# Structure of the course

1) Introduction
2) Therapy with proton and ion beams
3) X- ray sources
4) Sources for nuclear medicine
5) Detection of photons (physics and detectors)
6) **Image quality ***
7) Image reconstruction
8) X-ray imaging
9) Computed tomography
10) Planar scintigraphy
11) Emission tomography
12) Magnetic Resonance Imaging
13) Multimodal systems

**sources** (3–4)

**principles / tools** (5)

**objective** (6)

**method** (7)

**imaging modalities** (8–12)

**Medical imaging** (3–13)

* Prince and Links, Medical Imaging Signals and Systems, Chap 3.

# Measures of Quality

- Physics-oriented issues:
  - contrast, resolution
  - noise, artifacts, distortion
  - quantitative accuracy

- Task-oriented issues:
  - sensitivity, specificity
  - diagnostic accuracy

slides from Yao Wang lectures at NYU-Poly

# Image reconstruction

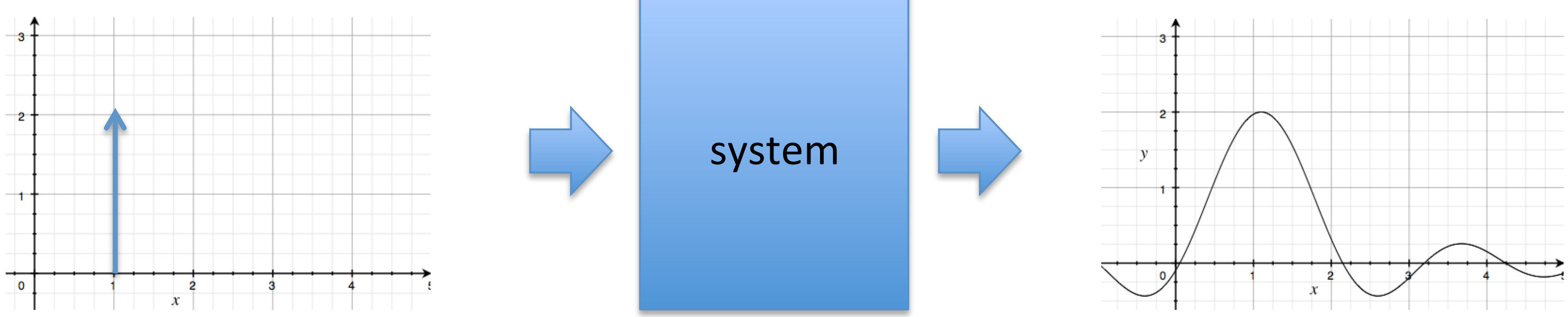
Input = object to be imaged

System = device to used to image an object

Output = obtained image from the system (interpretation of the object)

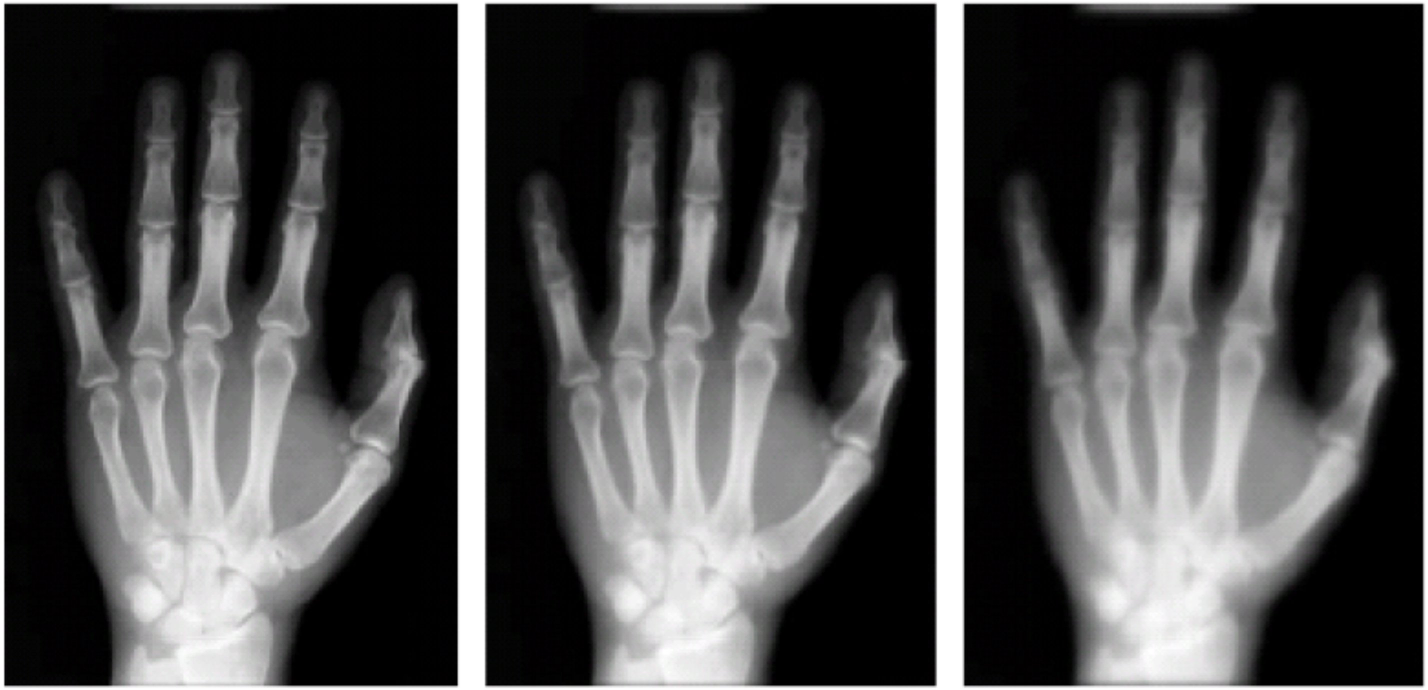
Input signal
f(x,y)

Output signal
g(x,y)

