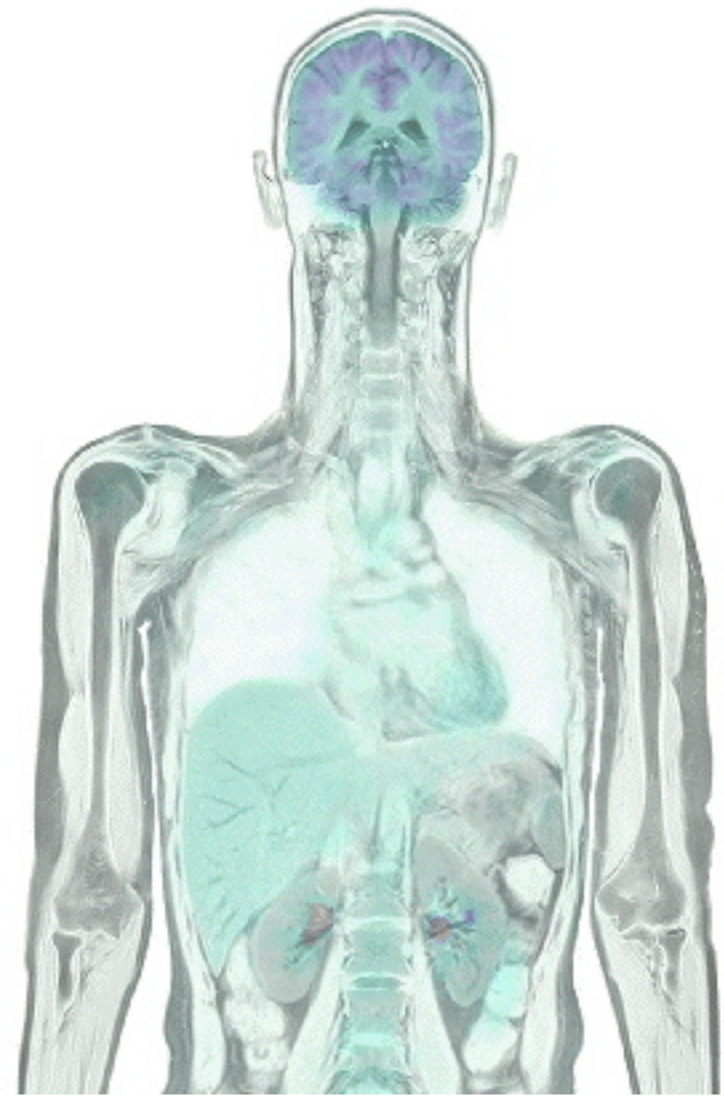
Physics 428: Imaging Detectors for Medical and Health Sciences

- Lead Instructor: Paul Kinahan
- Lectures: Tuesday 6:30-8:50 PM, PAA Room 110
- **Objective**:

  Provide an introduction to the specific imaging methods of x-ray, gamma-ray, CT, SPECT, PET, and PET/CT imaging
- Text: There is no required textbook for this course
- Prerequisite: At least undergraduate freshman-level physics or chemistry, and some advanced coursework typical of engineering or science majors; calculus, algebra and trigonometry, and preferably PHYS 575 and 576
- Grading: Midterm exam. Final paper and class presentation. Class participation in seminars and discussions.



Lecture Sequence

Lecture	Date	Instructor	Topic
1	April 2	PK	Overview: Imaging equation, inverse problem, 2D-LSI imaging systems
2	April 9	PK	X-ray physics: formation and interaction
3	**April 16**	WH	X-ray detection and imaging systems
4	April 23	PK	X-ray computed tomography (CT) systems
5	April 30	AA	Computed tomography: Biomedical applications
6	May 7	PK	Midterm Exam. Contrast, noise, and image quality
7	**May 14**	LM	Nuclear decay schemes and isotopes
8	May 21	RM	Gamma cameras: components and systems
9	May 28	WH	Tomography in molecular imaging: SPECT scanners
10	June 4	SB	Positron emission tomography (PET) and hybrid PET/CT scanners
11	**June 11**	WH/PK	Group project presentations

* draft schedule

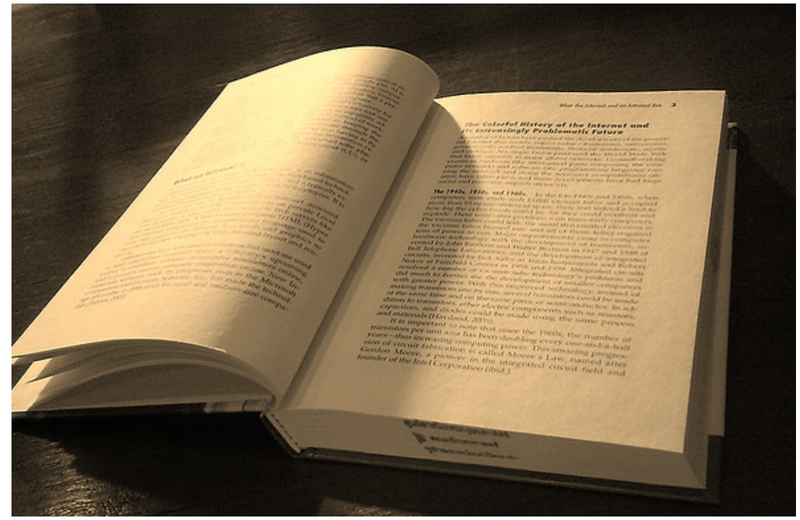
PK = Paul Kinahan
WH = William Hunter
AA = Adam Alessio
LM = Larry MacDonald
RM = Robert Miyaoka
SB = Steve Bowen

Course notes

- Course site: http://courses.washington.edu/phys428/
- Online lecture site: http://uweoconnect.extn.washington.edu/phys428/
- UW Outreach site (for lecture recordings etc): http://moodle.extn.washington.edu/course/view.php?id=4008
- Class email: TBD
- All students must take the midterm exam during the scheduled time
- No course incompletes will be given, except per UW regulations

