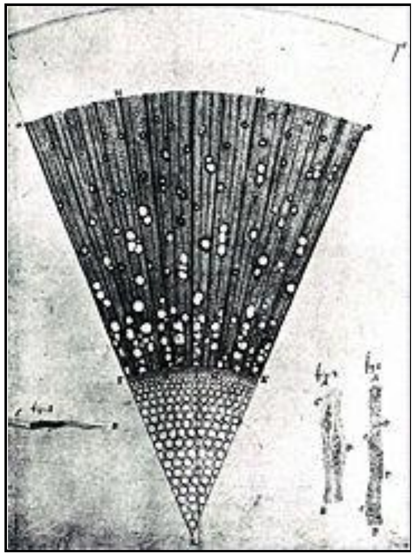
Computational Imaging:

A Survey of Medical and Scientific Applications

Douglas Lanman*

* presented by Douglas Lanman, adapted from slides by Marc Levoy: http://graphics.stanford.edu/talks/

Computational Imaging in the Sciences



Driving Factors:

- new instruments lead to new discoveries

  (e.g., Leeuwenhoek + microscopy → microbiology)
- Q: most important instrument in last century?

  A: the digital computer

What is Computational Imagining?

- according to B.K.P. Horn:

  "*…imaging methods in which computation is inherent in image formation.*"
- digital processing has led to a revolution in medical and scientific data collection

  (e.g., CT, MRI, PET, remote sensing, etc.)

Computational Imaging in the Sciences

Medical Imaging:
- transmission tomography (CT)
- reflection tomography (ultrasound)

Geophysics:
- borehole tomography
- seismic reflection surveying

Applied Physics:
- diffuse optical tomography
- diffraction tomography
- scattering and inverse scattering

Biology:
- confocal microscopy
- deconvolution microscopy

Astronomy:
- coded-aperture imaging
- interferometric imaging

Remote Sensing:
- multi-perspective panoramas
- synthetic aperture radar

Optics:
- wavefront coding
- light field photography
- holography

Medical Imaging

Overview:

- (non-invasive) reconstruction of internal structures of living organisms
- generally involves solving an inverse problem
- includes: radiology, endoscopy, thermal imaging, microscopy, etc.

Methods:

- tomography (includes: CT, MRI, PET, ultrasound)
- electroencephalography (EEG) and magnetoencephalography (MEG)

Key Issues:

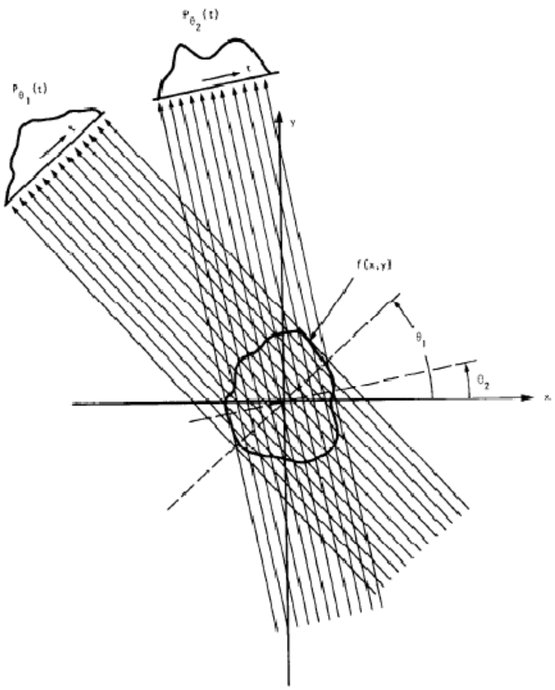
- safety (e.g., ionizing radiation)
- minimally invasive
- temporal and spatial resolution
- cost (to a lesser degree)

Two brain MRI images removed due to copyright restrictions.

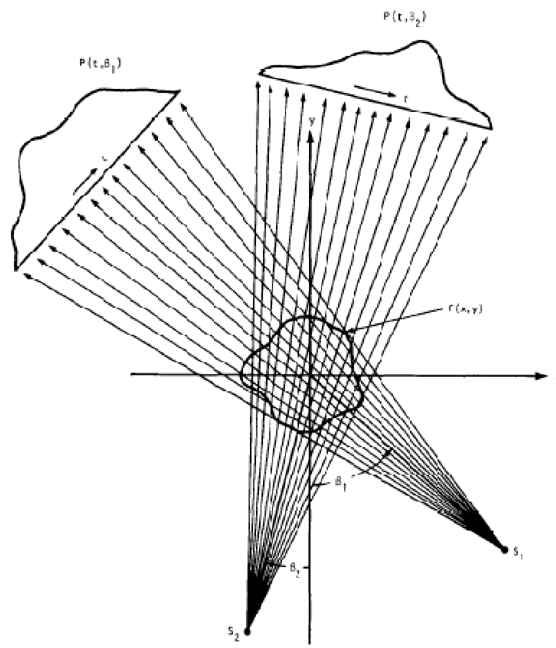
What is Tomography?

Definition:

- imaging by sectioning (from Greek *tomos:* “a section” or “cutting”)
- creates a cross-sectional image of an object by transmission or reflection data collected by illuminating from many directions



Parallel-beam Tomography

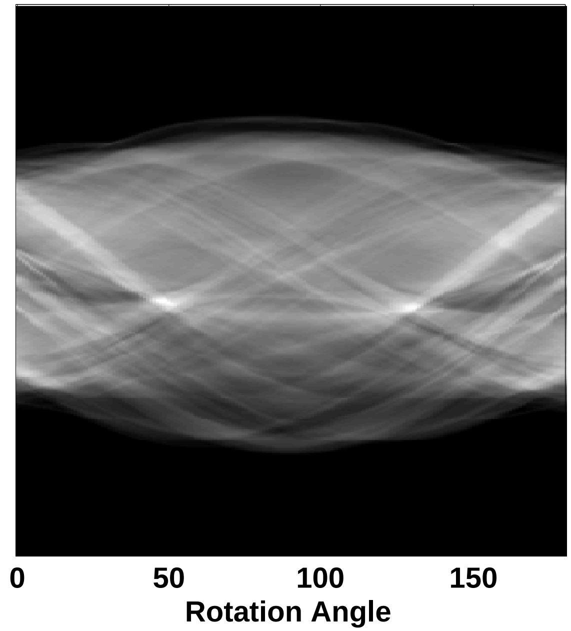


Fan-beam Tomography

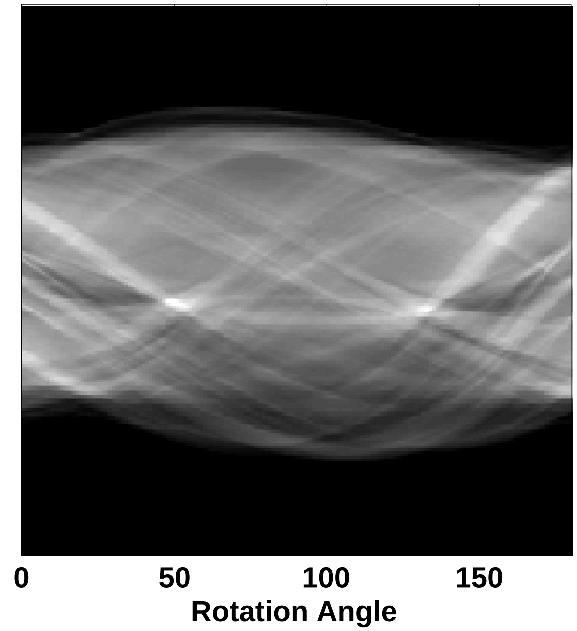
* Fig 3.2 and 3.3 in A.C. Kak and M. Slaney, ***Principles of Computerized Tomographic Imaging***, 1988

Simulated Tomograms

density function

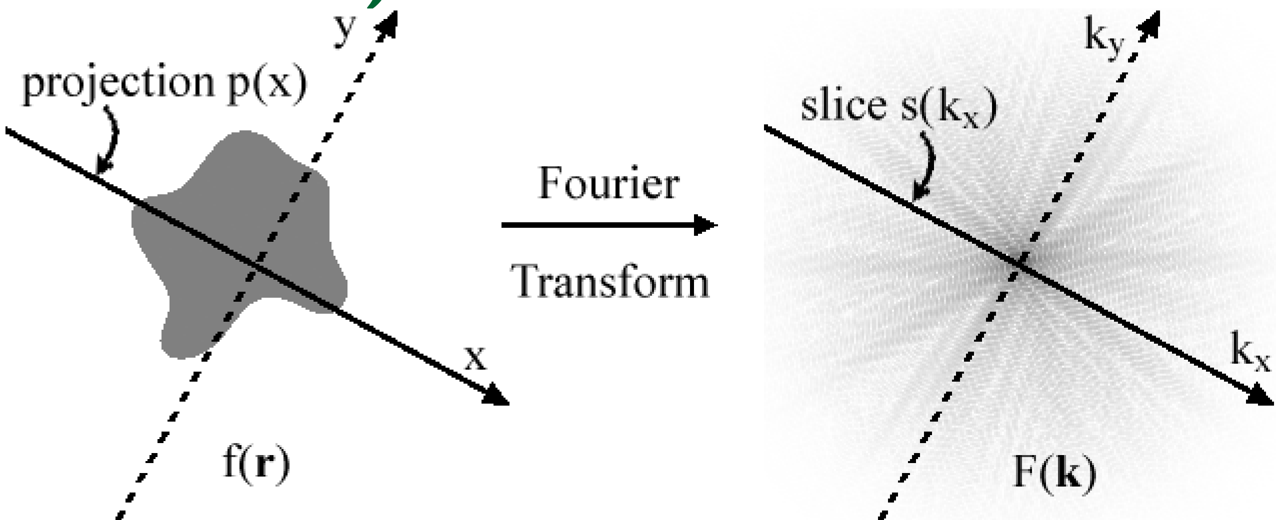


parallel-beam projections
(Radon transform)



