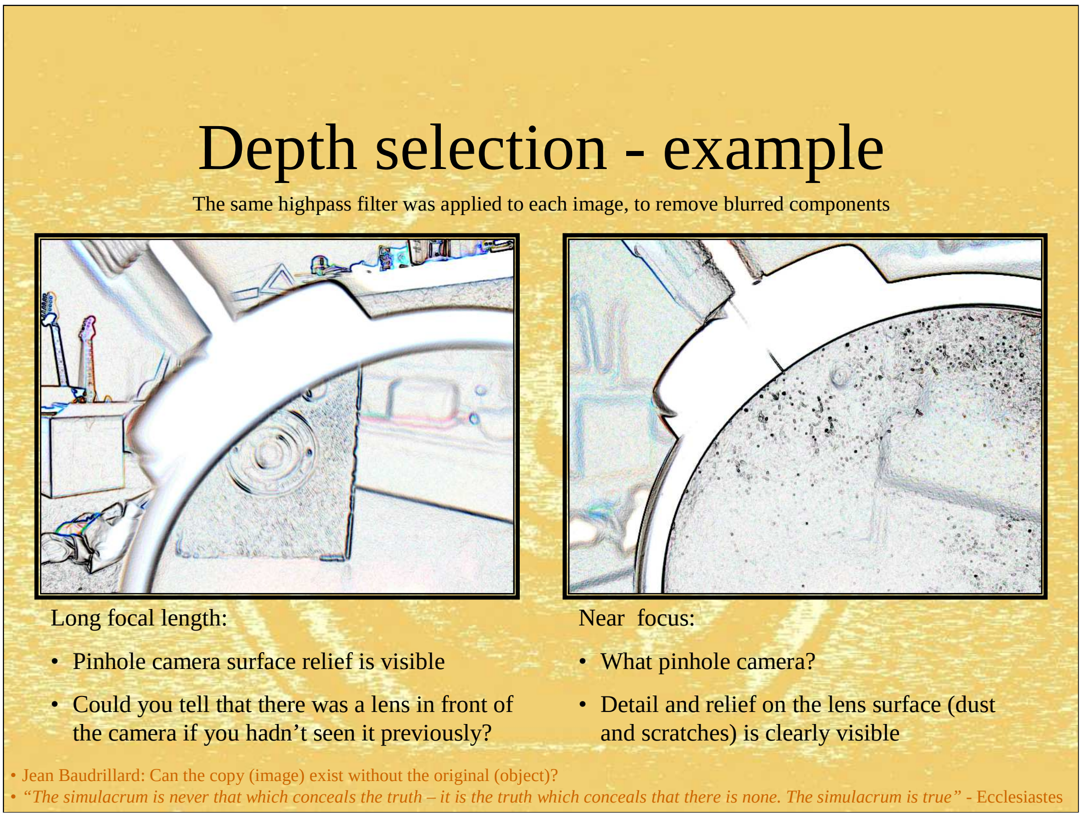
Near focus (focused on lens):

- Scratches and dust on the lens are visible, as its surface is in the focal plane
- When is a lens not a lens?

Higher spatial frequencies are blocked by the aperture, if they originate from planes further from the focal plane

Thus high spatial frequencies *in* the focal plane stand out, edge detail is preserved only for objects *in focus*

* Left: Due to focusing effect of the lens, the cardboard box in the background is also in focus, despite being ~20x further away than the pinhole camera!



Left:

Lens surface detail is blurred strongly → removed by highpass filter

Pinhole camera surface is in focus → sharp details survive the highpass

Right:

Pinhole camera is blurred strongly → removed by highpass filter

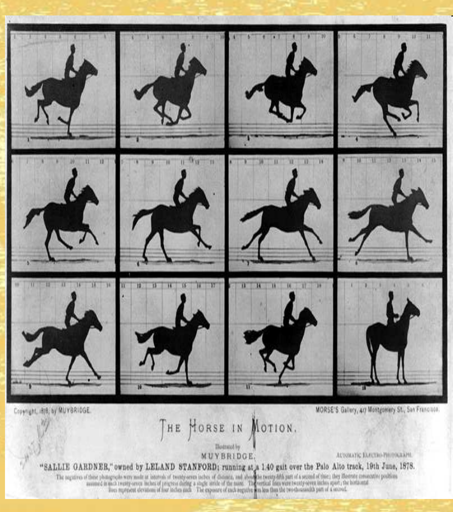
Specks and scratches on the lens are in focus → visibility is enhanced by highpass filter

Specular reflections of light-source behind the observer are visible in the left image (long focal length), but not in the right (short focal length) – why?