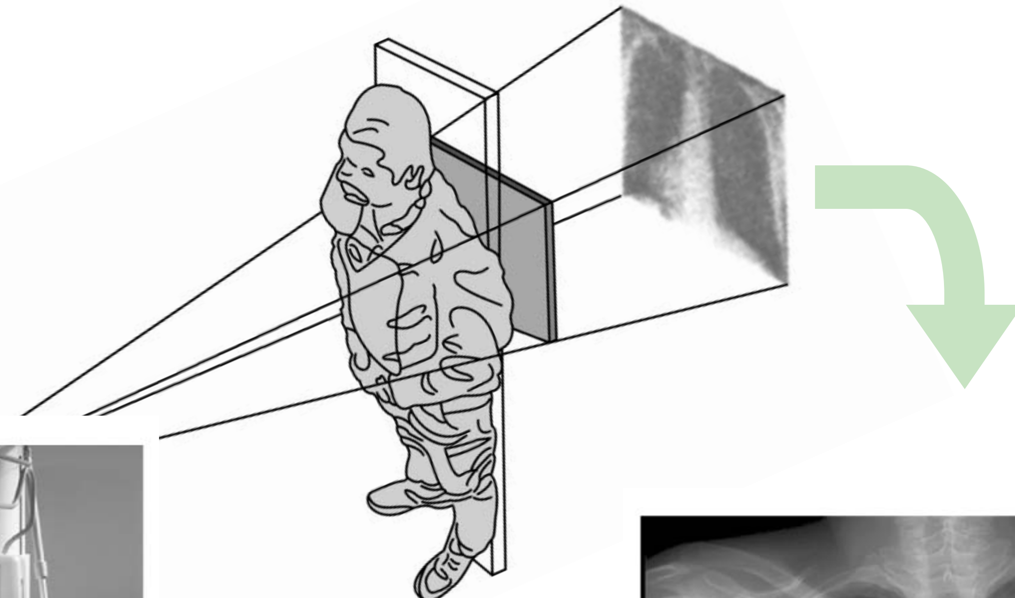
Images

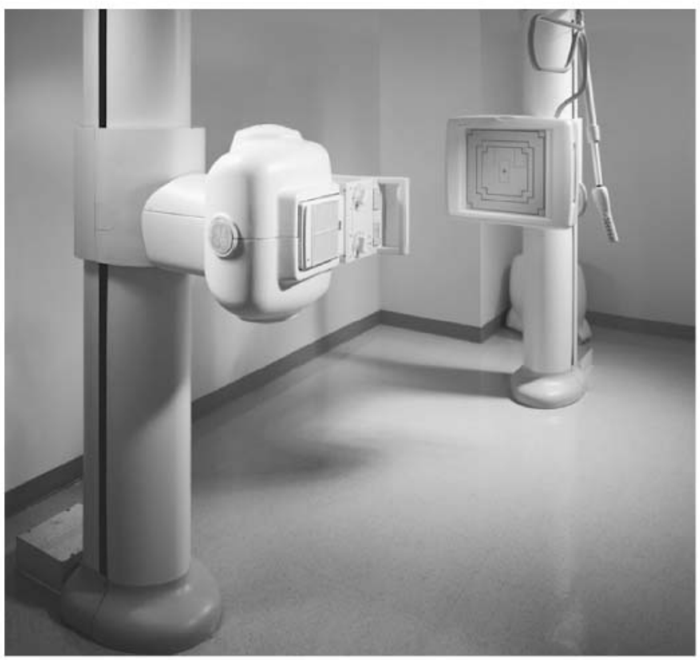
Types of Images: 2D Images

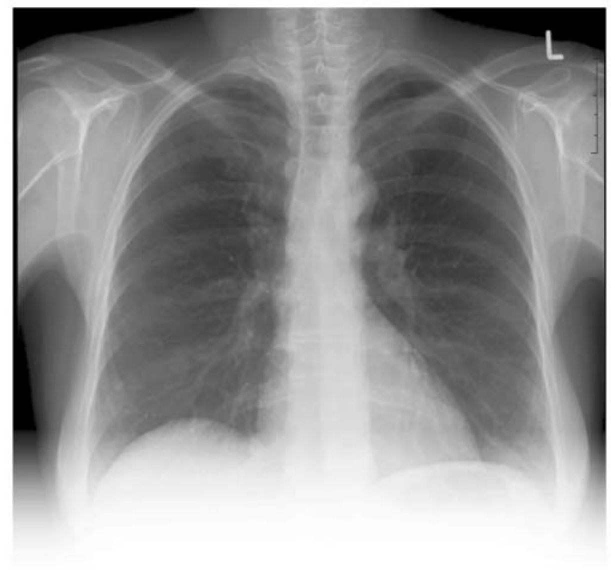


René Magritte *The Treachery of Images* 1928

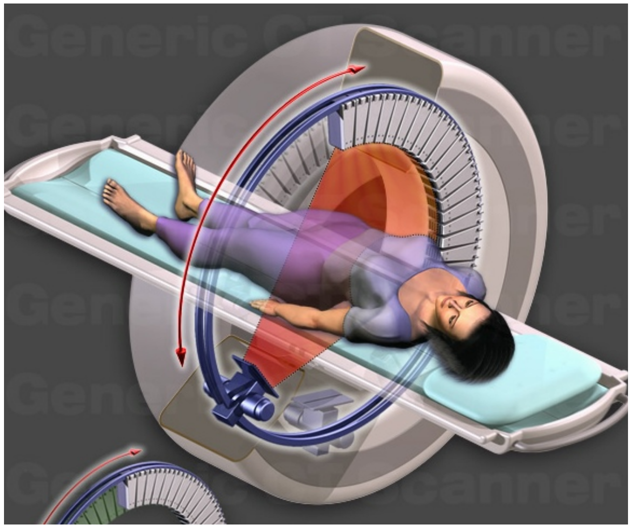
Types of Images: Projection Imaging



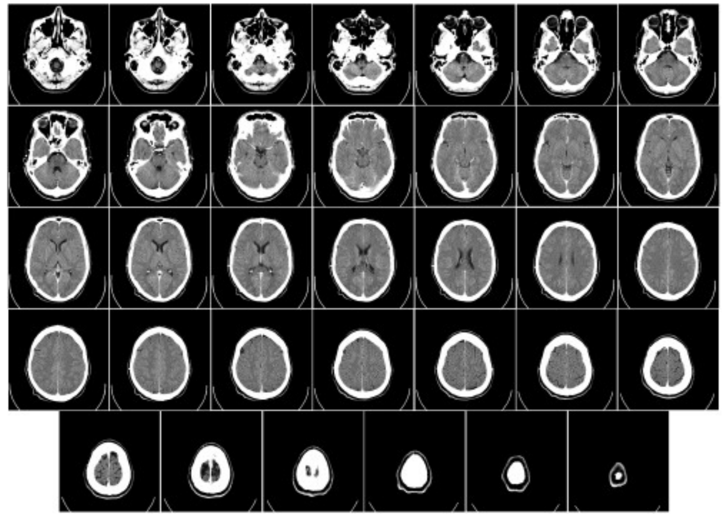




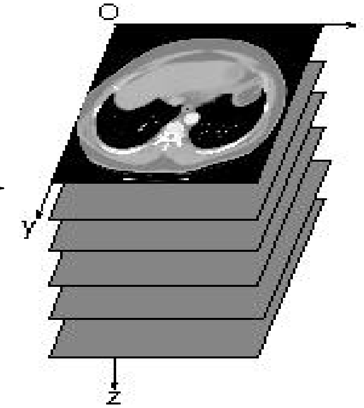
Types of Images: Tomography Imaging



tomographic acquisition



reconstruction of multiple images



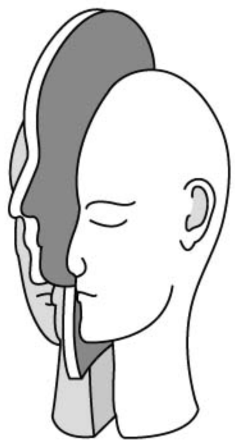
form image volume

image processing

simple

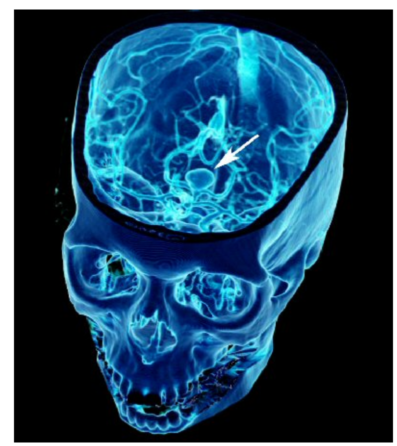
transaxial or axial view

coronal view



sagittal view

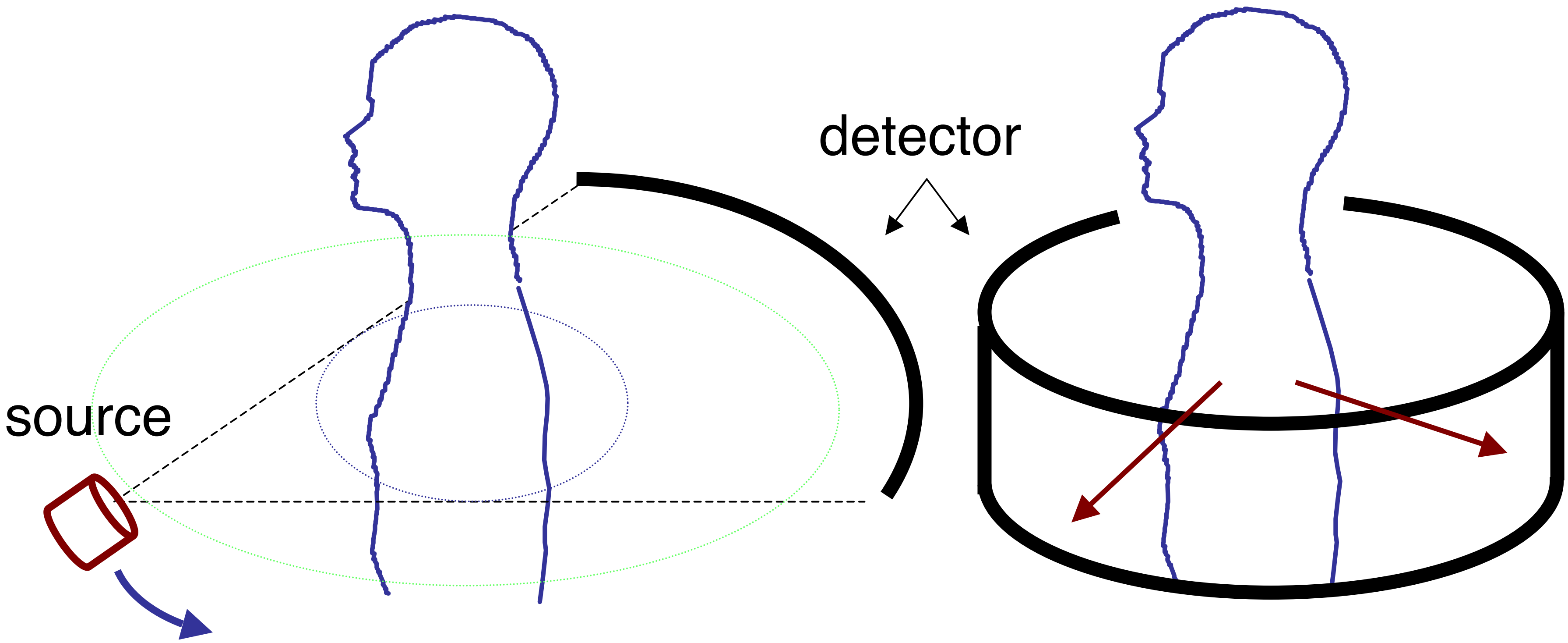
sophisticated



basilar tip aneurysm

Two Types of Tomography

'Tomo' + 'graphy' = Greek: 'slice' + 'picture'