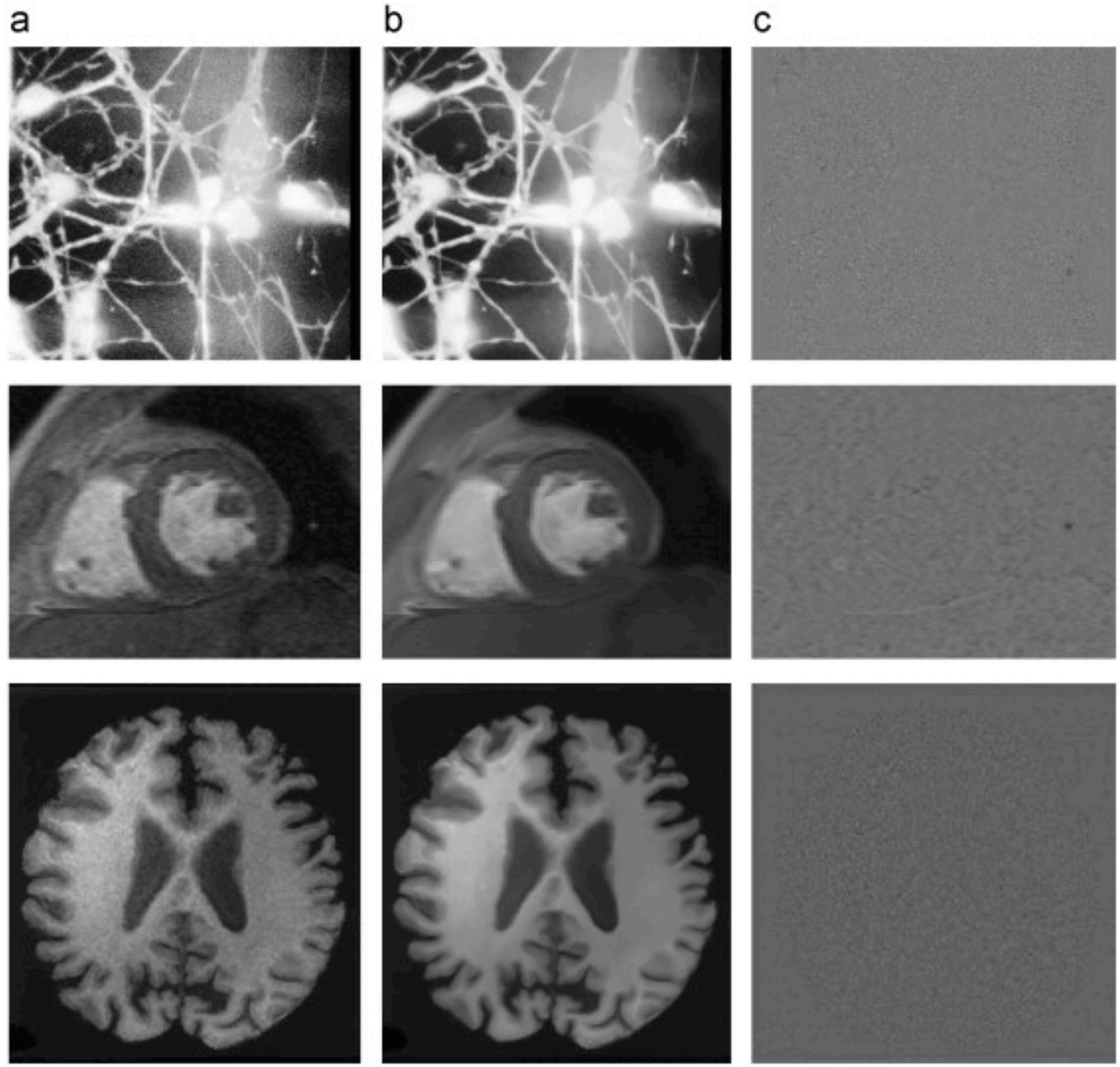


# Introduction

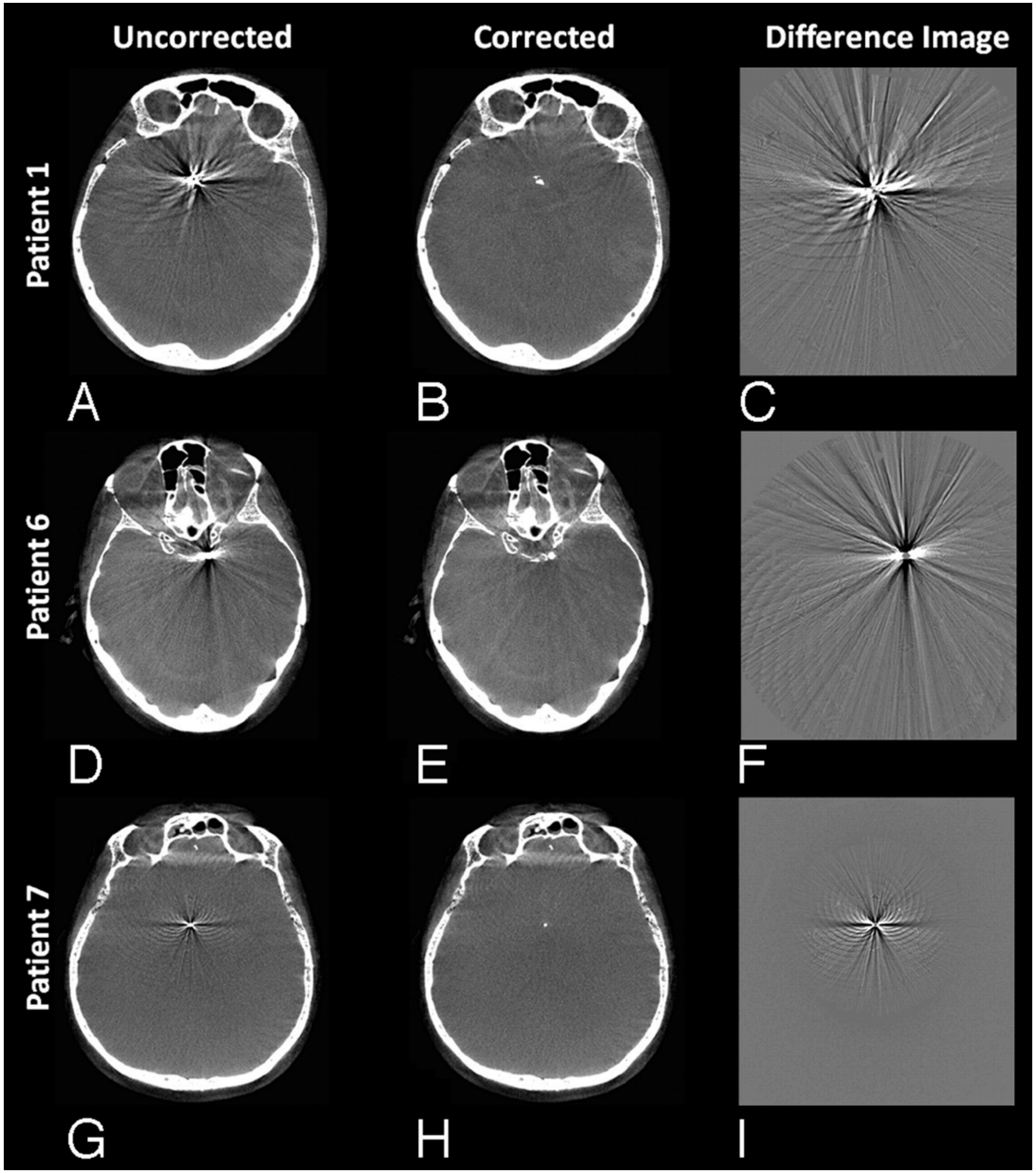
- Contrast
- Resolution
- Noise
- Artifacts
- Distortions



- Contrast
- Resolution
- Noise
- Artifacts
- Distortions

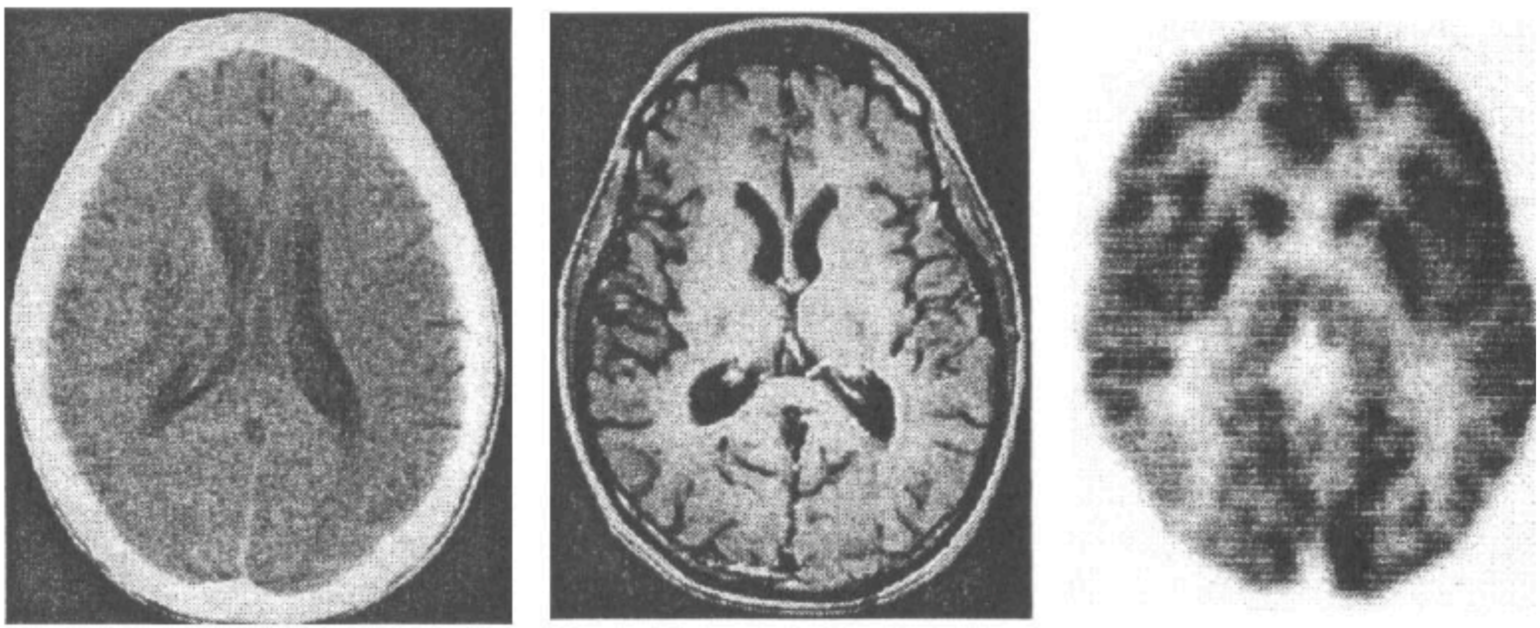


- Contrast
- Resolution
- Noise
- Artifacts
- Distortions



# Contrast

- Difference between image characteristics of an object of interest and surrounding objects or background
- Which image below has higher contrast?