fan-beam projections

Fourier Projection-Slice Theorem



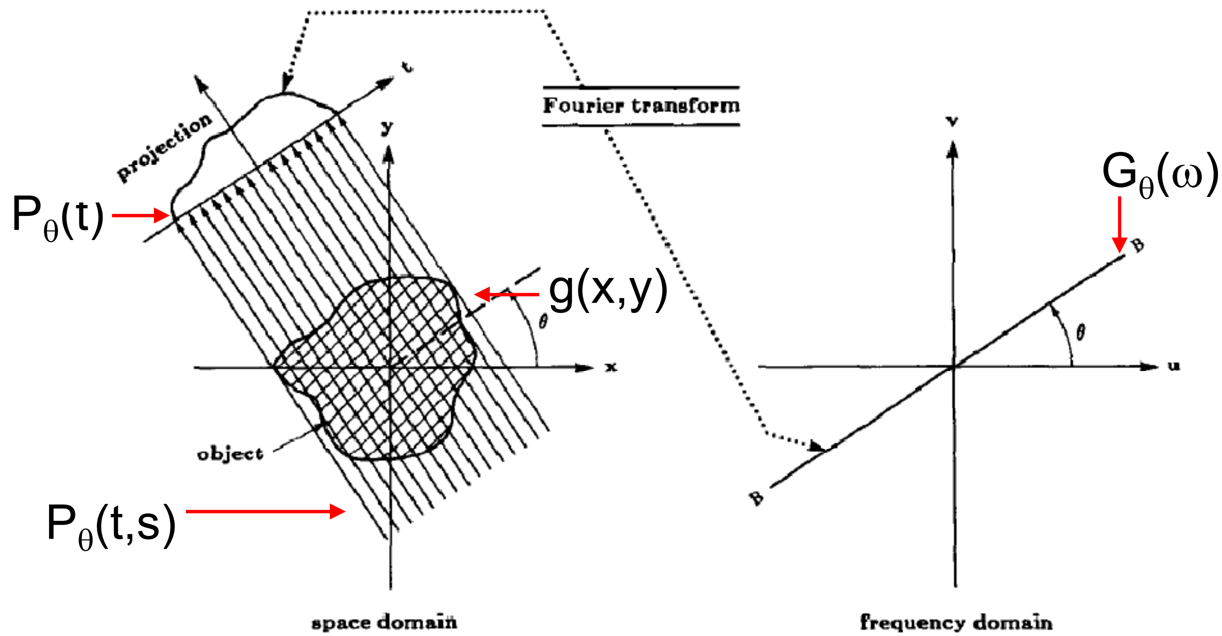
$$p(x) = \int_{-\infty} f(x,y)\,dy.$$

$$F(k_x, k_y) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(x,y)\,e^{-2\pi i(xk_x + yk_y)}\,dxdy.$$

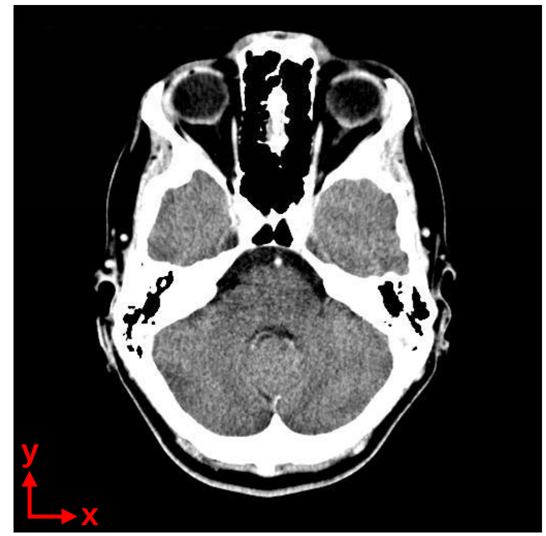
$$\begin{aligned} s(k_x) = F(k_x, 0) &= \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(x,y)\,e^{-2\pi i x k_x}\,dxdy \\ &= \int_{-\infty}^{\infty}\left[\int_{-\infty}^{\infty} f(x,y)\,dy\right] e^{-2\pi i x k_x} dx \\ &= \int_{-\infty}^{\infty} p(x)\,e^{-2\pi i x k_x} dx \end{aligned}$$

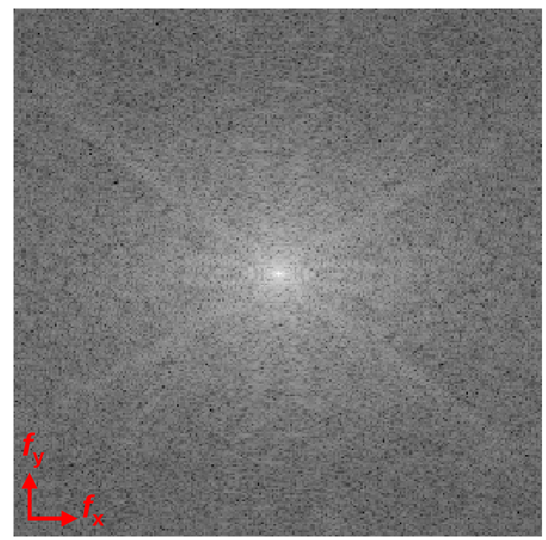
* Image: Wikipedia, *Projection-Slice Theorem*, retrieved on 11/03/2008 (public domain);
A.C. Kak and M. Slaney, ***Principles of Computerized Tomographic Imaging***, 1988

Reconstruction: Filtered Backprojection



Courtesy of A. C. Kak and Malcolm Slaney. Used with permission.



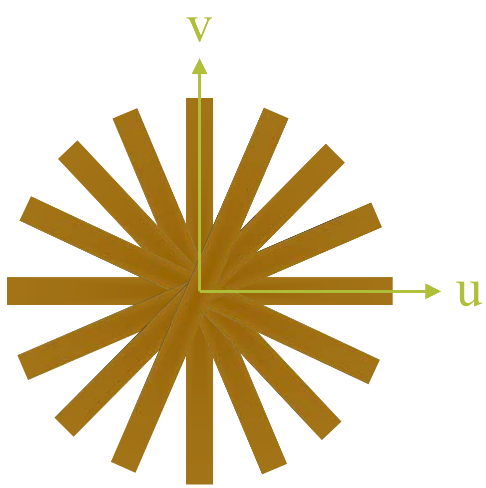


Fourier Projection-Slice Theorem:

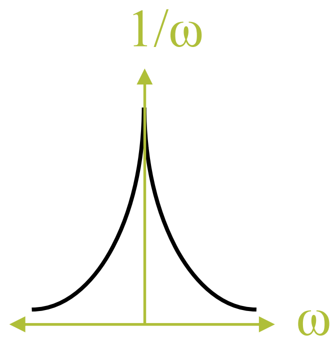
- $\mathcal{F}^{-1}\{G_\theta(\omega)\} = P_\theta(t)$
- add slices $G_\theta(\omega)$ into {u,v} at all angles θ and inverse transform to yield g(x,y)
- add 2D backprojections $P_\theta(t)$ into {x,y} at all angles θ

* Left: Fig. 3.6 in A.C. Kak and M. Slaney, ***Principles of Computerized Tomographic Imaging***, **1988**

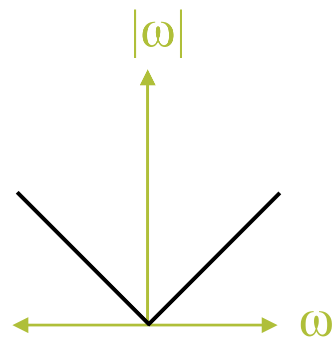
Sampling Requirements and Limitations



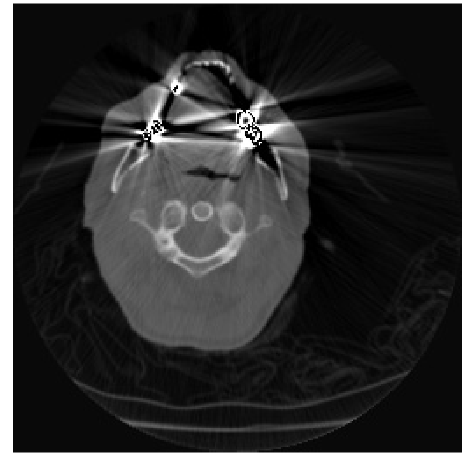
Diagrams courtesy of Marc Levoy.