CT: Transmission

PET: Emission

Major Modalities

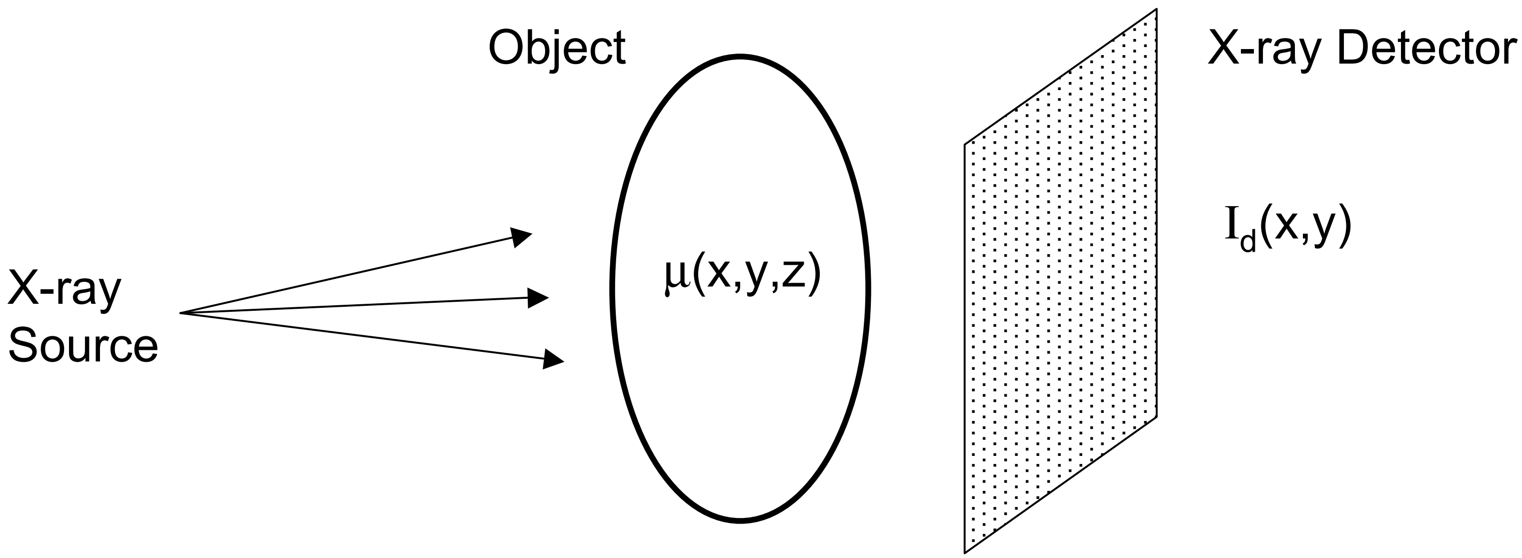
- X-ray Radiography and Computed Tomography (CT)
- Nuclear Medicine (SPECT, PET)
- Ultrasound
- Magnetic Resonance Imaging
- Optical Tomography

There are many other types of biomedical imaging

Of interest are hybrid imaging methods

  - PET/CT, PET/MR
  - Photoacoustic

Projection X-ray Imaging



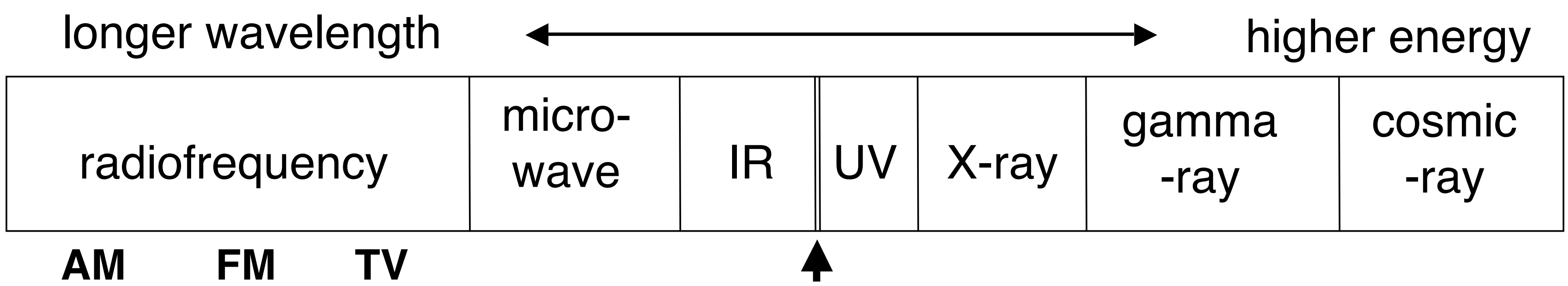
- Image records transmission of x-rays through object

$$I_d(x,y) = I_0 \exp(-\int \mu(x,y,z)dl)$$

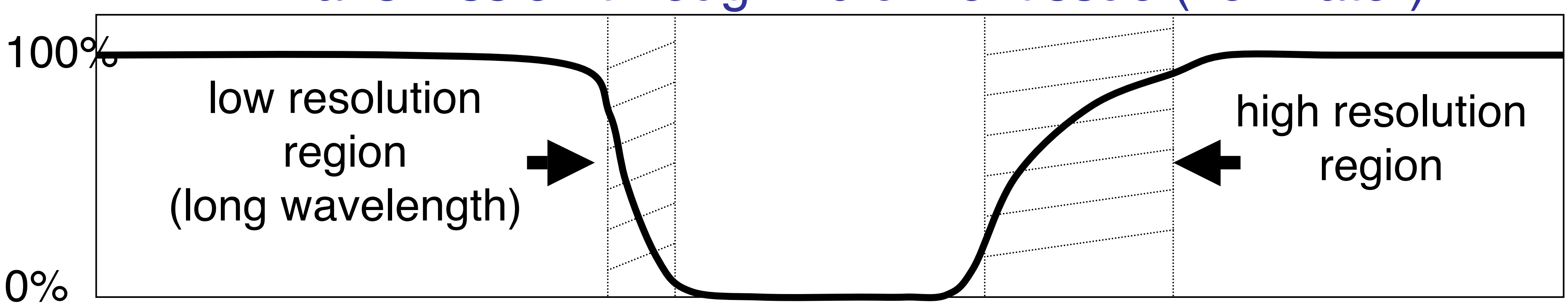
- The integral is a line-integral or a "projection" through obj
- $\mu(x,y,z)$ – x-ray attenuation coefficient, a tissue property, a function of electron density, atomic #, …

Physics of photon imaging

The Electromagnetic Spectrum



Transmission through 10 cm of tissue (i.e. water)



what is Transmission through 1 cm of tissue?