(a) (b) (c)

Figure I.4

*Medical Imaging Signals and Systems*, by Jerry L. Prince and Jonathan Links.

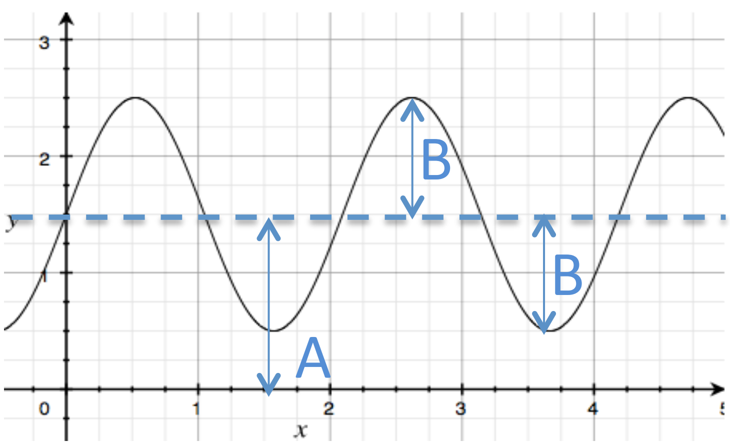
# Contrast

- Difference between image characteristics of an object of interest and surrounding objects or background
- General definition:

  $f_{max}$, $f_{min}$: maximum and minimum values of the signal in an image

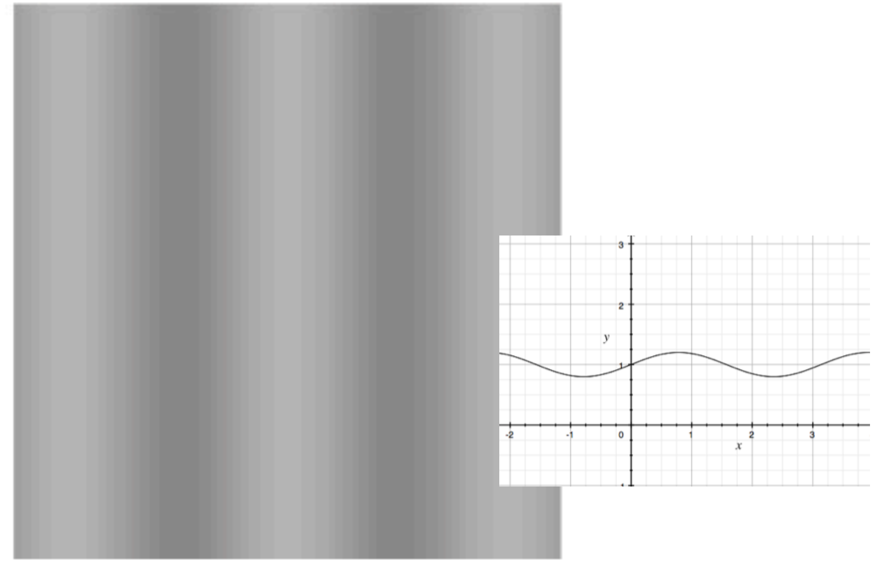
  contrast = modulation = $$m_f = \frac{amplitude}{average} = \frac{f_{max} - f_{min}}{f_{max} + f_{min}}$$