"hot spot"

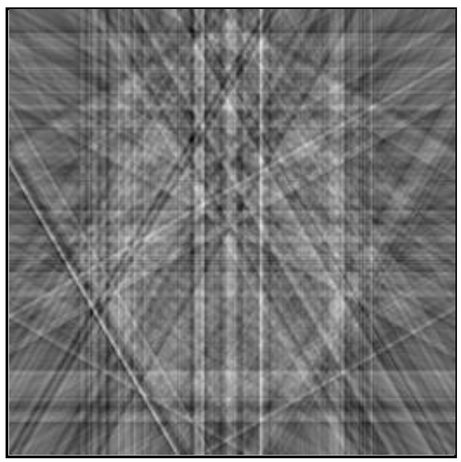


correction filter (Ram-Lak)

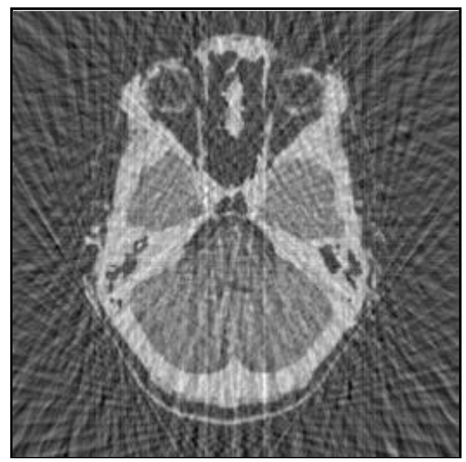


effect of occlusions

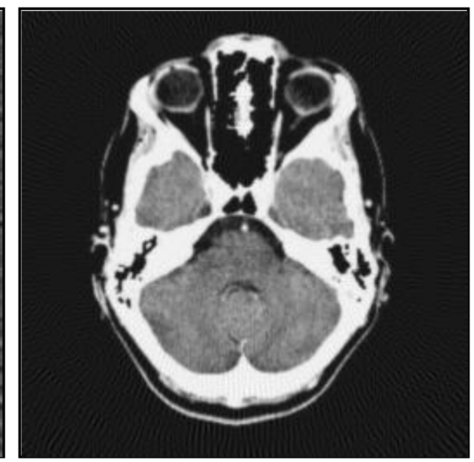
original density



30 deg. spacing



5 deg. spacing



1 deg. spacing

Medical Applications of Tomography

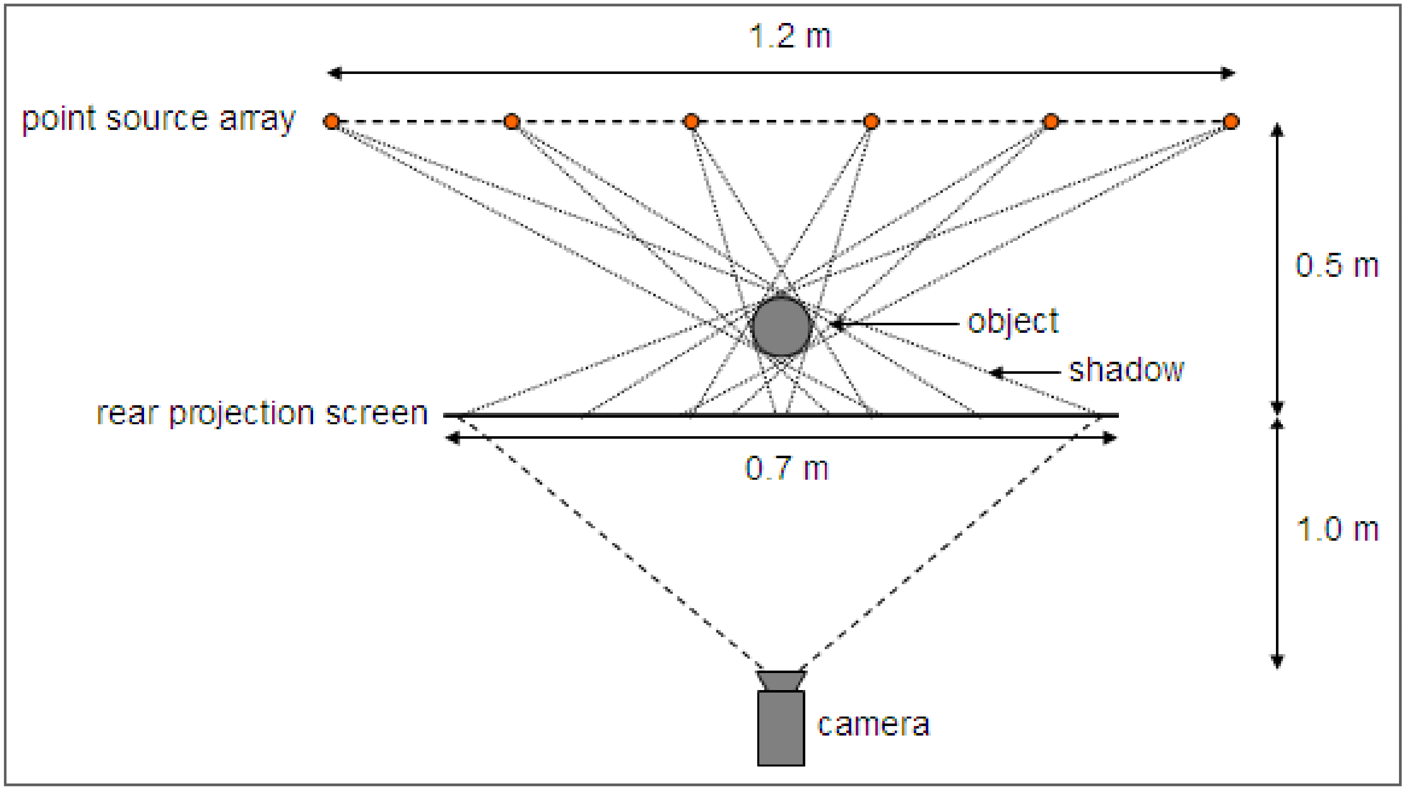
Video still removed due to copyright restrictions.
See Tuttle9955i. "CT at max speed." March 1, 2008.
http://www.youtube.com/watch?v=2CWpZKuy-NE

Medical images removed due to copyright restrictions.

Physical phenomenon	Type of tomograph
X-rays	CT
gamma rays	SPECT
electron-positron annihilation	PET
nuclear magnetic resonance	MRI
ultrasound	ultrasonography
electrons	3D TEM
ions	atom probe

bone reconstruction   segmented vessels

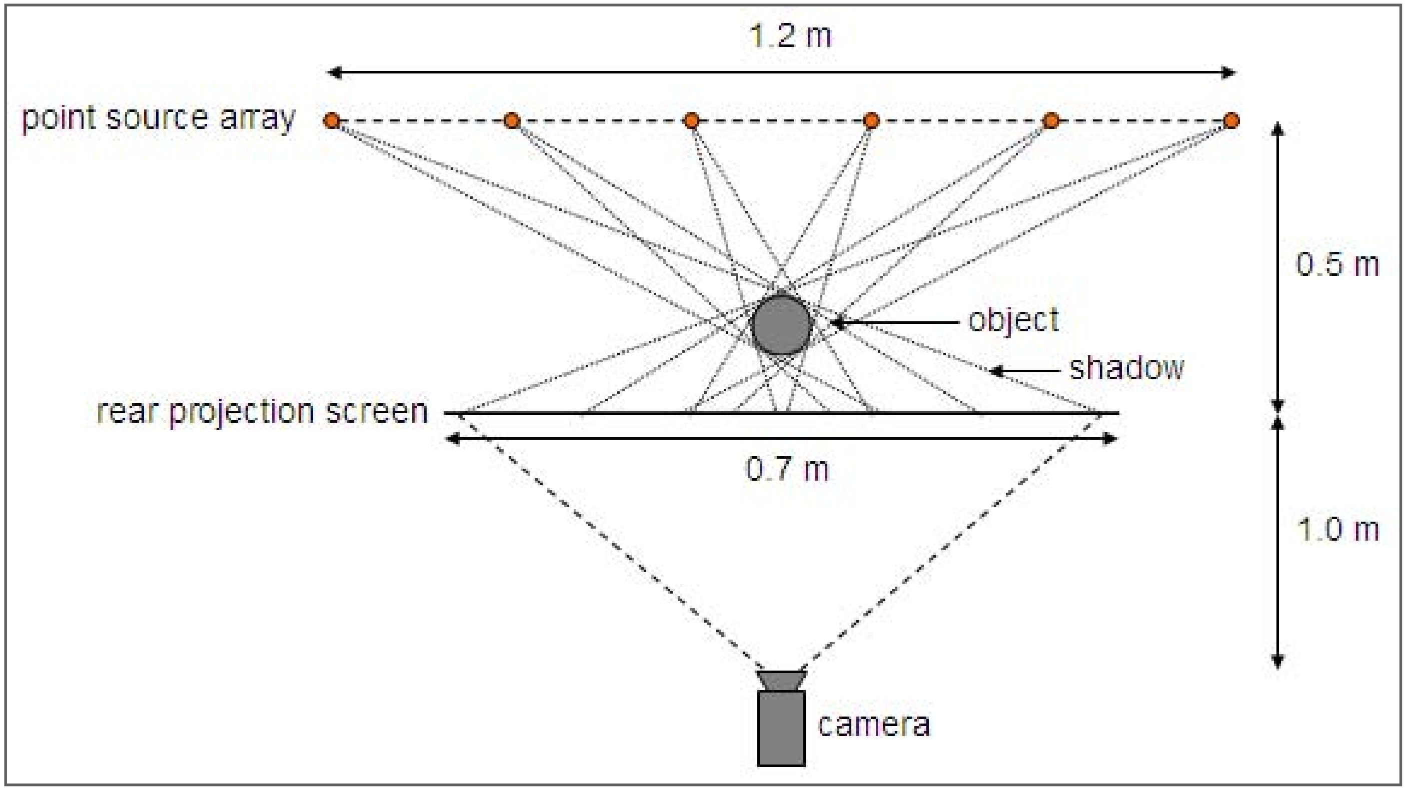
How to Eliminate Moving Parts?