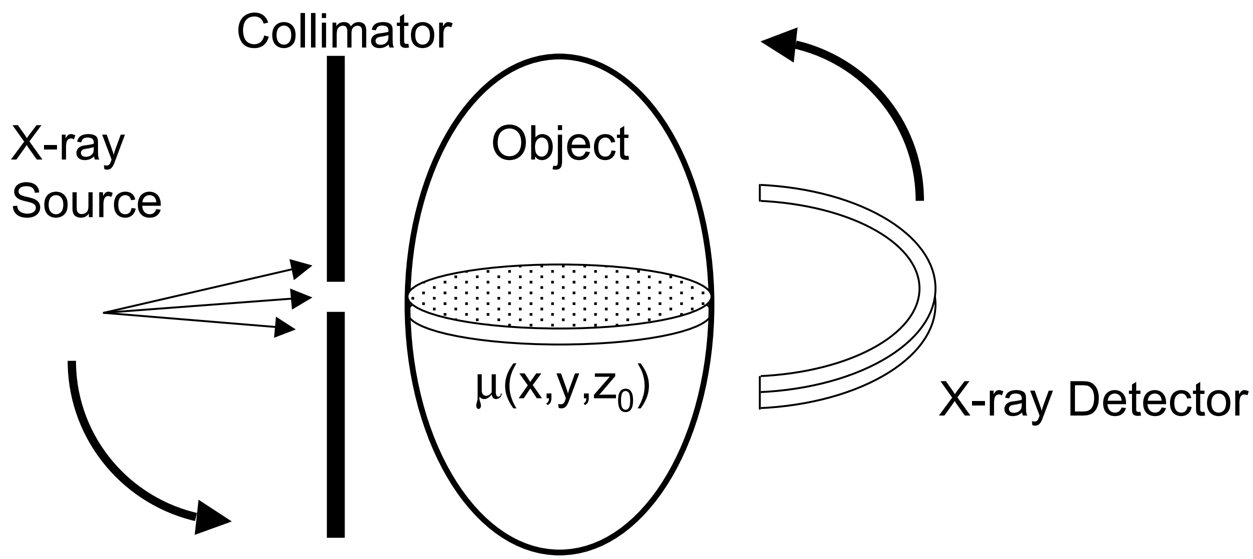
X-ray Imaging
Projection vs Tomographic

Projection Image

Chest Mass

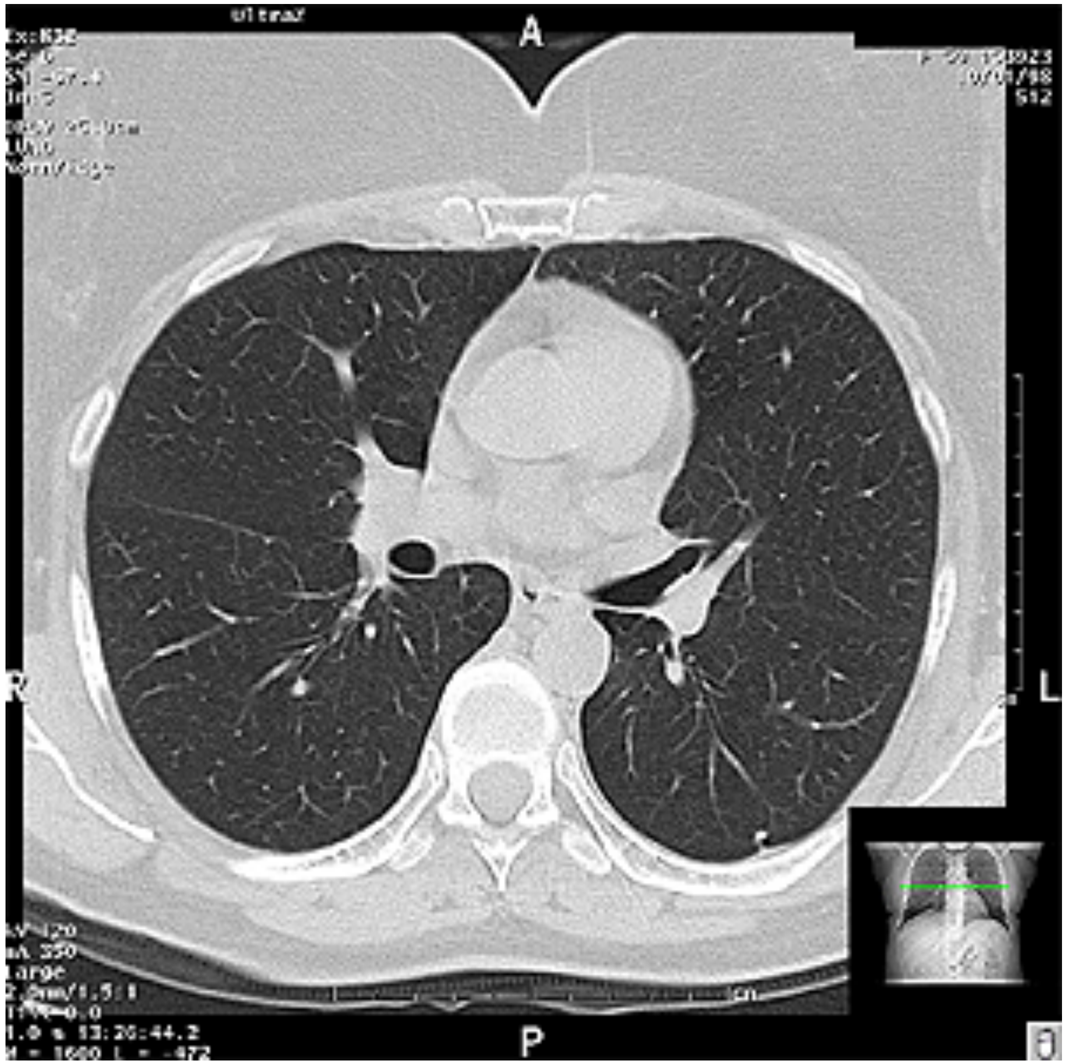
Cross-sectional Image

X-ray Computed Tomography

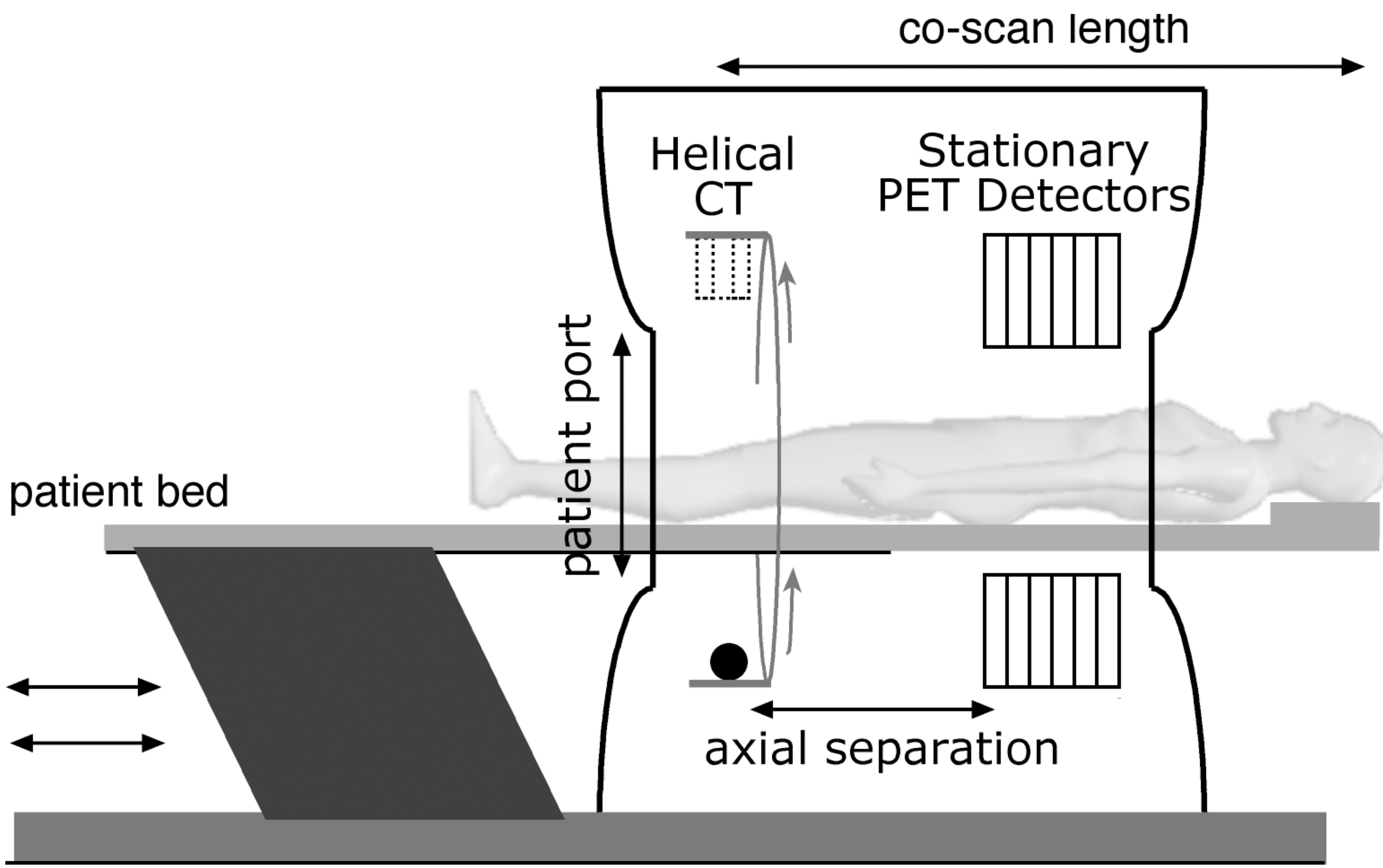


- Uses x-rays, but exposure is limited to a slice (or “a couple of” slices) by a collimator
- Source and detector rotate around object – projections from many angles
- The desired image, $I(x,y) = \mu(x,y,z_0)$, is computed from the projections