- Example: sinusoidal signal $f(x,y) = A + B\sin(2\pi u_0 x) \quad , A \geq B$

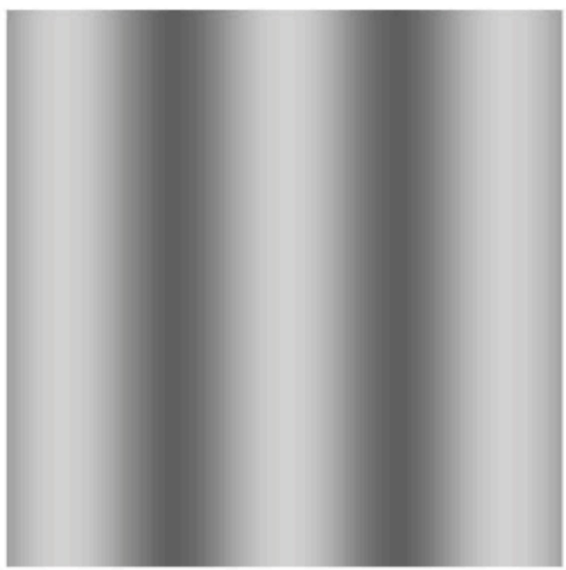



$$m_f = \frac{A + B - (A - B)}{A + B + A - B} = \frac{2B}{2A}$$

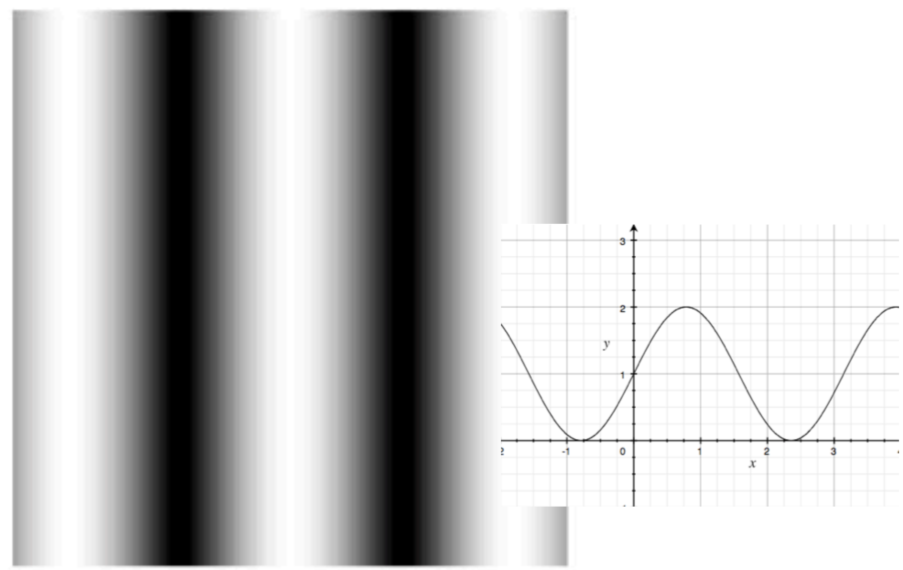
$m_f = 0$



$m_f = 0.2$



$m_f = 0.5$



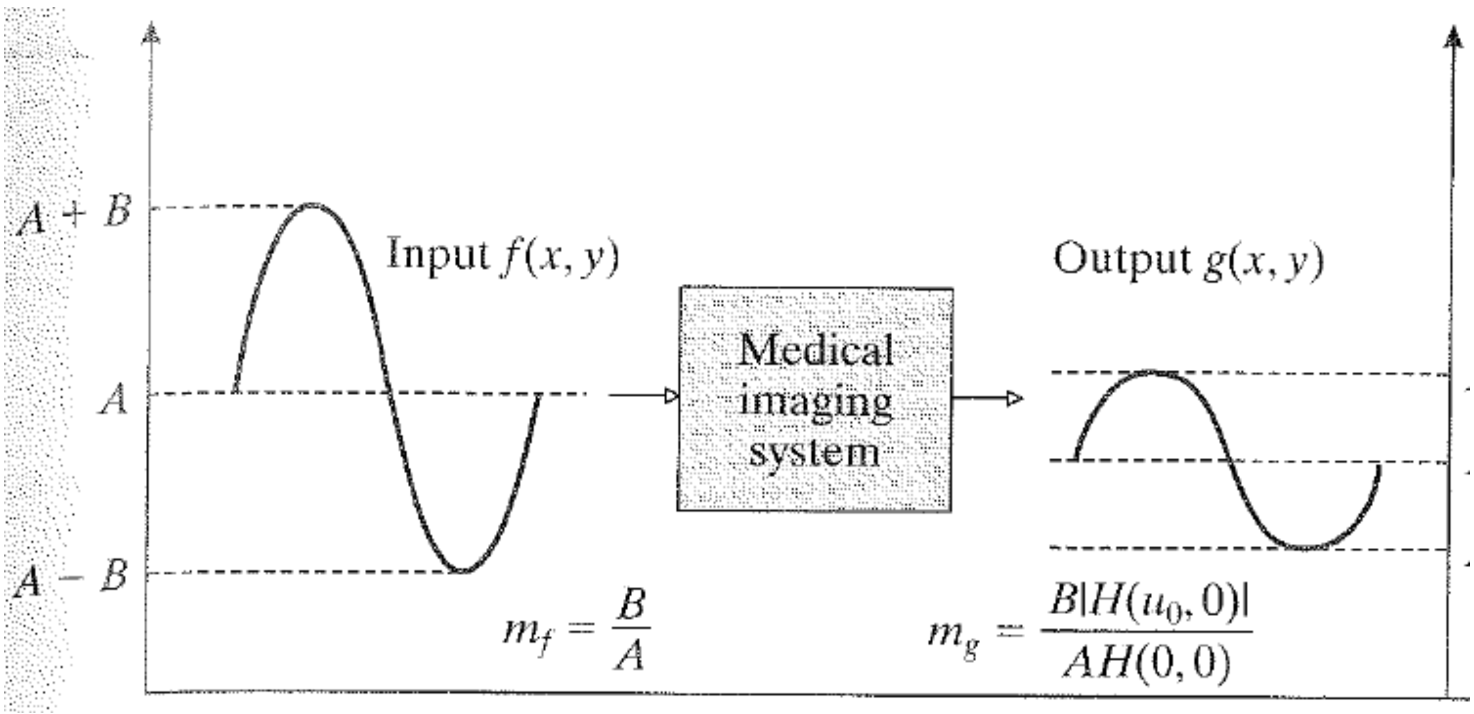
$m_f = 1$

*Medical Imaging Signals and Systems*, by Jerry L. Prince and Jonathan Links.
ISBN 0-13-065353-5. 

# Modulation transfer function

- The MTF at one specific frequency is the ratio of contrasts between image and source:

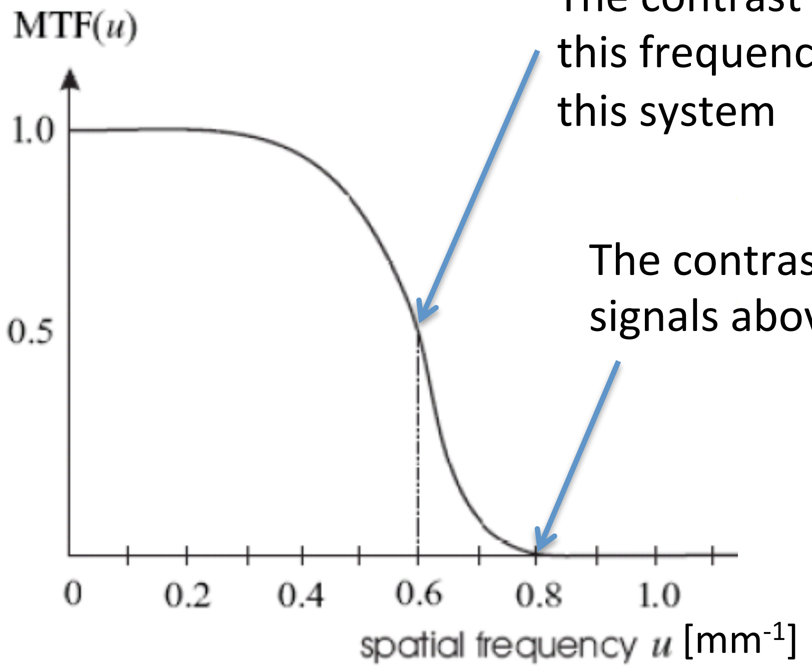
$$MTF(u) = \frac{m_g(output)}{m_f(input)}$$



# Modulation transfer function

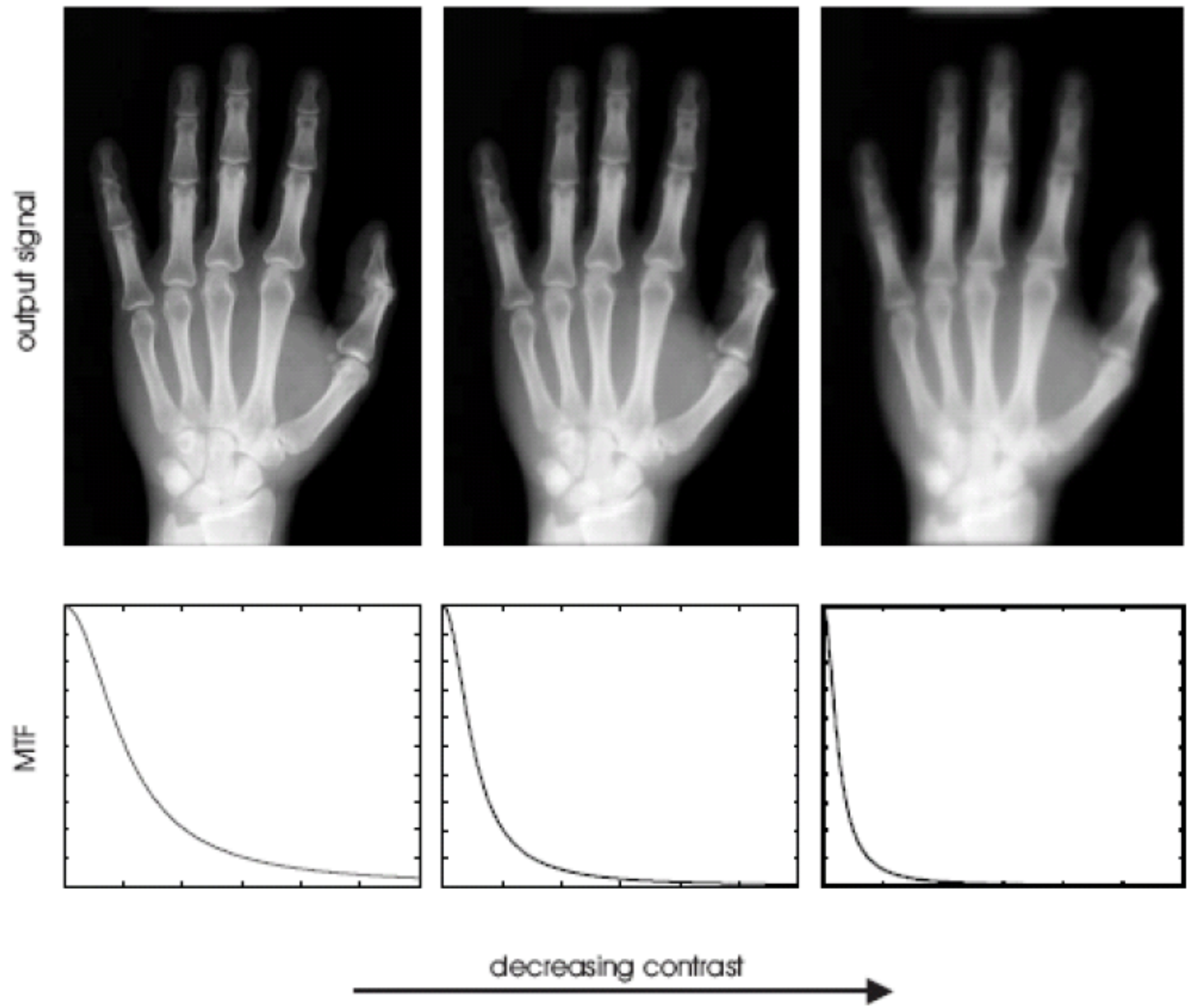
$$MTF(u) = \frac{m_g(output)}{m_f(input)}$$

Decreasing MTF at higher frequencies causes the blurring of high frequency features in an image