"The simulacrum is never that which conceals the truth – it is the truth which conceals that there is none. The simulacrum is true" - Ecclesiastes

Time selection

- Does a horse completely leave the ground when galloping?
- Are its legs completely outstretched at any point?
- Eadward Muybridge used an array of cameras triggered by a pulled string to take a series of photos in quick succession *[right]*
  Different shutter timings resulted in their respective cameras capturing different time-slices of the motion
- A shutter allows “time-selection”, analogous to depth-selection (but with a sharper cutoff rather than blurring)



Woodcuts representing Muybridge’s photos

Images were painted onto a glass wheel, which was rotated and projected through a pinhole and shutter, to display a “motion picture”

Strobelight effect – the importance of the shutter, for “freezing time”

This projection device, the Zoopraxiscope is considered by some to be the first video projector (and is often wrongly credited to Edison!)

Flash photography

- Subject is illuminated with light from imaging device's source
- Light is reflected or scattered off object
- Size of a aperture restricts which reflected rays can enter the camera
- Rays that enter the camera are detected and the intensity field across sensor recorded

→ Camera illuminates the object, then records reflected light rather than relying on external illumination

The imaging device is also the source of light

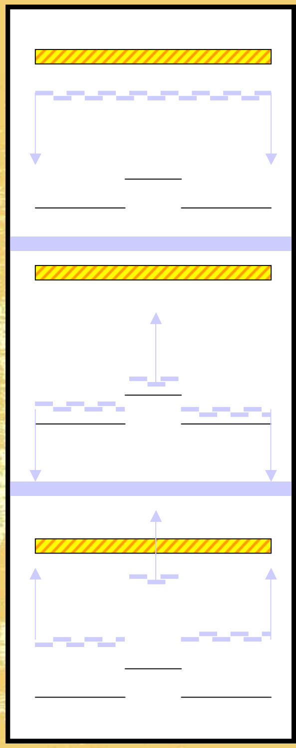
The object merely manipulates the probe light, and its effect on the light (in this case, reflection) is detected

Brighter flash → Better signal-to-noise in image

Very bright flash? → Blind/burnt subject – **POWER IS LIMITED**

Thought experiment: Pulse-echo imaging with shutter & flash

- Bounce a wave off a surface 50cm away
- Detect the back-reflected wavefront – shape of the reflected wavefront gives information about the surface relief of the object.
  - 50 cm out + 50 cm return → 100 cm path length
- What time-resolution (shutter rate) is needed to detect a 5mm bump?
  - 5 mm bump → 1 cm (1%) change in path length?
- Assuming a perfect sensor and emitter, what bandwidth is required to transmit information to a computer, from a single sensing element?
  - Perfect: zero rise and fall time
  - Assume poorest dynamic range (1-bit: high/low)
- Light travels one metre in 3ns
  - 5 mm detail → 30 ps time-shift
  - 30 ps → 30 GHz
  - 30 Gbit/s bandwidth: the maximum bandwidth of a high-end PC graphics card link (32 Gbit/s for 16-lane PCI Express) - per sensing element
- Sound (in air) travels one metre in 3ms (~0.2ms in soft tissue)
  - 5 mm detail → 30 µs time-shift
  - 30 µs → 30 kHz
  - 30 kbit/s: a hundred such elements could share a single Bluetooth link 450 kbit/s for imaging in soft tissue – less bandwidth than a digital radio station