X-ray Computed Tomography



PET/CT Scanner

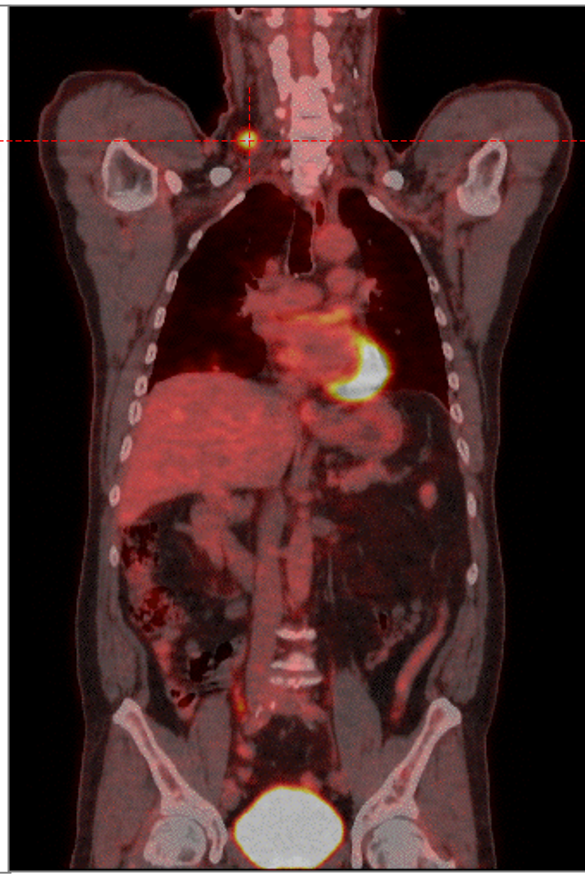


All 3 (couch, CT and PET) must be in accurate alignment

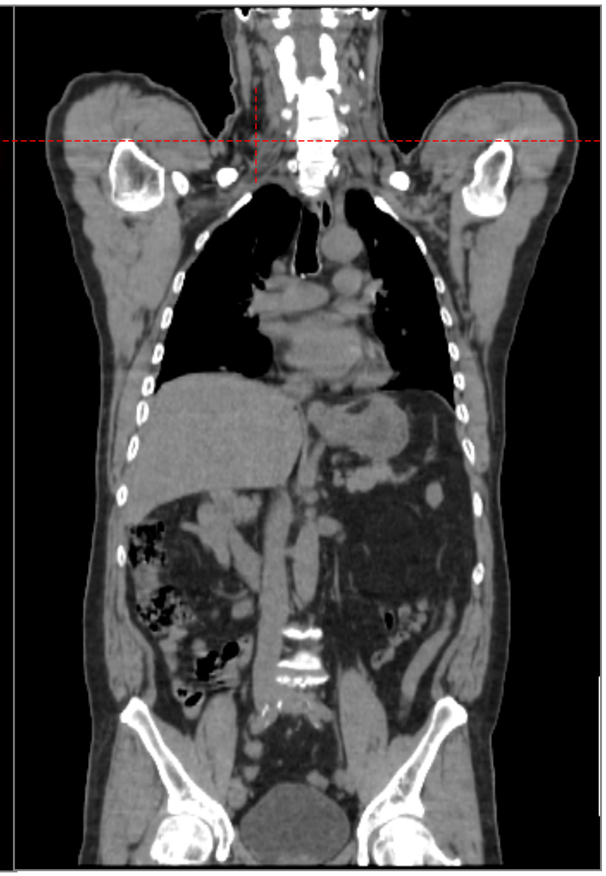
Commercial/Clinical PET/CT Scanner

Molecular imaging using PET/CT is a powerful tool for detection, diagnosis, and staging of cancer