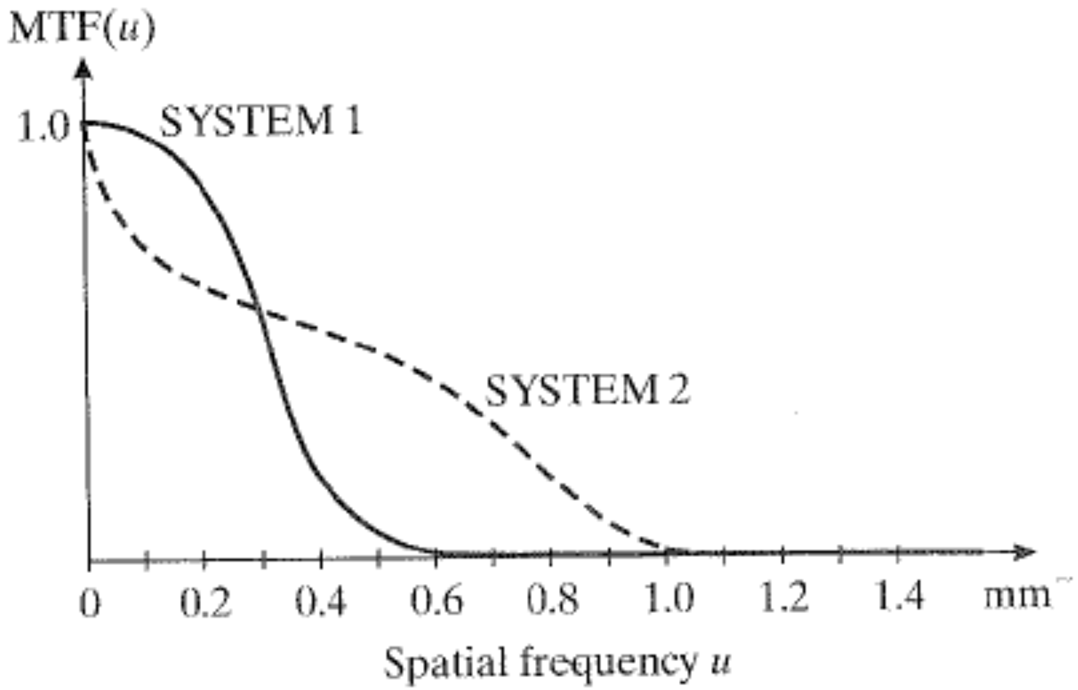



- MTF characterizes how the contrast (or modulation) of a signal component at a particular frequency changes after imaging.
- Typically it is : $0 \le MTF(u) \le MTF(0) = 1$

# MTF and Image Contrast



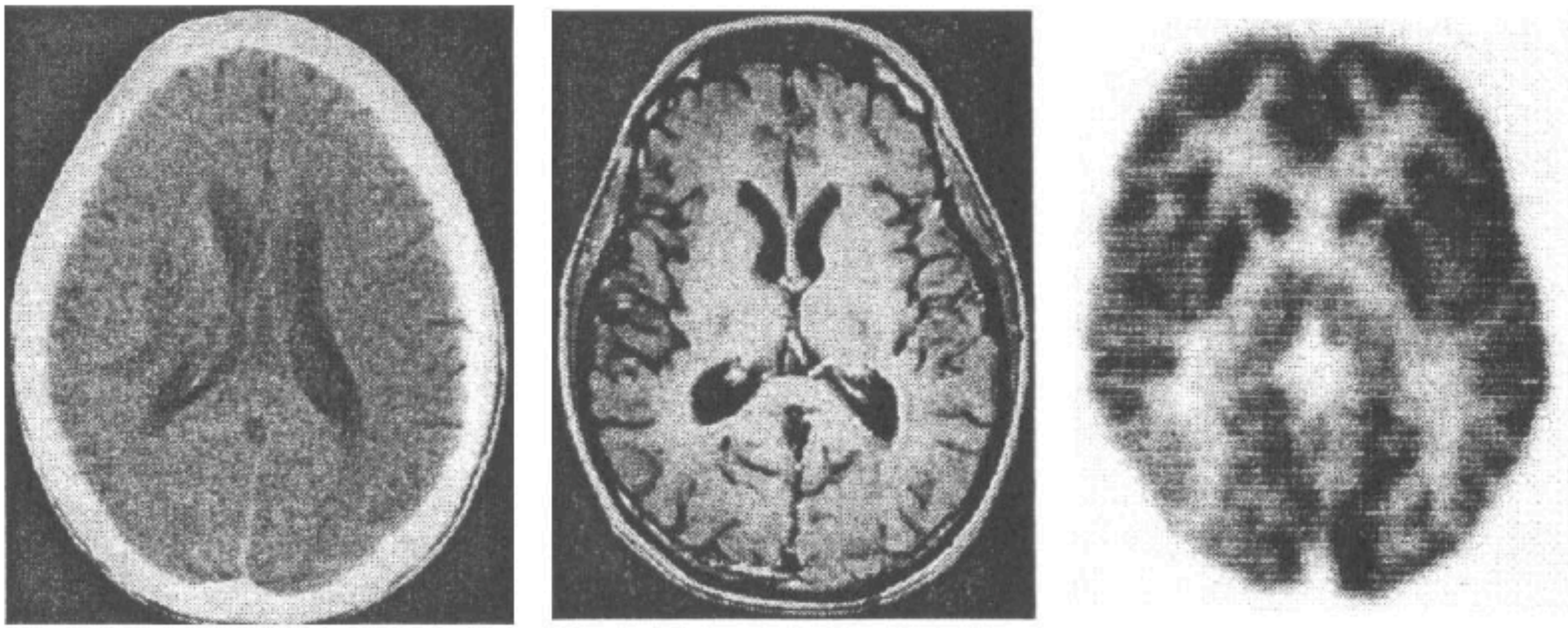
# System comparison




- SYSTEM 1 has better low-frequency contrast = better imaging of coarse details
- SYSTEM 2 has better high-frequency contrast = better imaging of fine details

# Resolution

- The ability of a system to depict spatial details.
- Which image below has higher resolution?



(a) (b) (c)

Figure I.4

*Medical Imaging Signals and Systems*, by Jerry L. Prince and Jonathan Links.
ISBN 0-13-065353-5. 

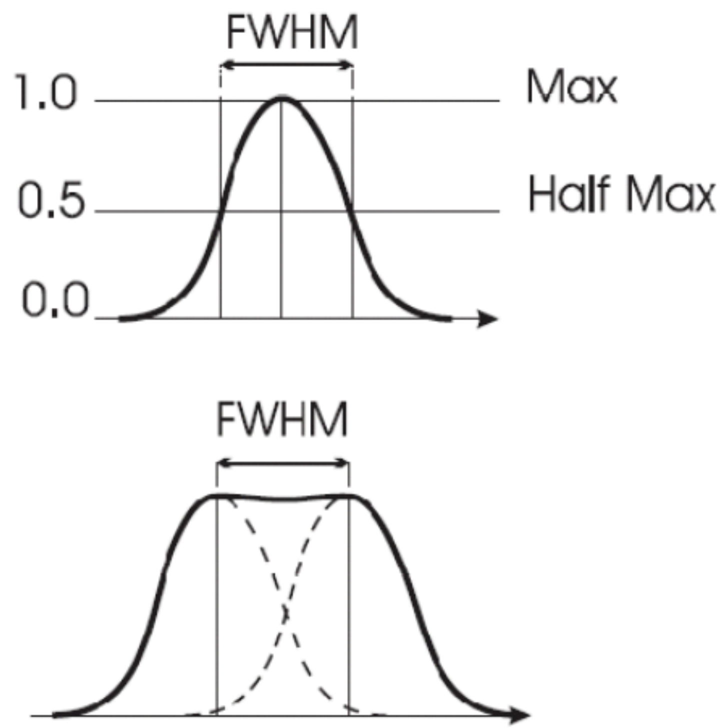
# Resolution

- The ability of a system to depict spatial details.
- Resolution of a system can be characterized by its line spread function