Prior CT Generations: Time-sequential Projections

- moving parts
- synchronization and exposure timing
- costs (up-front, operating, and maintenance)
- dynamic scenes (RF interference, switching costs for X-ray tubes)

How to Eliminate Moving Parts?

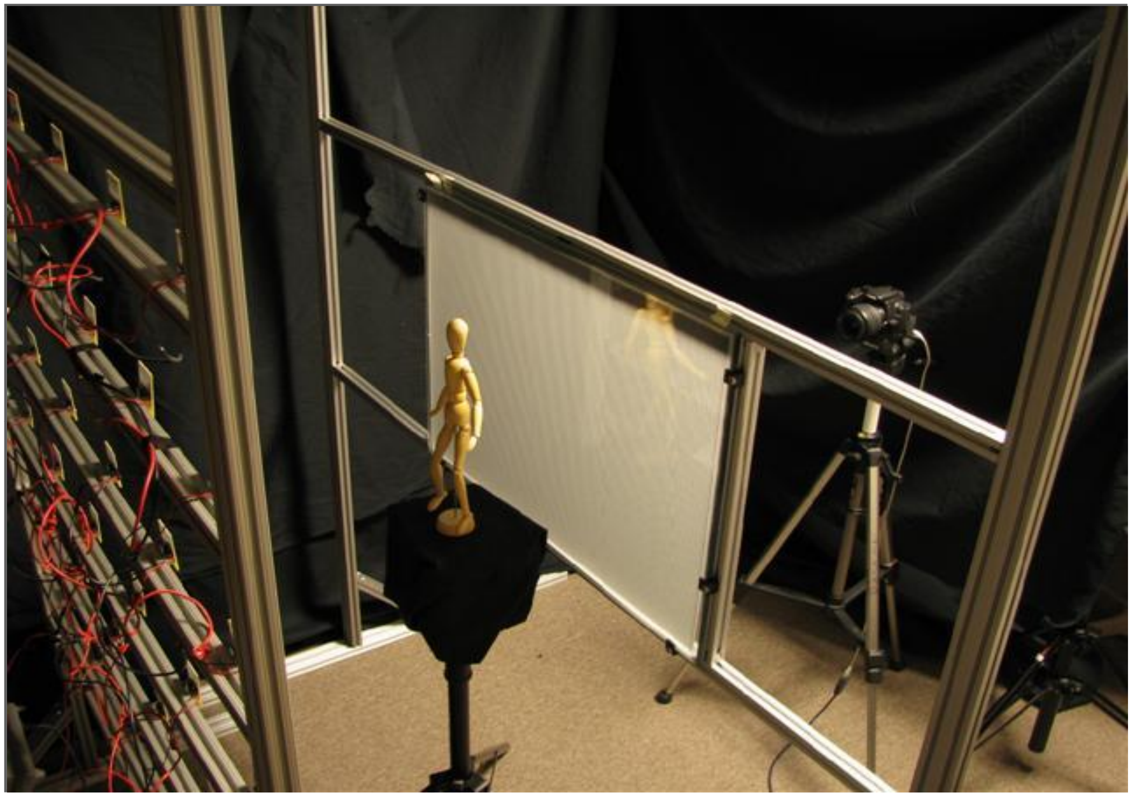


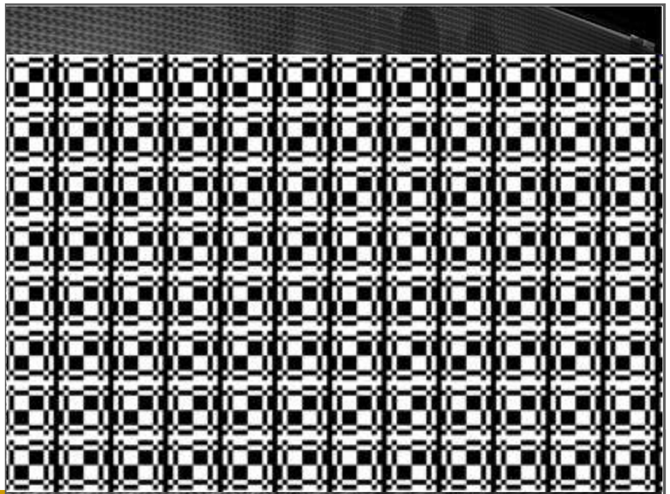
Our Solution: Simultaneous Projections

- <u>**no moving parts**</u>
- no synchronization → uses "always-on" sources
- lower costs (simpler mechanical construction and X-ray sources)
- well-suited for high-speed capture of dynamic scenes

Shield Fields:

Simultaneous Projections using Attenuating Masks

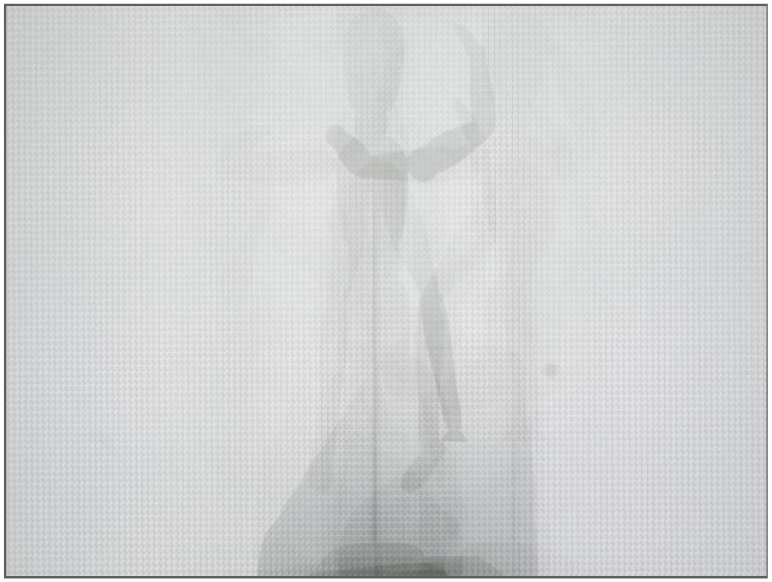


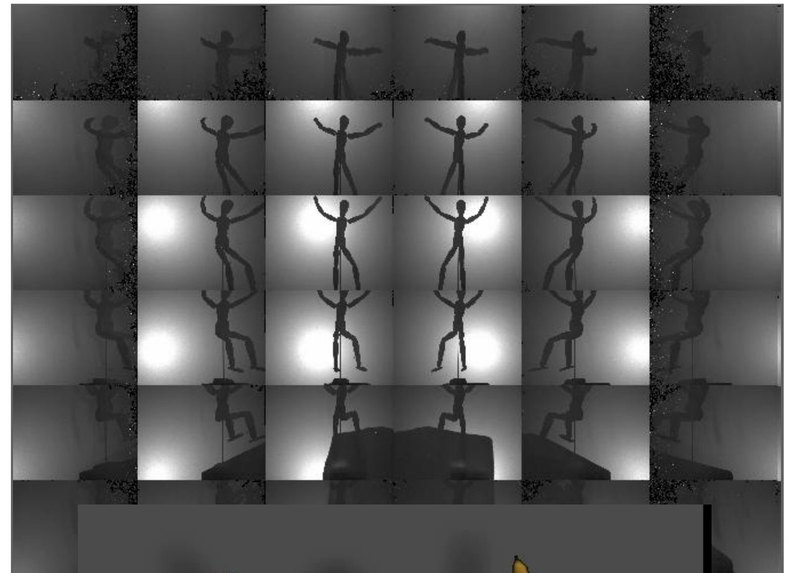


our "magic" pattern:
allows spatial heterodyning

Shield Fields:

Simultaneous Projections using Attenuating Masks





Geophysical Applications

Two diagrams removed due to copyright restrictions.
Borehole tomography and map of seismosaurus.
From Reynolds, J.M., *An Introduction to Applied and Environmental Geophysics.* Wiley, 1997.

mapping a *seismosaurus* in sandstone using microphones in 4 boreholes and explosions along radial lines

Borehole Tomography:

- receivers measure end-to-end travel time
- reconstruct to find velocities in intervening cells
- must use limited-angle reconstruction methods (e.g., ART)

* Slide derived from Marc Levoy

Geophysical Applications

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Borehole tomography.
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Photo removed due to copyright restrictions.
Stone map fragment from Stanford Forma Urbis Romae Project.
http://formaurbis.stanford.edu/fragments/color_mos_reduced/010g_MOS.jpg

mapping ancient Rome using explosions in the subways and microphones along the streets?