PET Image of Function

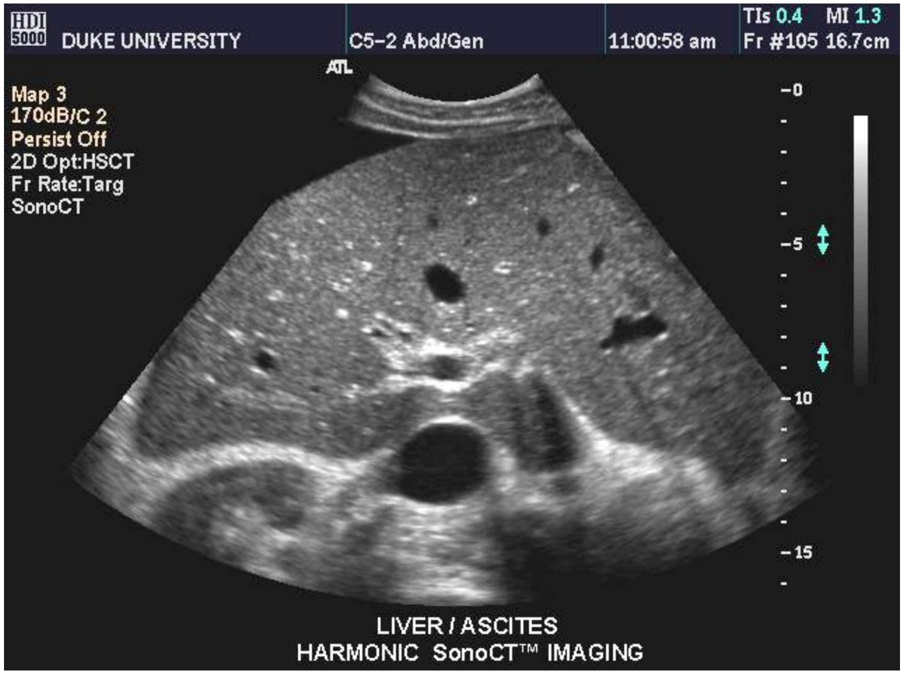


Function+Anatomy

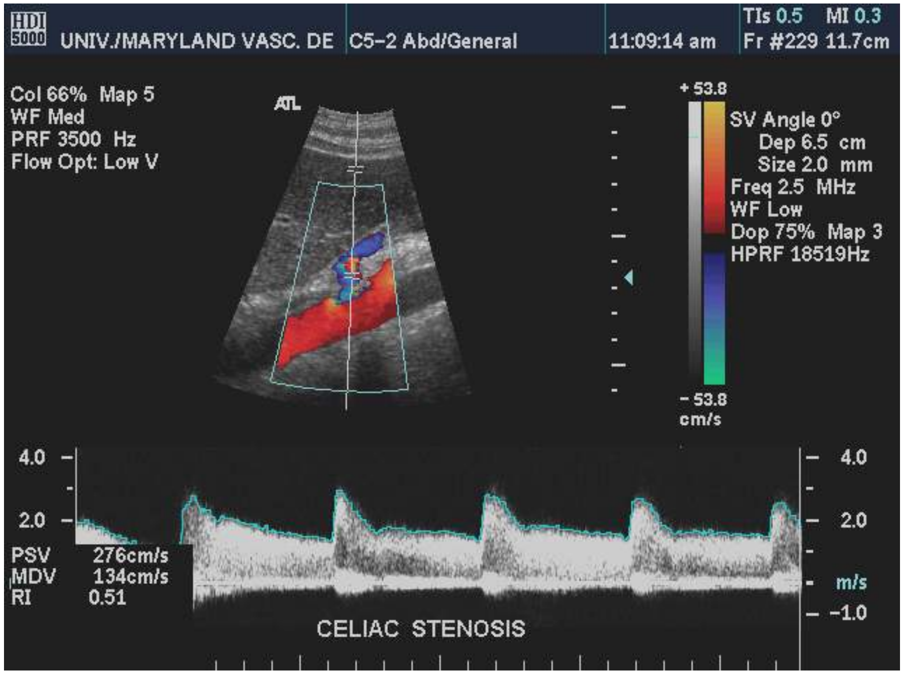


CT Image of Anatomy

Ultrasound Imaging

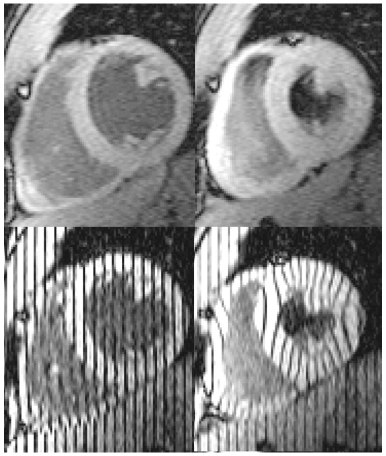


High-Resolution

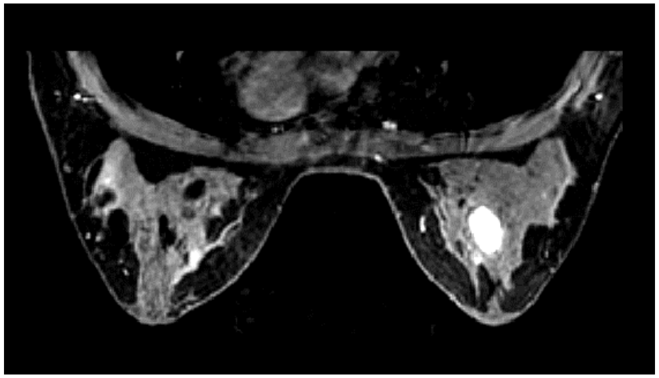


Color Doppler

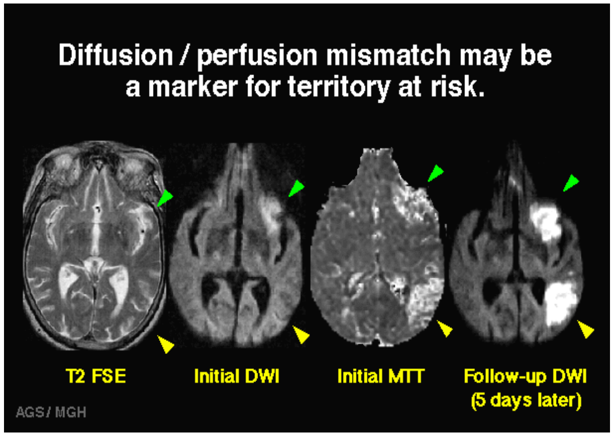
MRI



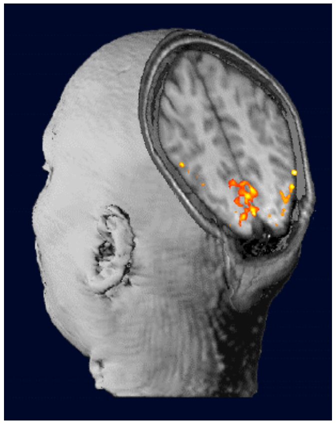
cardiac



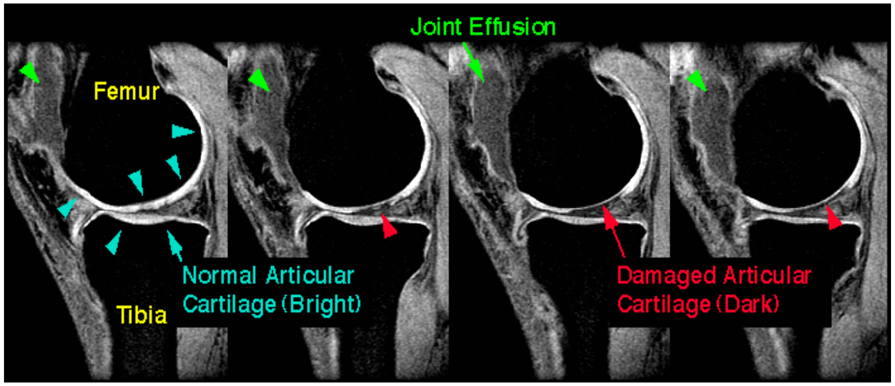
cancer



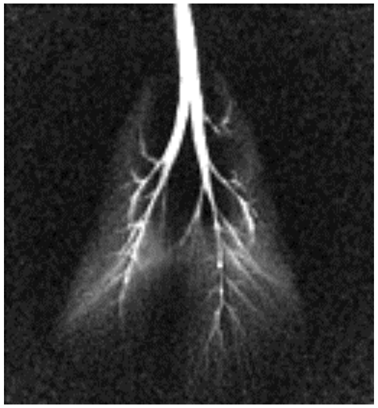
stroke



neuro function



joint



lung

Medical Imaging

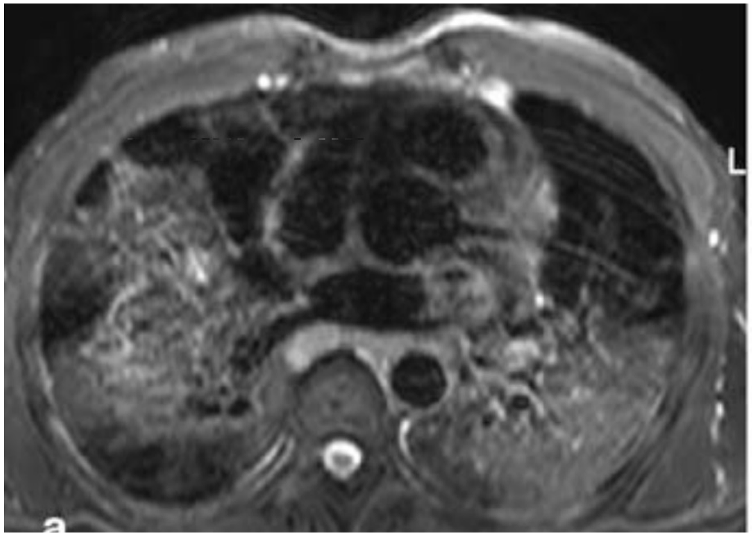
- Visualization of internal organs, tissue, organ function, bio-physiological status, etc.
  - Pathologies and diseases often have different imaging characteristics from normal states, either static (e.g. anatomy) or dynamic (functional)
  - Often pathologies are undetectable in one one approach and visible in another
- Image: a 2D signal $f(x,y)$ or 3D signal $f(x,y,z)$
- Imaging provides localized information, unlike global or *systemic* diagnostics
  - i.e. where is the disease?
  - imaging can be more sensitive by providing a localized measurement

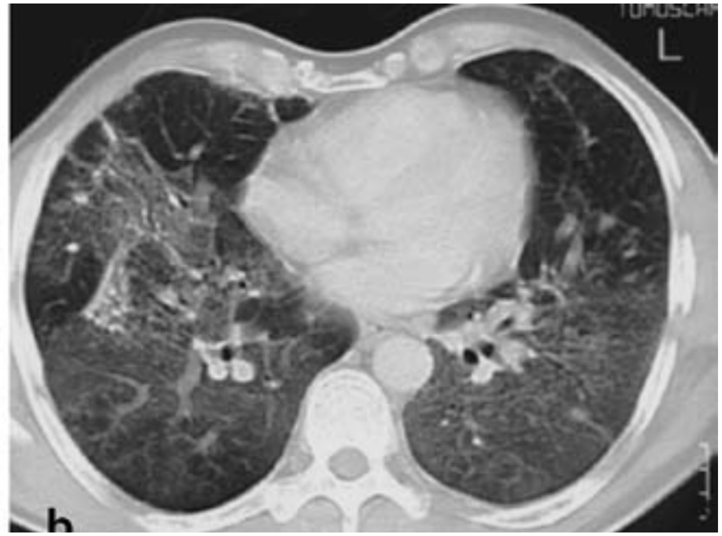
Common themes in biomedical imaging

- Where does the signal come from?
  - This is modality specific
  - determines the quantity displayed in images
- Contrast agents
- The imaging equation: What is the mathematical description of the acquisition of the raw data?
- The inverse problem: How do we form an image from the raw data?
- Signal to noise ratio
- Safety
- Cost versus usefulness
- Clinical versus research applications
- Diagnosis versus therapy