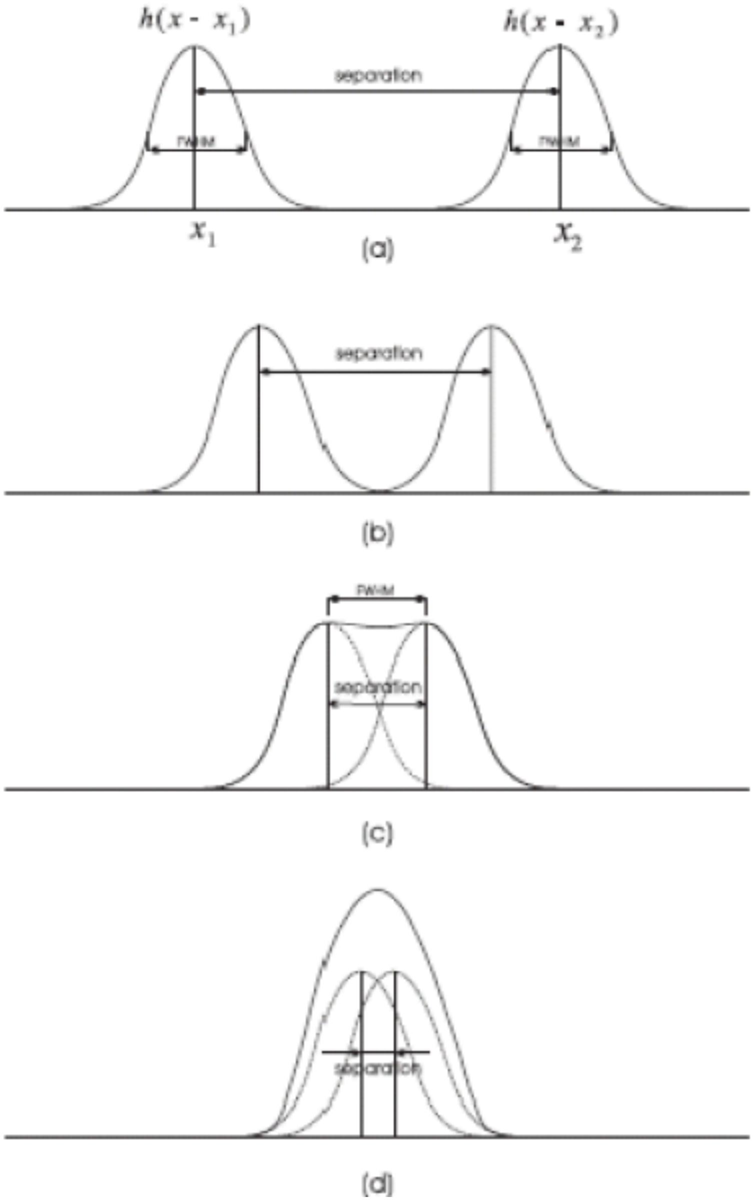
– How wide a very thin line becomes after imaging

– Full width at half maximum (FWHM) determines the distance between two lines which can be separated after imaging

– The smaller is FWHM, the higher is the resolution




* Resolution can be defined in space, time and frequency




Distance > FWHM

Distance > FWHM

Distance = FWHM
(barely separate)

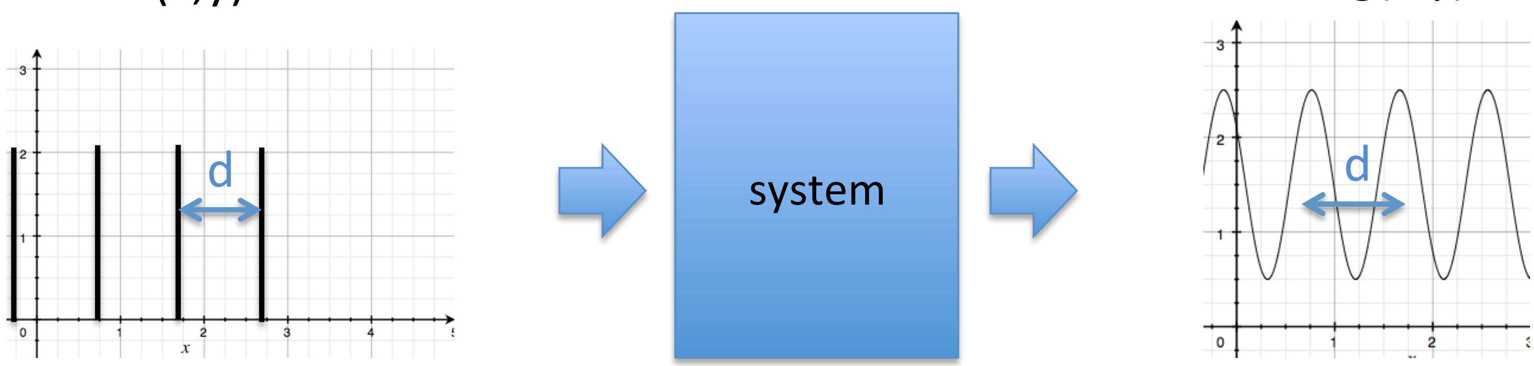
Distance < FWHM
(cannot separate)

# Resolution and MTF

- A pure vertical sinusoidal pattern can be thought of as the blurred image of uniformly spaced vertical lines
- The distance between lines is equal to distance between maxima ($d=1/u_0$)

Input signal
$f(x,y)$

Output signal
$g(x,y)$




- If $MTF(u_0)=0$, the sinusoidal patterns become all constant and one cannot see different lines
- If $MTF(u)$ becomes 0 at frequency $u > u_c$, the minimum distance between distinguishable lines is $d_{min} = 1/u_c$
- The resolution is directly proportional to the stopband edge in MTF

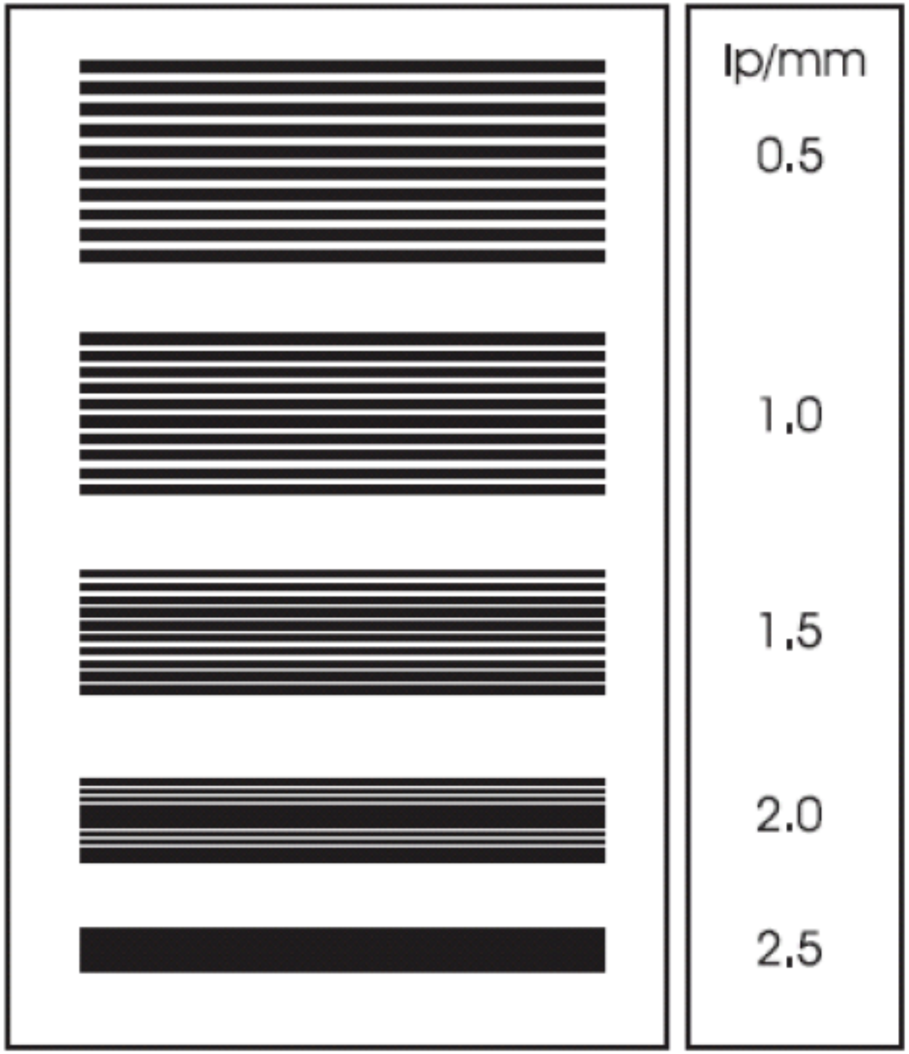
# Resolution calibration

• The resolution of an imaging system can be evaluated by imaging a bar phantom.