Borehole Tomography:

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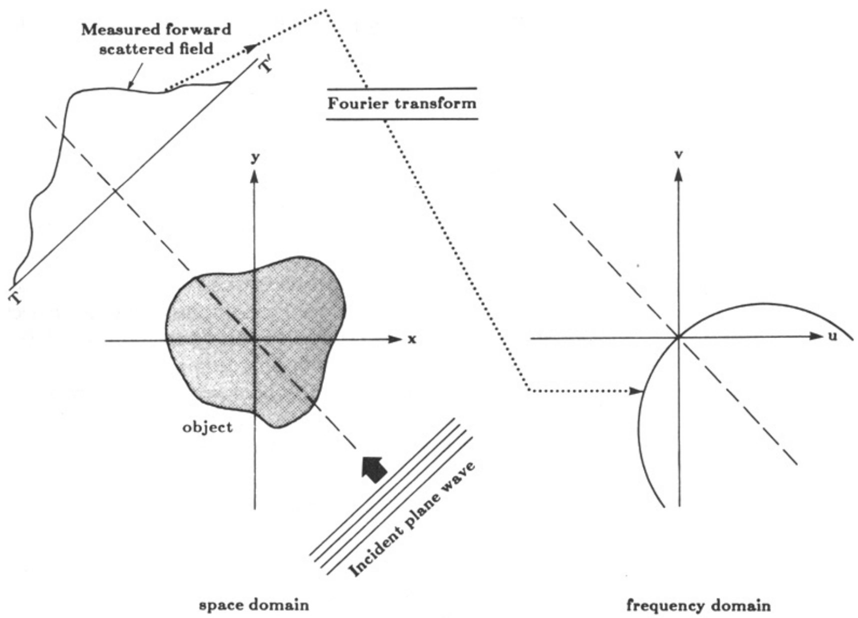
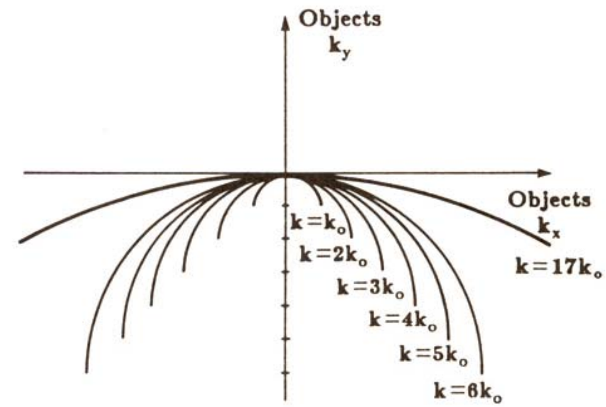
Optical Diffraction Tomography (ODT)





limit as $\lambda \to 0$ (relative to object size) corresponds to Fourier Slice Theorem

Courtesy of A. C. Kak and Malcolm Slaney. Used with permission.

- weakly-refractive media using coherent plane-wave illumination
- the amplitude and phase of the forward-scattered field can be described using the Fourier Diffraction Theorem, such that:
  F {scattered field} = arc in F{object}
- repeat for multiple wavelength, use F^{-1} to reconstruct volume
- broadband hologram will yield 3D structure (i.e., refraction indices)

Figures from A.C. Kak and M. Slaney, ***Principles of Computerized Tomographic Imaging***, **1988**

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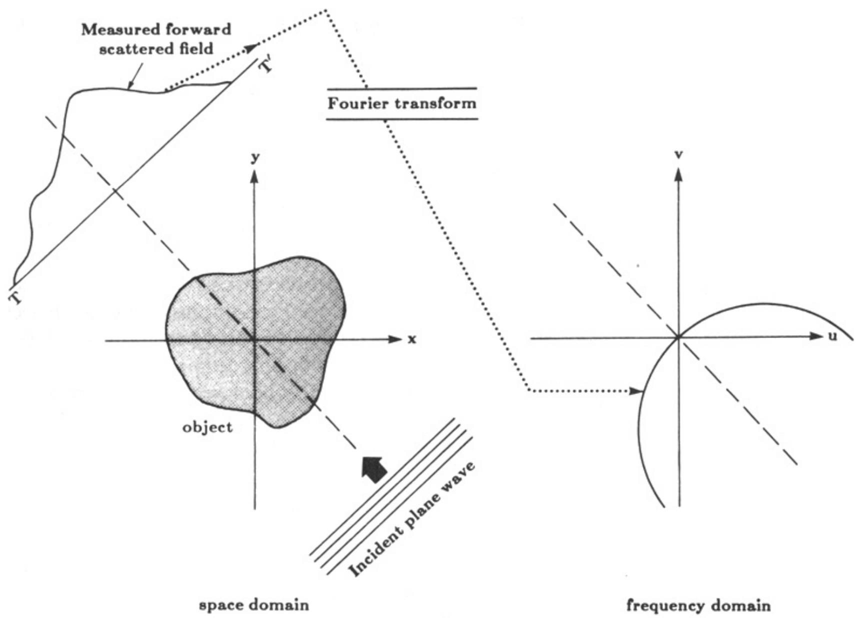
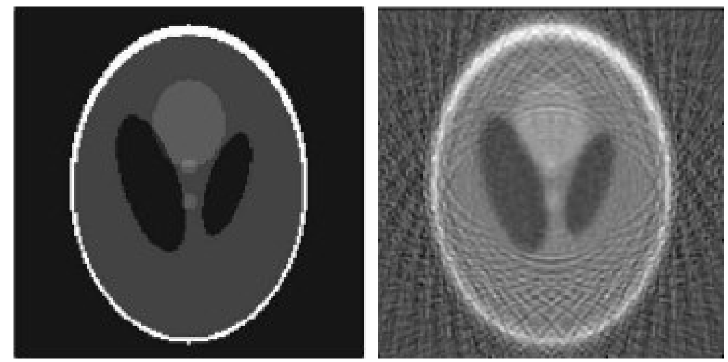
Optical Diffraction Tomography (ODT)





synthetic ODT reconstruction example

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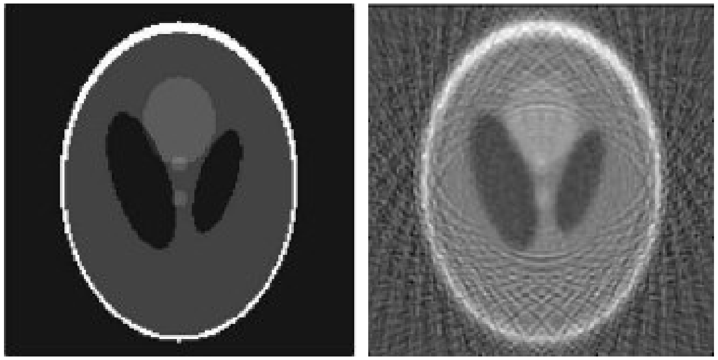
* Slide derived from Marc Levoy

Optical Diffraction Tomography (ODT)

Diagram removed due to copyright restrictions. Source: Jebali, Asma. "Numerical Reconstruction of semi-transparent objects in Optical Diffraction Tomography." Diploma Project, Ecole Polytechnique, Lausanne, 2002.



synthetic ODT reconstruction example

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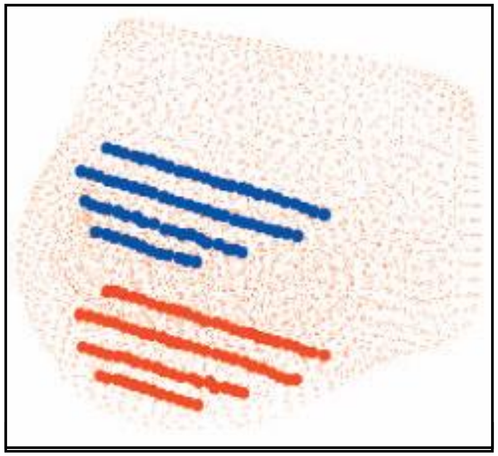
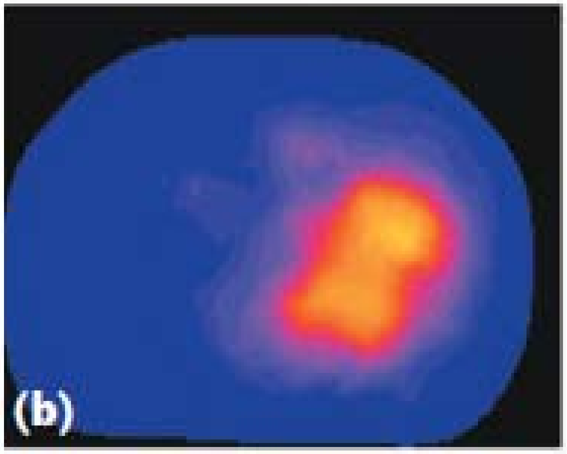
- the amplitude and phase of the forward-scattered field can be described using the Fourier Diffraction Theorem, such that:
  F {scattered field} = arc in F{object}
- repeat for multiple wavelength, use F^{-1} to reconstruct volume
- backprojection possible using a depth-variant filter

* Slide derived from Marc Levoy

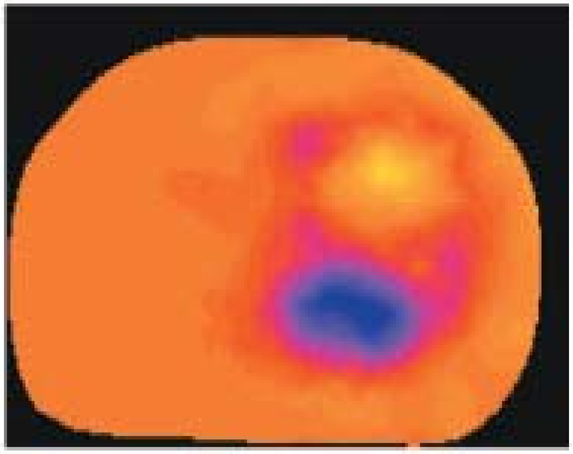
Diffuse Optical Tomography (DOI/DOT)



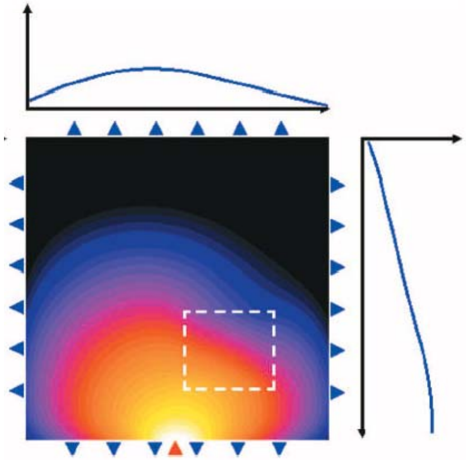
mammography application: sources (red), detectors (blue)



absorption (yellow is high)