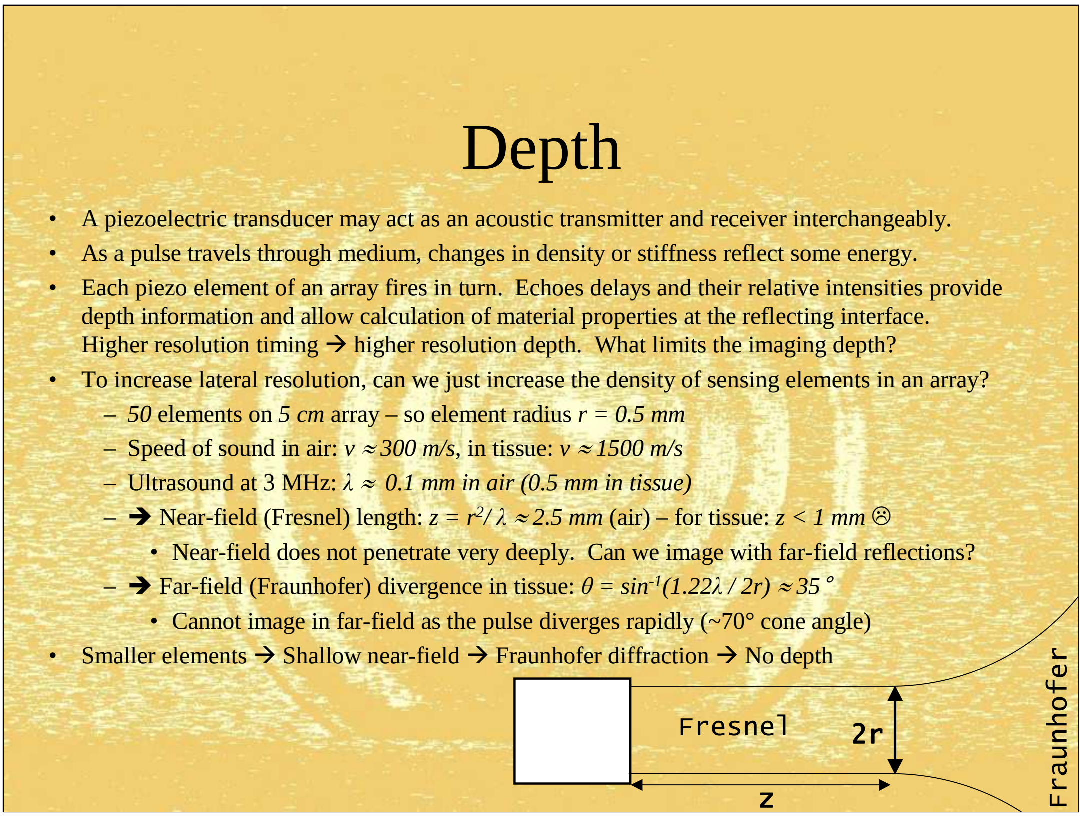


Light:

Fast sensor, fast electronics, fast data link needed (One PCIe x16 PER ELEMENT)

Sound:

Technology already exists – 20 kHz is the limit of human hearing – add Nyquist limit → a £20 computer sound card can generally sample at (or exceed) 44 kHz. The average microphone and amplifier however may not respond to a transient this short.



Slide:

Transmit power is limited, as we don't want to damage the object (i.e. patient needs to be alive to be treated, power is limited!)

What limits the spatial range of the imaging device? What limits its resolution?

Why 1-10 MHz?

Sub MHz – cavitation

Higher frequencies – more strongly attenuated by soft tissue

Extra:

Imagine a 2D flat surface between object and detector, parallel to detector

Treat the surface as array of point-sources

Depth of object element (viewed from detector) → Delay in "emission" of an interstitial point-source on the 2D surface

Reflect a wave off the object → "Trigger" the point-source array

Points corresponding to object elements nearer the detector "flash" earlier

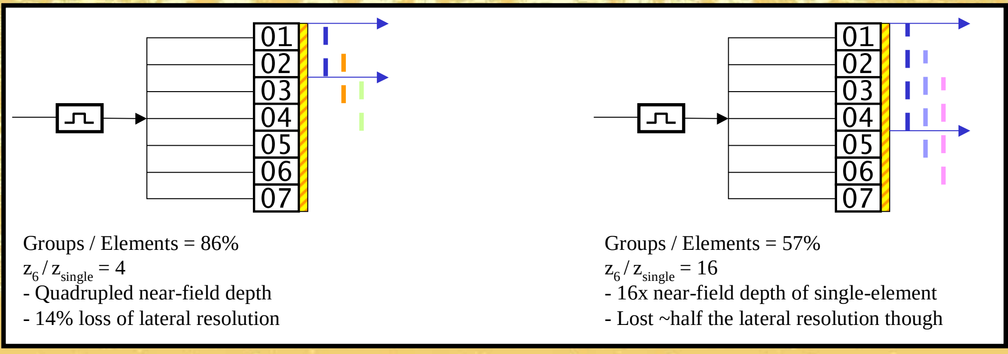
A shutter may be used to detect only light emitted at a certain time

Only sources that fired at a certain time are detected

"Slice" through the object is obtained, representing parts of it at a certain depth