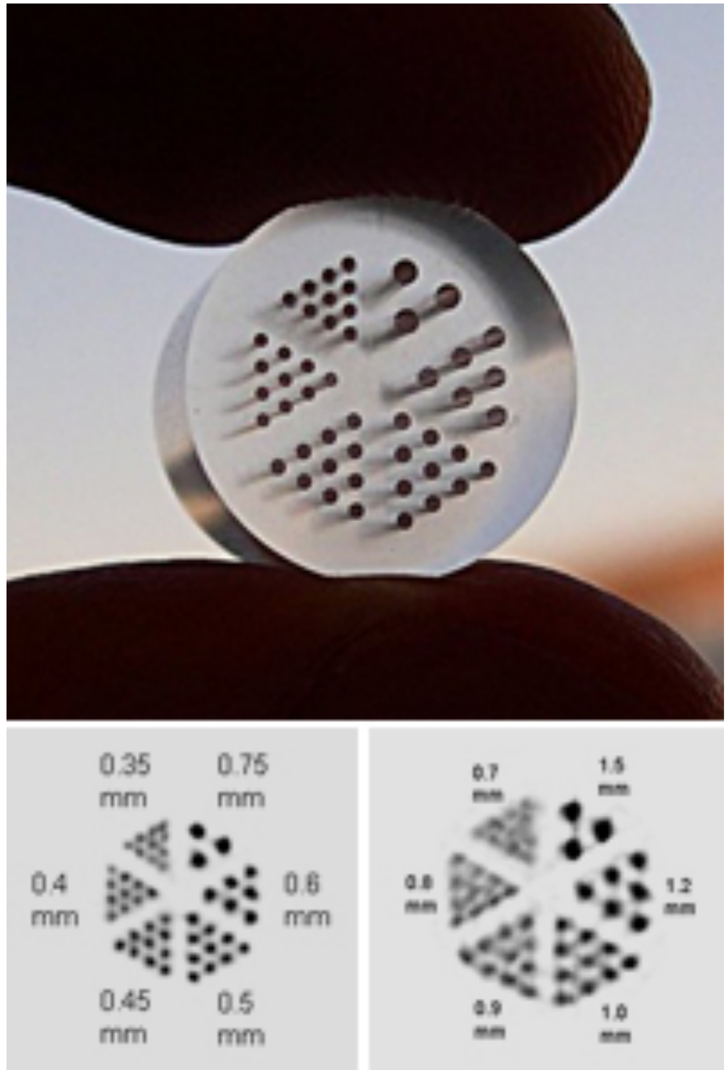
• The resolution is the frequency in line pairs per millimeter (lp/mm) of the finest line group that can be resolved after imaging.

– Gamma camera: 2-3 lp/cm
– CT: 2 lp/mm
– chest x-ray: 6-8 lp/mm

Typical material: Tungsten
for nuclear imaging need sources

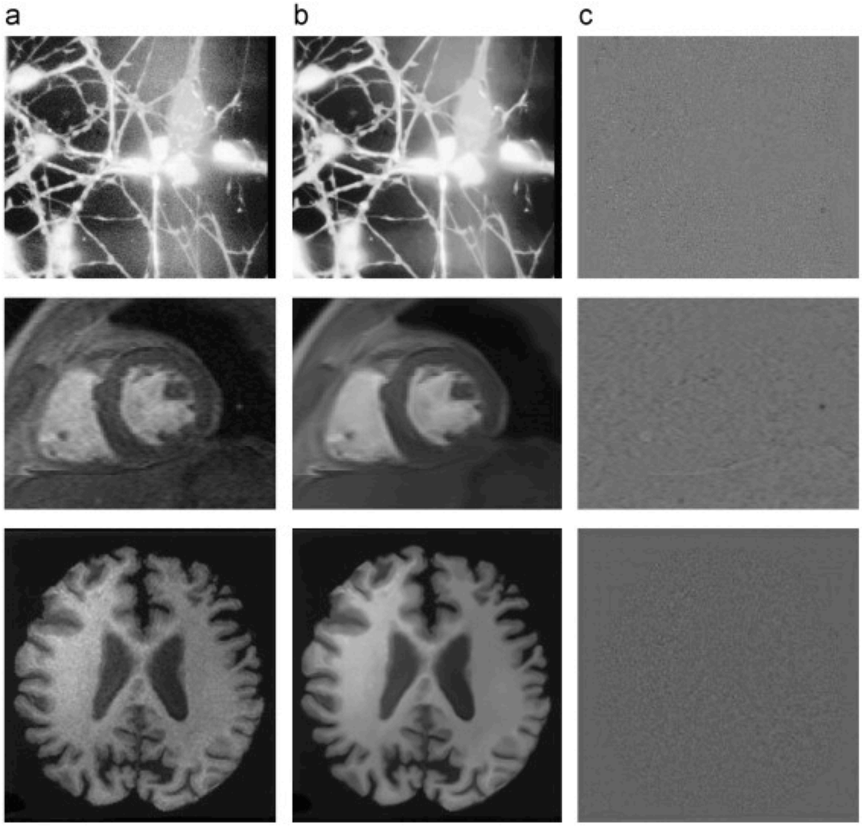


# Derenzo resolution phantom



# Noise

- Random fluctuations in image intensity that are not due to the signal
- The source of noise in an imaging system depends on the physics and instrumentation of the imaging modality
- Which image below is most noisy?



# Noise

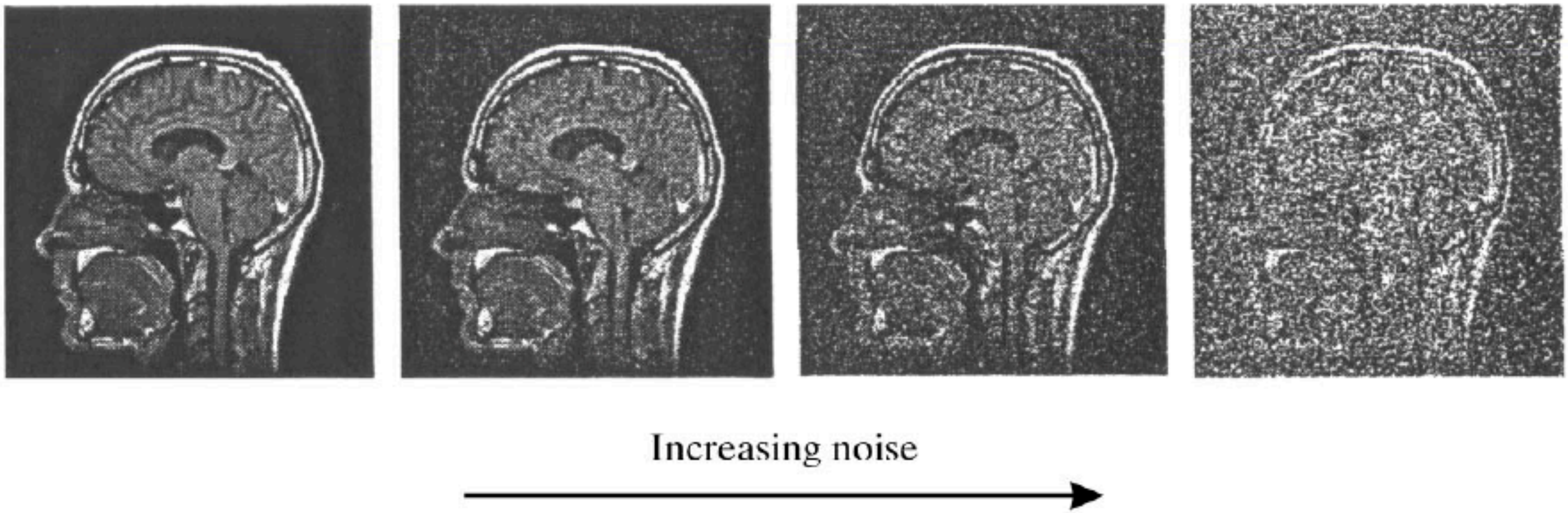



Figure 3.10

*Medical Imaging Signals and Systems*, by Jerry L. Prince and Jonathan Links.