Scattering (yellow is high)



- strongly-refractive media using inverse-scattering
- assumes propagation due to multiple scattering
- models transport as a diffusion process
- inversion is non-linear and ill-posed (i.e., hard)
- example: 81 emitters and 81 receivers, where time-of-flight gives initial estimate for absorption

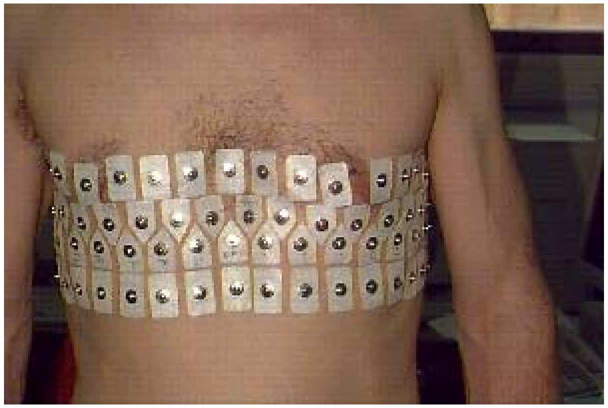
Diffuse Optical Tomography (DOI/DOT)

Images removed due to copyright restrictions.
See Figure 4 in Gibson, A. P., et al. “Recent Advances in diffuse optical imaging. “ *Physics in Medicine and Biology* 50, no. 4 (2005): R1.
http://www.medphys.ucl.ac.uk/research/borl/pdf/gibson_pmb_2005.pdf

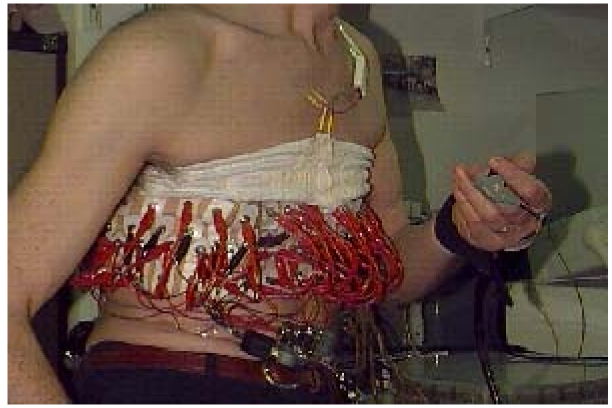
- strongly-refractive media using inverse-scattering
- assumes propagation due to multiple scattering
- models transport as a diffusion process
- inversion is non-linear and ill-posed (i.e., hard)

Electrical Impedance Tomography

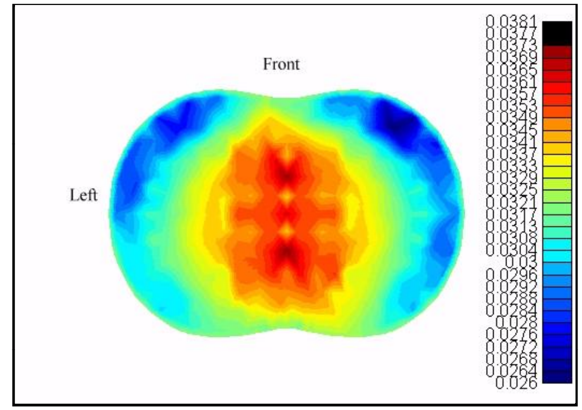
Kerrouche, N. et al. *Physiol. Meas*. 22 No 1 (February 2001) 147-157



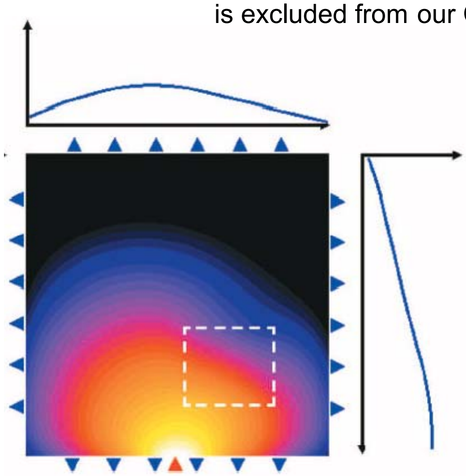
chest electrode array



electrode array (wires attached)



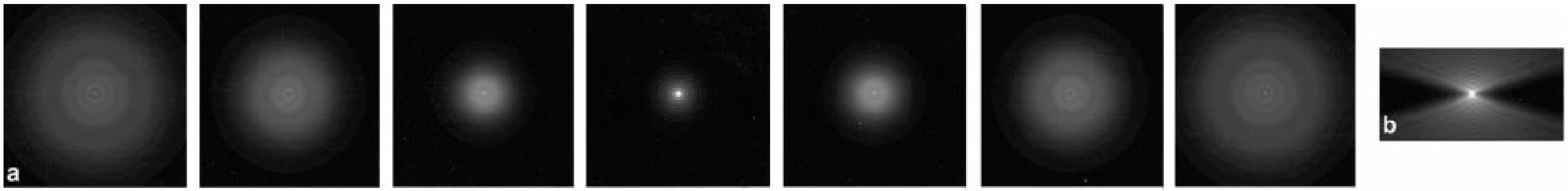
reconstructed conductivity map



- strongly-refractive media using inverse-scattering
- assumes propagation due to multiple scattering
- models transport as a diffusion process
- inversion is non-linear and ill-posed (i.e., hard)
- EIT: inverse problem called “Calderón Problem”

Image: Schweiger, M., et al. "Computational Aspects of Diffuse Optical Tomography." *IEEE* Computing in Science and Engineering 5, no. 6 (November/December 2003): 33-41.

Biology: 3D Deconvolution



focal stack of a point in 3D is the 3D PSF of the imaging system

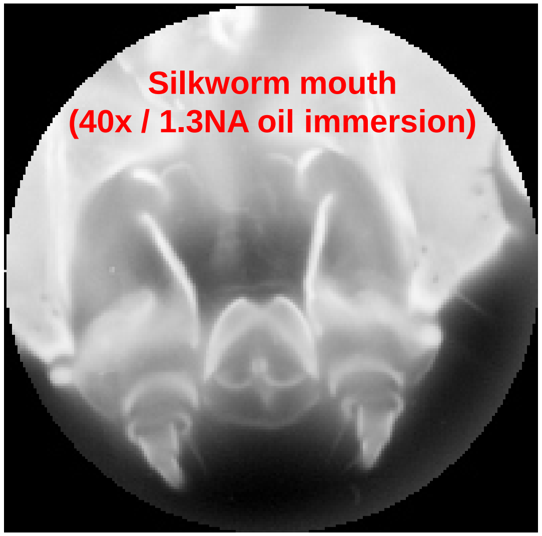
Basics of 3D Deconvolution for Microscopy:

- object * PSF → focal stack
- F{object} × F{PSF} → F{focal stack}
- F{focal stack} ÷ F{PSF} → F{object}
- spectrum contains zeros (due to missing rays)
- imaging noise is amplified by division by ~zeros
- reduce by regularization (smoothing) or completion of spectrum
- improve convergence using constraints, e.g. object > 0 (positivity)

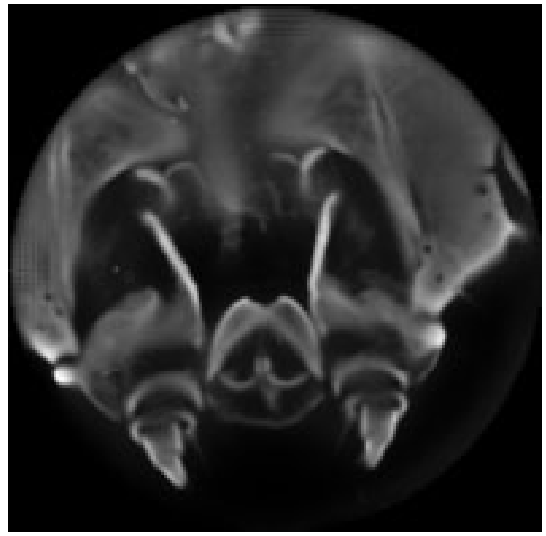
* Slide derived from Marc Levoy

Biology: 3D Deconvolution

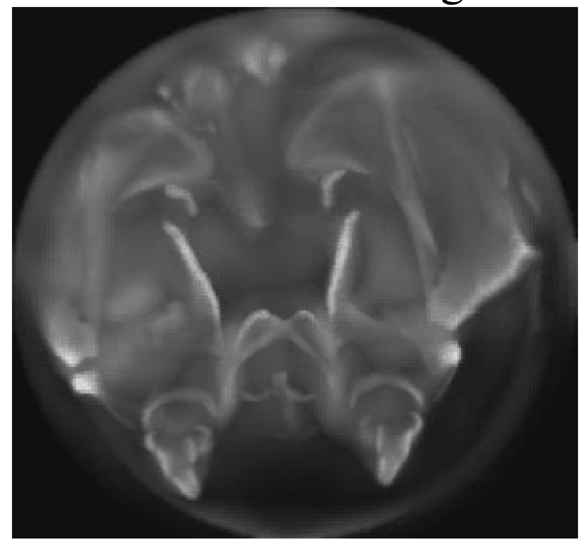
slice of focal stack



slice of volume



volume rendering



3D Deconvolution Microscopy:

- object * PSF → focal stack
- F{object} × F{PSF} → F{focal stack}
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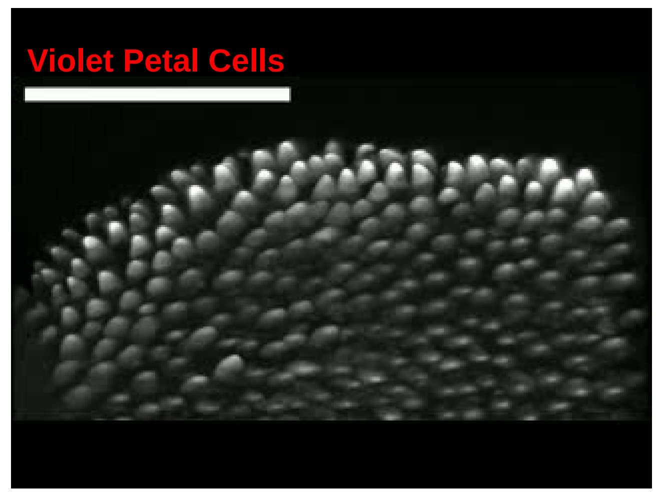
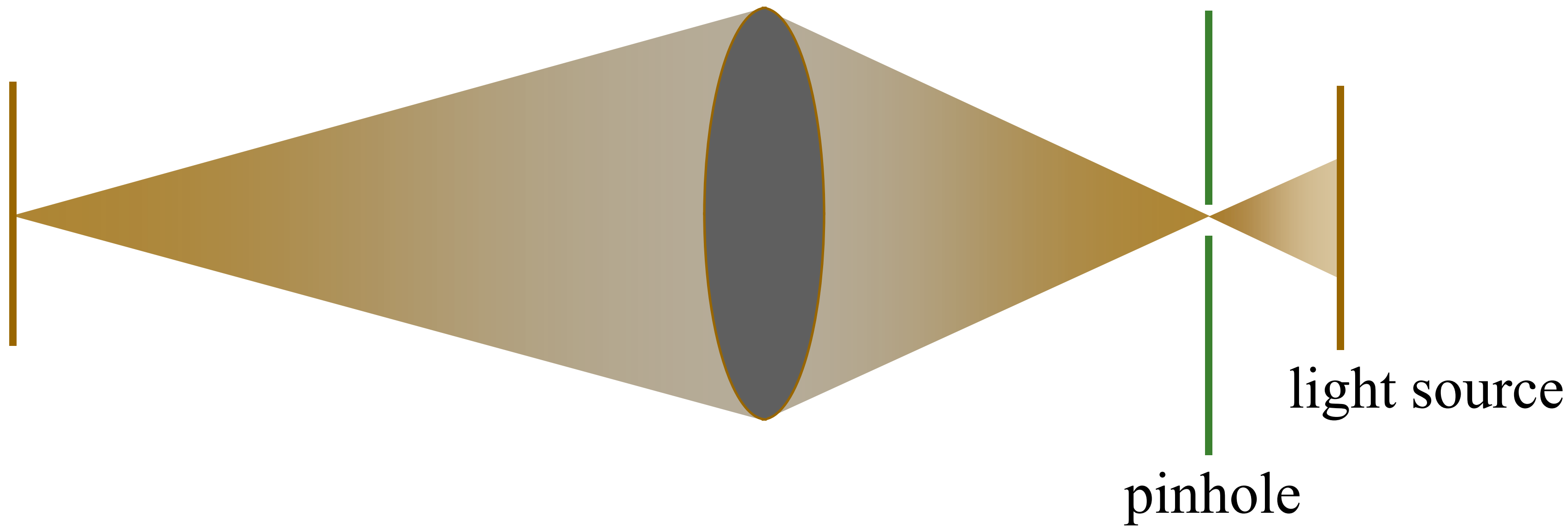