Linear array

- To achieve a deep near-field with high element density, group elements together and fire each group as one large element!
  - Large groups → more depth, less lateral resolution (less groups)
  - Small groups → less depth, increased lateral resolution
  - Several elements at once → more energy in a pulse → better signal-to-noise



Group elements together into overlapping bands and fire simultaneously

More energy in wave (but same energy density) – minimal extra risk

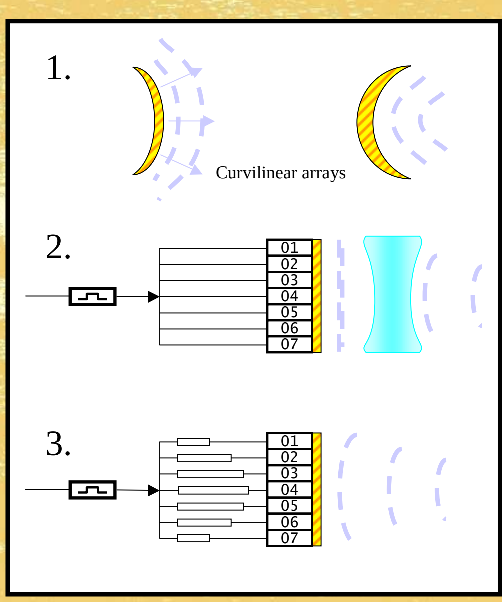
Allows higher spatial resolution than using large elements, but maintains a deep near-field due to low diffraction

Image is blurred due to wider sensing pulses – **deconvolution required**

Different group sizes allow one imaging device to non-mechanically adjust resolution and depth ranges as needed for different applications (resolution ⇔ depth)

Synthetic aperture

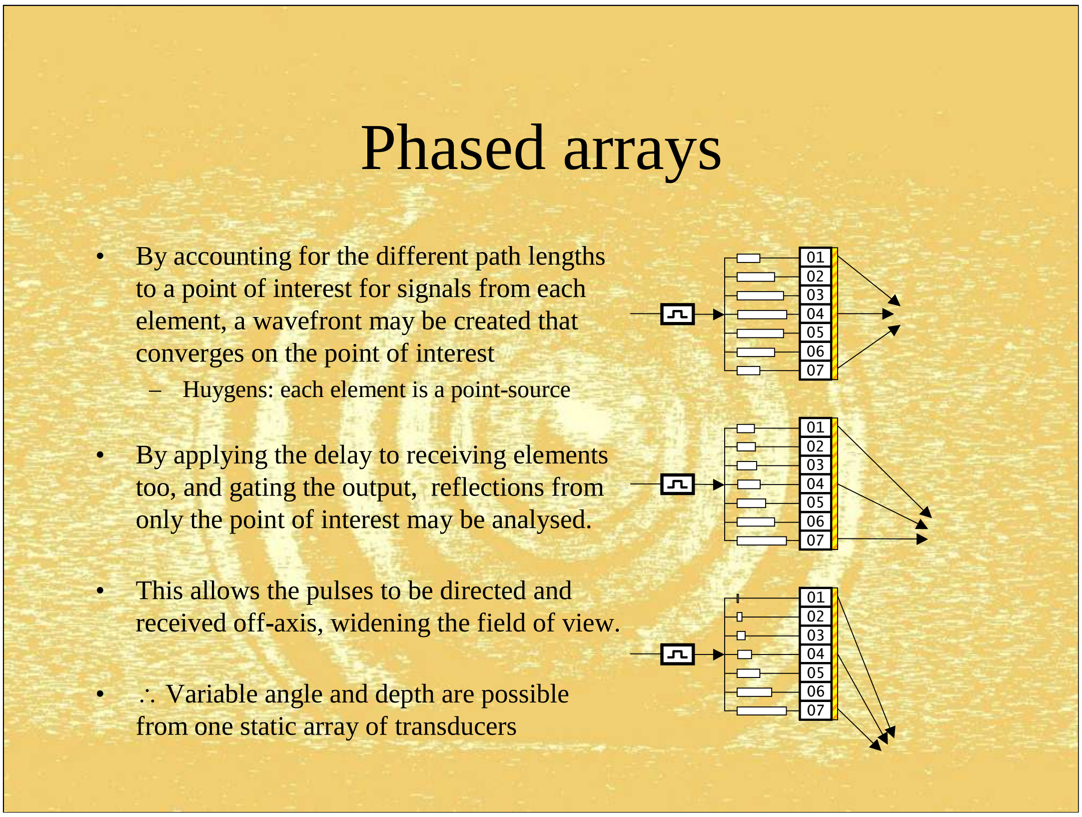
- With ultrasound at MHz frequencies, μsec-resolution time measurements are possible – with the clock of an average PC!
- Likewise, artificial delays may be introduced into the transmission elements.
- Rather than sending flat wavefronts, we can shape the outgoing wavefronts by
  1. Shaping the transmitter element
  2. Using lenses
  3. Delaying transmission of different parts of the wavefront
     - Variable wavefront shape/curvature: focus the array to a range of depths!
     - Allows the whole array to be fired at once: lots of depth & stronger pulse!
- Nobel prize in Physics (1974):
  Martin Ryle, Anthony Hewish
  <u>Aperture synthesis</u>