Lung images with different modalities

MRI

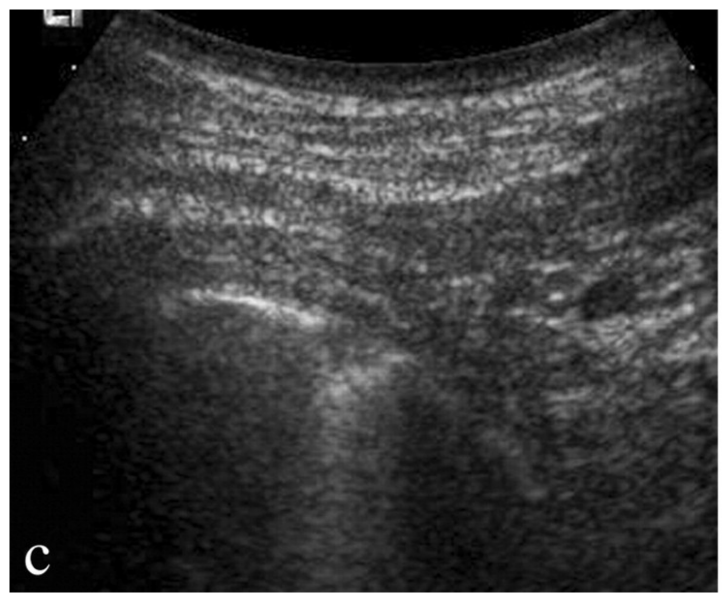




CT

What do the image values represent?

PET



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Contrast / Contrast Agents / Tracers

- To image inside the body we need something to provide a signal (i.e. a difference or contrast) that we can measure
- Contrast can be *intrinsic* or *extrinsic*
  - Intrinsic: Already present, e.g. tissue density differences seen with x-ray imaging
  - Extrinsic: A <u>contrast agent</u> put into a patient (ingested, injected, etc.) to provide a signal. Acts as a signal amplification.
- Targeted contrast agents use different mechanisms (e.g. antibodies) to attach to specific objects or processes
- Needed amount of contrast agent is a critical parameter
  - Ideally, a contrast agent does not alter anything (i.e. a *tracer*)
  - Safety and toxicity are critical parameters

Contrast / Contrast Agents / Tracers

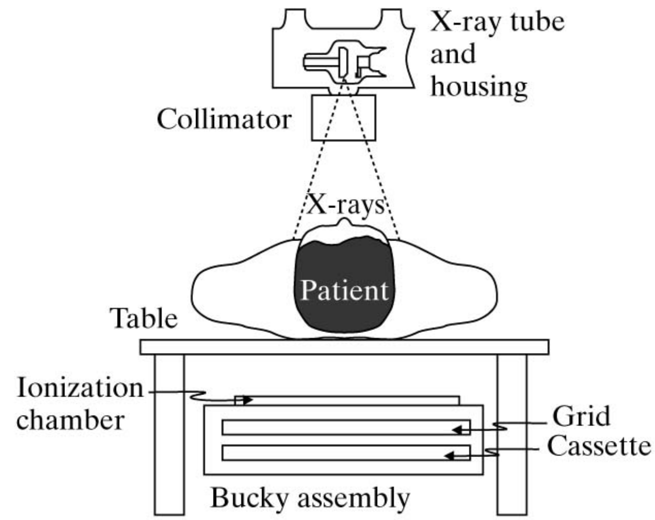
Modality	Intrinsic (already present)	Extrinsic (added)
Nuclear, SPECT, PET	None	Radioisotope-labeled tracers (radiotracers)
x-ray, CT	Photon absorption by Compton scattering (density) and photoelectric absorption	Iodine, barium to enhance photon absorption
Ultrasound	Vibrational wave reflectance due to tissues differences	Micro-bubbles to enhance reflectance
MRI	Radiofrequency (RF) signals generated by stimulated oscillating nuclear magnetic moments. RF signal depends on density and magnetic relaxation time differences in local microenviroment	chelated gadolinium and superparamagnetic iron oxide (SPIO) particles to alter magnetic relaxation times
Optical tomography	Changes in scattering, absorption, polarization. Also time- or frequency-dependent modulation of amplitude, phase, or frequency	microspheres, absorbing dyes, plasmon-resonant or magnetomotive nanoparticles

Contrast Agent Example


no
contrast
with
contrast

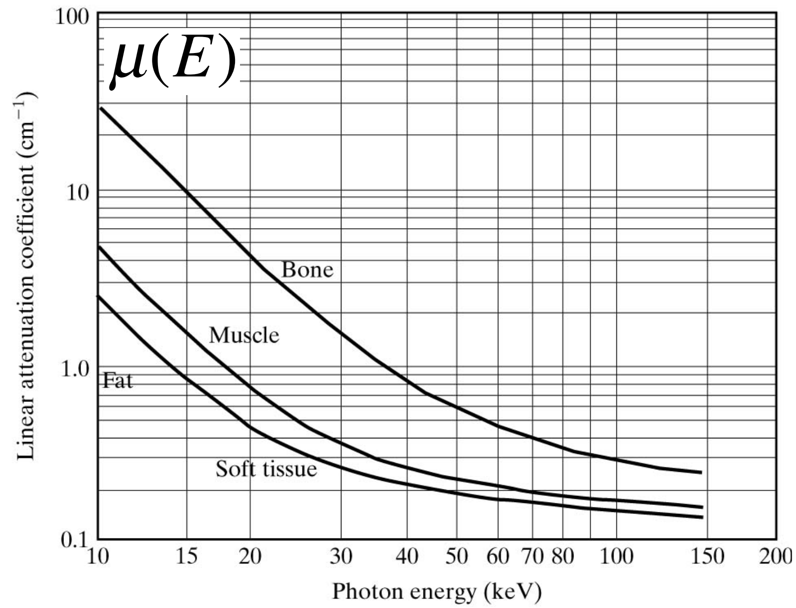
X-ray imaging system

- The attenuation of x-rays in the body depends on material and energy
- We can enhance attenuation by using 'contrast agents', typically iodine (injected) or barium (ingested)



X-ray physics: Imaging equation

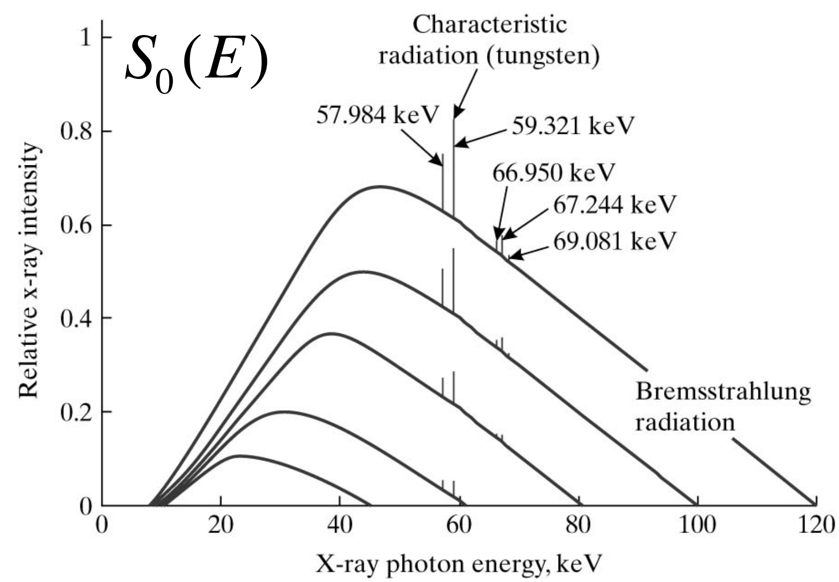
- Attenuation μ of x-rays depends on material (thus position of material) and energy
- From x-ray tubes there is a weighted distribution of energies S
- X-ray imaging equation: Detector signal I at position x