* Slide derived from Marc Levoy

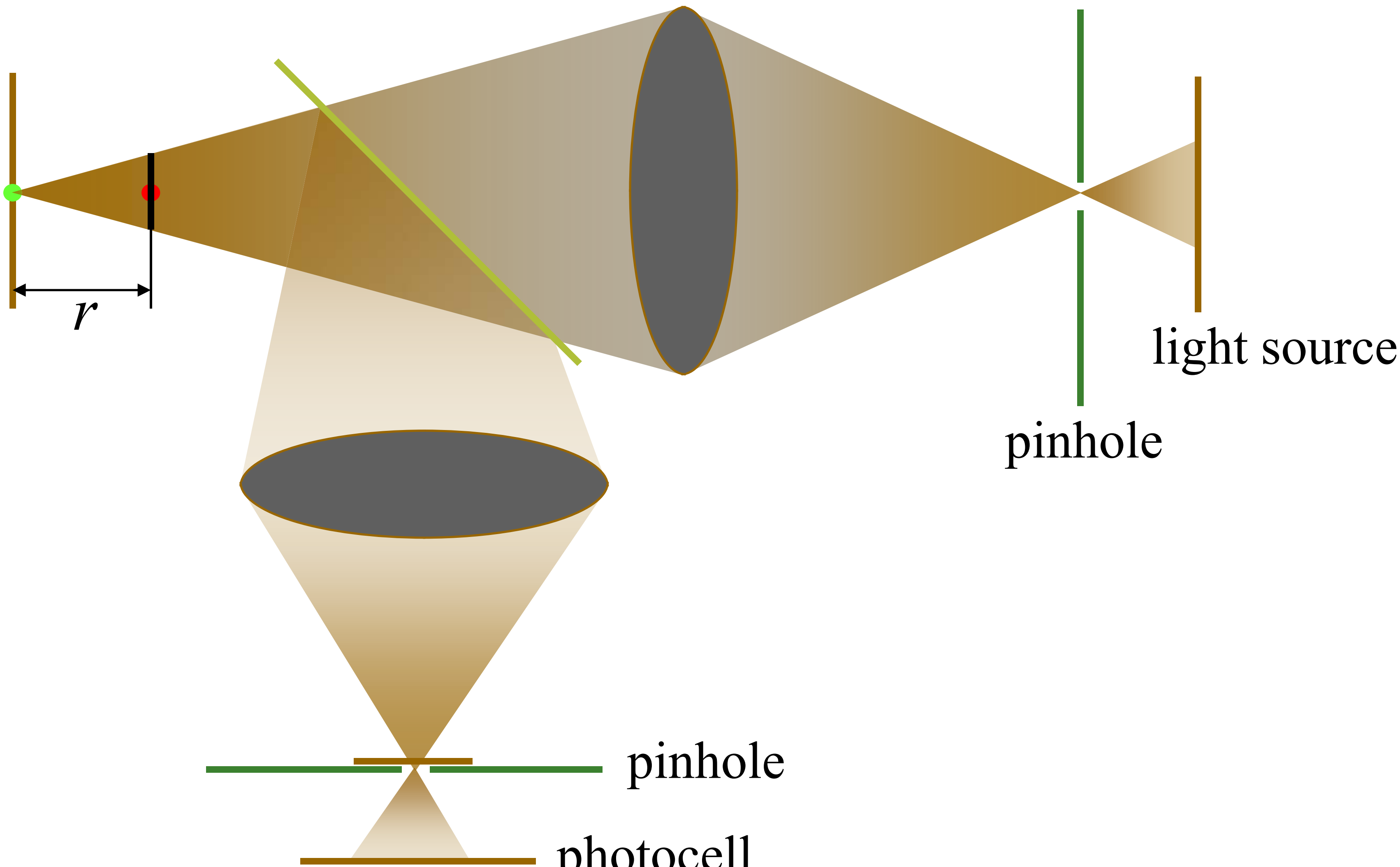
Biology: Confocal Microscopy*



* Slide derived from Marc Levoy

* first patented by Marvin Minsky in 1957

Biology: Confocal Microscopy



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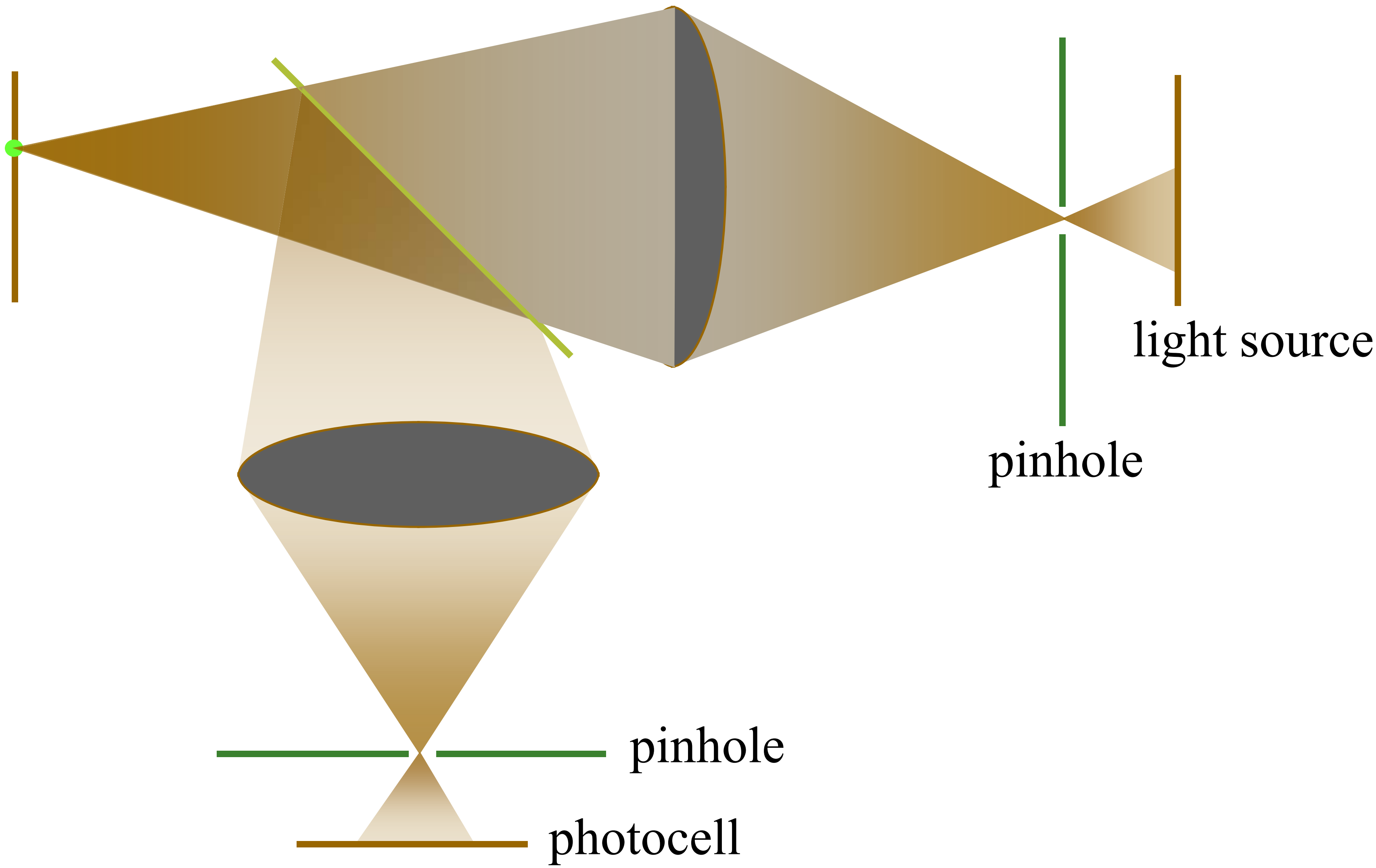
Biology: Confocal Microscopy



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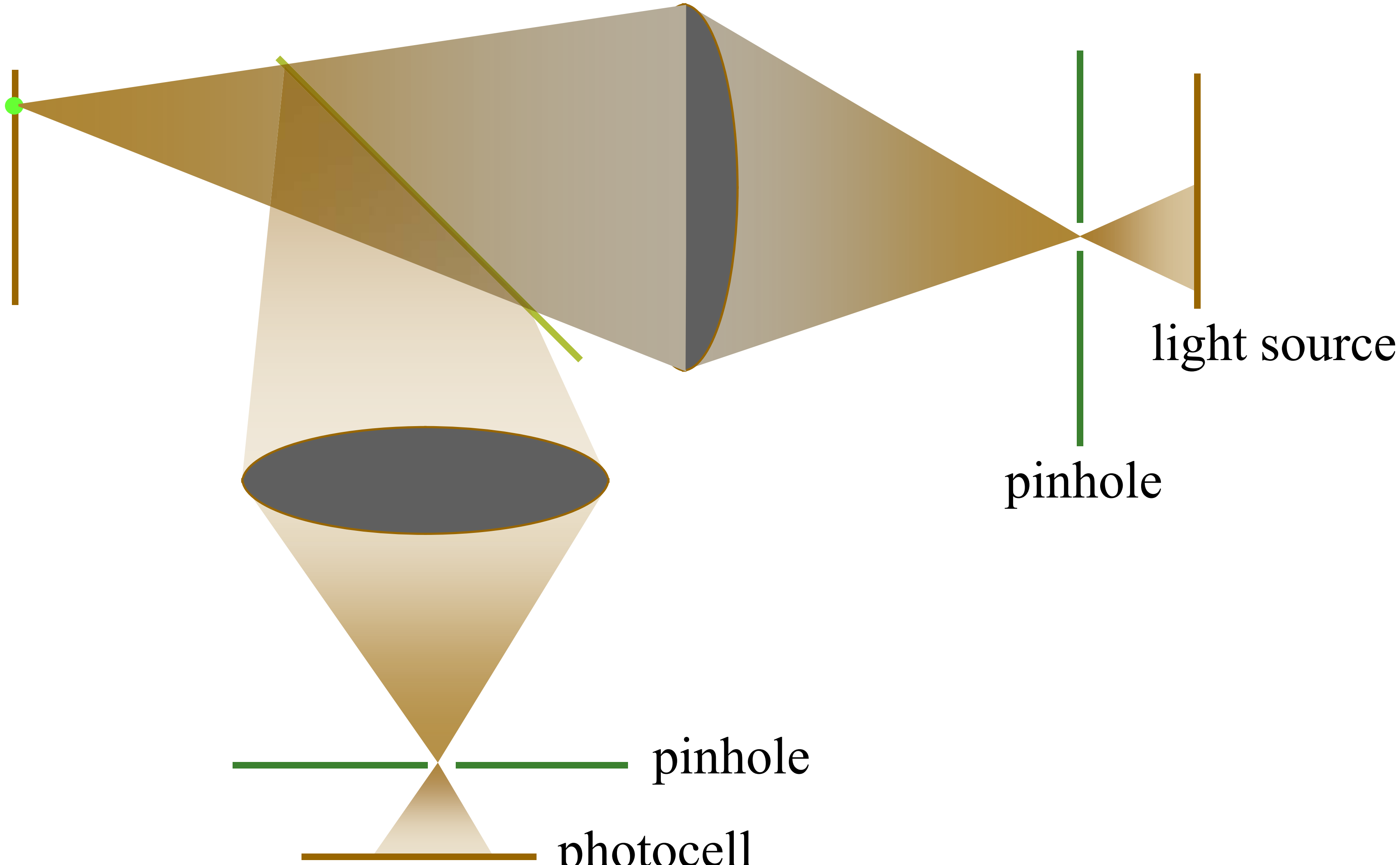
Biology: Confocal Microscopy



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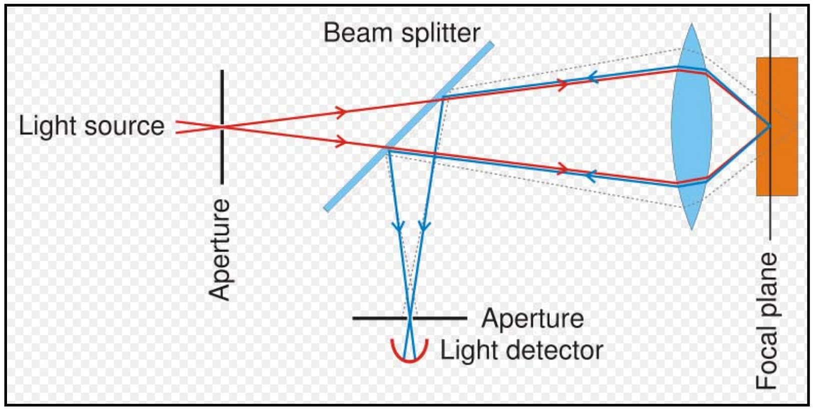
Confocal Microscopy Examples



Several confocal microscopy images removed due to copyright restrictions.

Astronomy: Coded Aperture Imaging

Images removed due to copyright restrictions. See
http://www.paulcarlisle.net/codedaperture

Diagrams removed due to copyright restrictions. Process for capturing and recontructing a coded aperture image; schematic of a shielded detector.

Gumballs – in focus

Gumballs – blurred

Coded Aperture Imaging:

- cannot practically focus X-rays using optics
- pinhole would work, but requires long exposures
- instead, use multiple pinholes and a single sensor
- produces superimposed shifted copies of source

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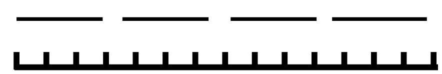
Gumballs – in focus

Gumballs – "montage of overlapping images" due to multiple pinholes



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- produces superimposed shifted copies of source

Astronomy: Coded Aperture Imaging

Gumballs – original image	*	MURA pattern	=	"..a huge mess"

Images removed due to copyright restrictions. See
http://www.paulcarlisle.net/codedaperture

Coded Aperture Imaging:

- cannot practically focus X-rays using optics
- pinhole would work, but requires long exposures
- instead, use multiple pinholes and a single sensor
- produces superimposed shifted copies of source
- MURA: Modified Uniformly Redundant Array
  (key property: 50% open, autocorrelation function is a delta function)

Astronomy: Coded Aperture Imaging

"..a huge mess" * MURA pattern = Gumballs – in focus (reconstructed)

Images removed due to copyright restrictions. See http://www.paulcarlisle.net/codedaperture

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Near-Field Coded Aperture Imaging

Diagrams removed due to copyright restrictions. Process for capturing and recontructing a coded aperture image; schematic of a shielded detector.

Diagram removed due to copyright restrictions. Schematic of flux passing through mask into detector.

Coded Aperture Imaging (Source Reconstruction):

- backproject each detected pixel intensity through each hole in mask
- superimposition of projections reconstructs source (plus a bias)
- essentially a cross-correlation of detected image with mask
- also works for non-infinite sources (in which case, must use voxel grid)
- assumes sources are not occluded (except by the mask)