Radar

Shape of lens unusual for focusing? Stiffer materials transmit sound *faster*, in contrast to conventional optics

Focus the wavefront, as if it had been passed through a lens and aperture

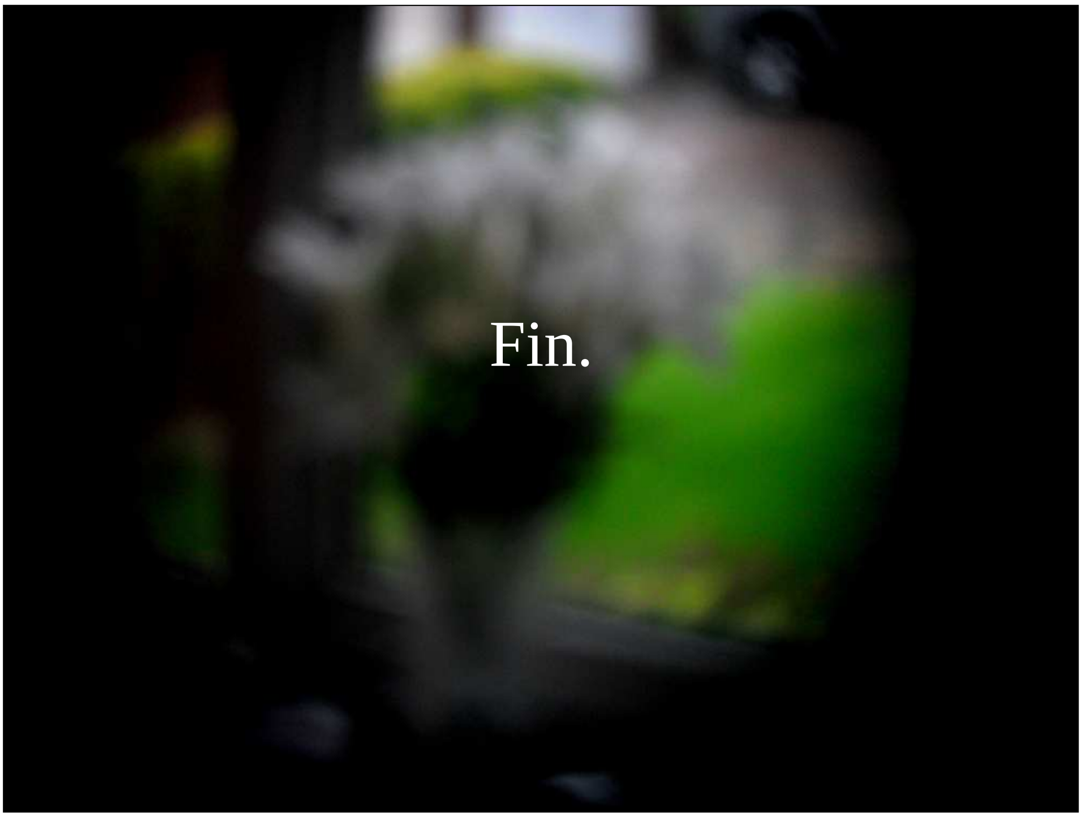


By shaping the wavefront electronically (instead of with a lens or curved array), the focal depth and lateral position may be varied electronically

Device can “scan” voxel by voxel or by detecting multiple echoes in various directions; short depth-of-field allows a plane to be imaged while a large depth-of-field allows a 3D image to be obtained

Imaging off-axis is possibly, the device does not need to be positioned directly over the object, nor does it need to be as larger as the object (less energy returns to detector as we go further off axis)

TODO: Heart sonogram – phased array image, non-phased image



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Farr’s Physics for Medical Imaging