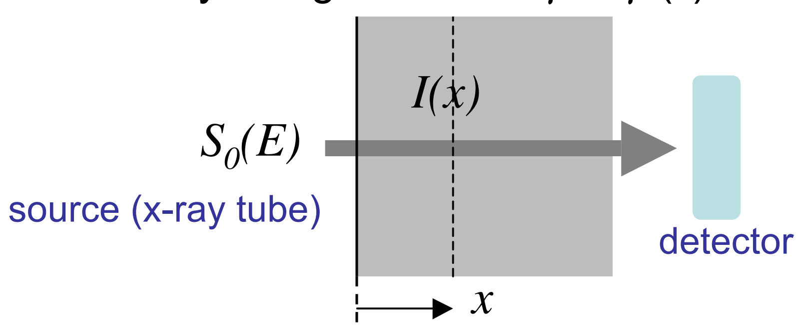
$$I(x)=\int_{E=0}^{E_{max}} E' S_0(E') e^{-\int_0^x \mu(x',E')\,dx'} dE'$$

what we measure: $I(x)$

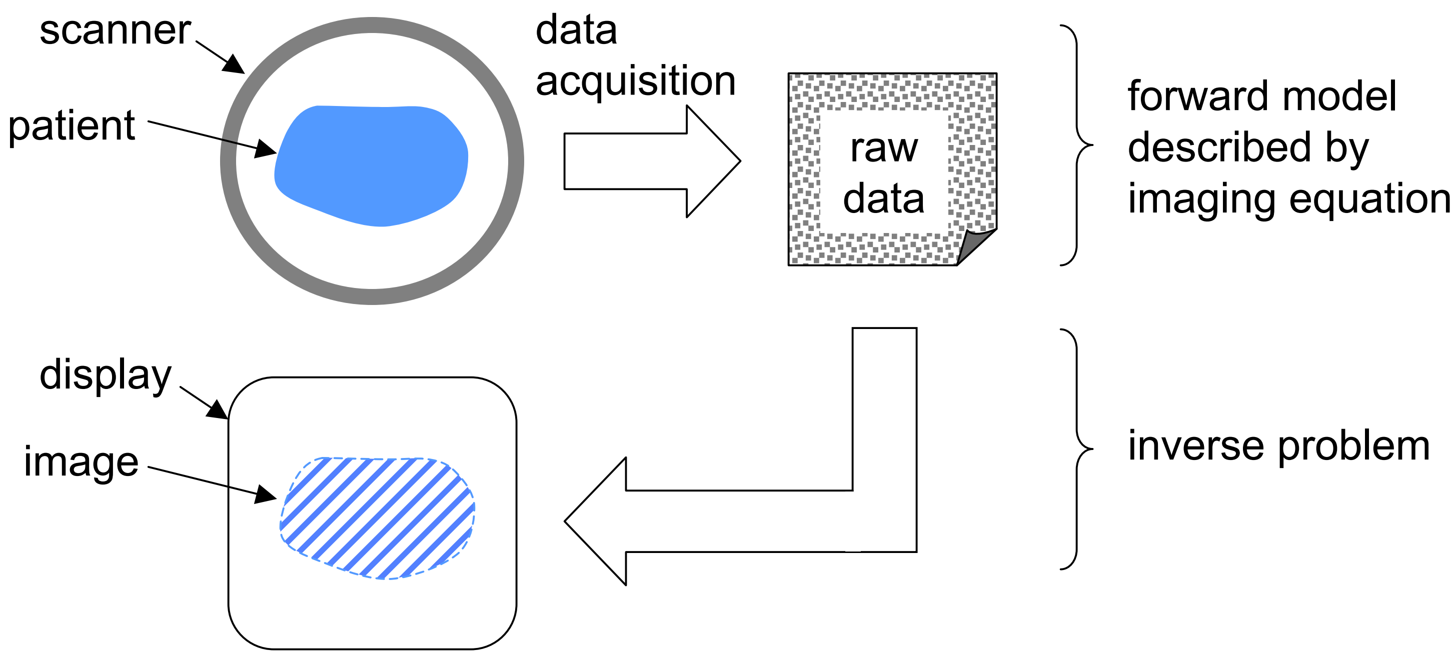
what we want to know: $\mu(x',E')$



beam intensity along a line with $\mu = \mu(x)$

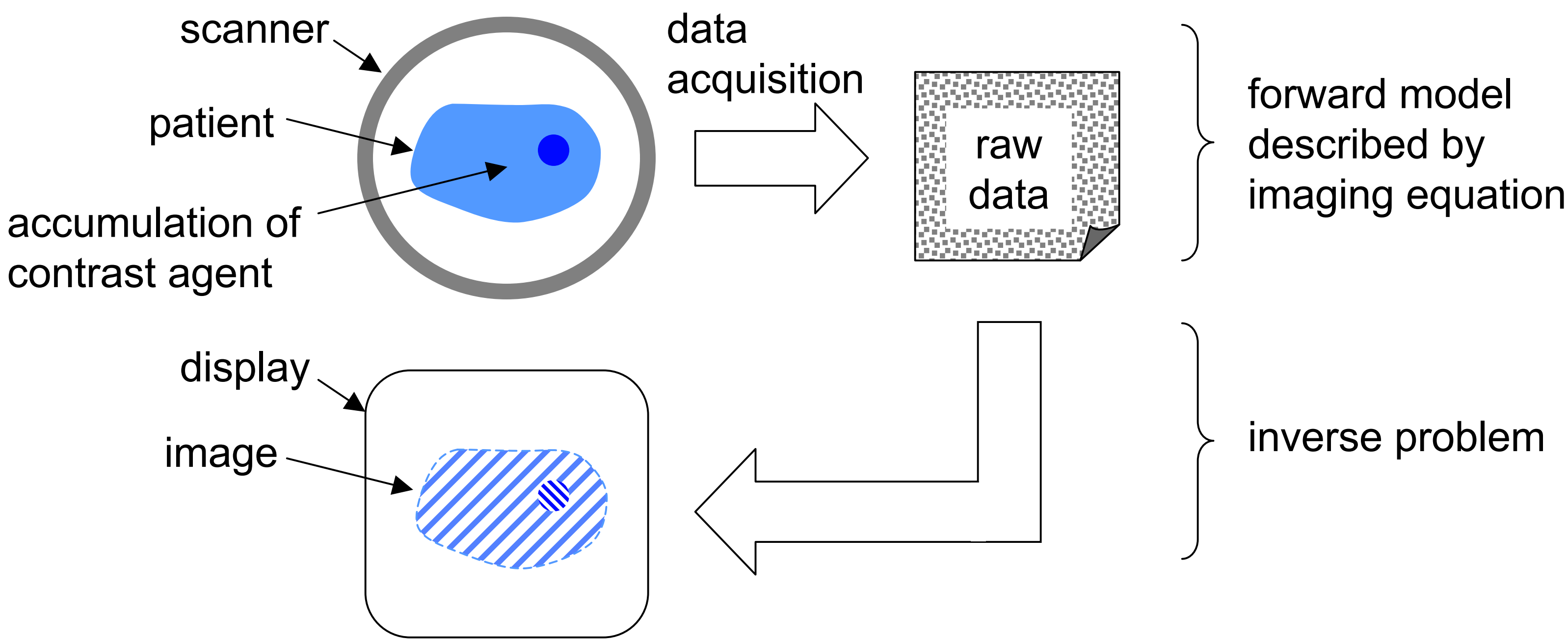


Biomedical Imaging Systems



- To estimate an image of property of interest, e.g. $\mu(x,y)$, from the raw data, we have to solve the inverse problem

Imaging Systems + Contrast Agents



- The use of a contrast agent can amplify the signal of interest, e.g. μ for iodine is much higher than μ for tissue.

Imaging Diagnostics vs. Therapy

- What is the relation between diagnostics and therapy?
- What are the major disease classes?
- How can imaging interact with therapy?

What is the relation between diagnostics and therapy?

- A diagnosis may (we hope) help select of guide therapy when we don't have enough information
- Therapy should be making a change, diagnosis should not make a change
- Diagnostic procedures can provide feedback on therapeutic effectiveness
- Some tools for diagnosis can be used for therapy and vice versa (or can occur at the same time)
- Cost / resources / time are more readily used for therapy than diagnosis

What are the classes of major bad things?

- Cancer
- Viral Infection
- Trauma
- Bacterial infection
- Cardiovascular
- Autoimmune
- Neurological
- Fungal infection
- Genetic abnormalities
- Acute radiation effects
- Stochastic radiation effects
- Metabolic/endocrine disorders

How can imaging interact with therapy?

- Monitor progression or response
- Guide surgery
- Real-time feedback of therapy
- Screening: simple, low FP & FN, safe, fast/easy, cheap, detection
- Diagnosis: what is it? where is it?
- Peace of mind
- Staging: How serious is it, what therapy do we use, what is the prognosis

Classifications in Biomedical Imaging

Projection	Tomographic
Transmission	Emission
Anatomical	Functional
With contrast agents	Without contrast agents
Clinical	Non-clinical (Clinical trials)
Therapeutic	Diagnostic

Cost