# Noise

Random variable defined by:

- mean ($\mu$) and standard deviation ($\sigma$) or variance ($\sigma^2$)

  for statistical processes if $\mu = N$, then $\sigma = \sqrt{N}$

Divided in two main categories:

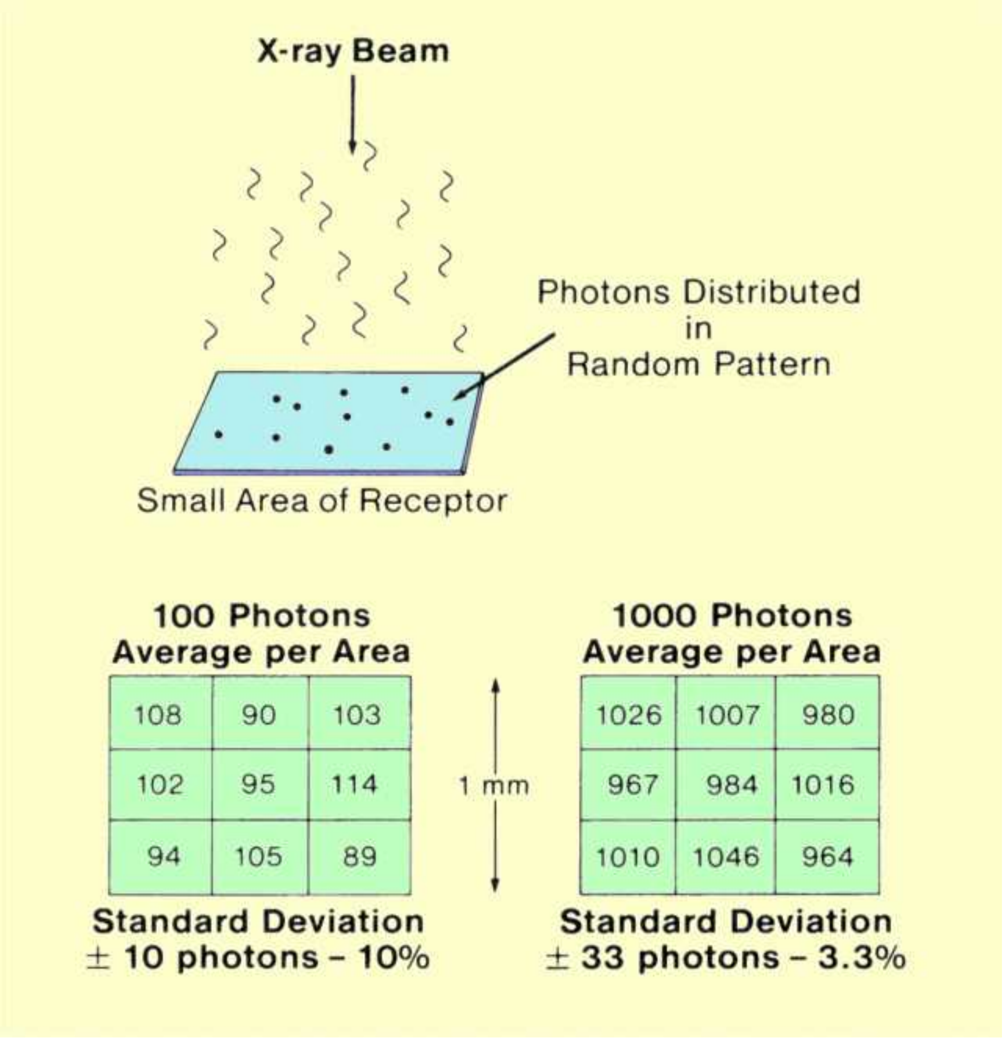
- White Noise: noise values at different positions are independent of each other, and position independent:
  - mean and variance at different (x,y) are the same
- Correlated noise: noise at adjacent positions are correlated

# Quantum noise

In case of imaging with photons the main source of white noise is quantum noise:

The random manner in which the photons are distributed within the image

Quantum noise is usually the factor that limits the use of highly sensitive film in radiography.




Courtesy of Dr. Perry Sprawls

# Singl-to-Noise ratio

$$SNR_a = \frac{Amplitude(f)}{Amplitude(N)} \qquad SNR_a = \frac{\mu}{\sqrt{\mu}} = \sqrt{\mu}$$

Meaning of “signal amplitude” and “noise amplitude” are case dependent.

- For projection radiography, the number of photons G counted per unit area follows a Poisson distribution.
- The signal amplitude is the average photon number per unit area ($\mu$) and the noise amplitude is the standard deviation of G

General trends of noise and signal:

- Longer exposure generally leads to higher $SNR_a$
- More contrast generally leads higher noise (lower $SNR_a$)
- More blur generally leads less noise
- Image subtraction doubles the (random) noise

# Non-Random Artifacts

Artifacts: Image features that do not correspond to a real object, AND are not due to noise

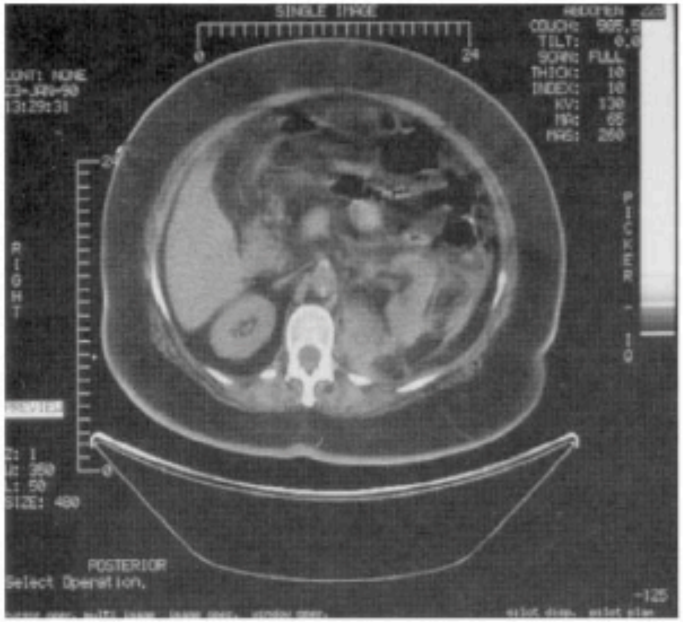
– Motion artifacts: blurring or streaks due to patient motion

– star artifact: in CT, due to presence of metallic material in a patient

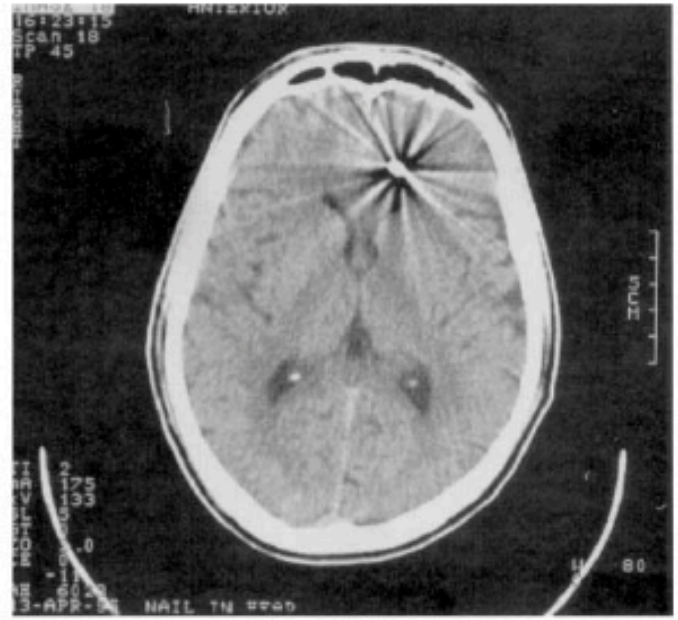
– beam hardening artifact: broad dark bands or streaks, due to significant beam attenuation caused by certain materials

– ring artifact: because detectors are out of calibration

Motion artifact



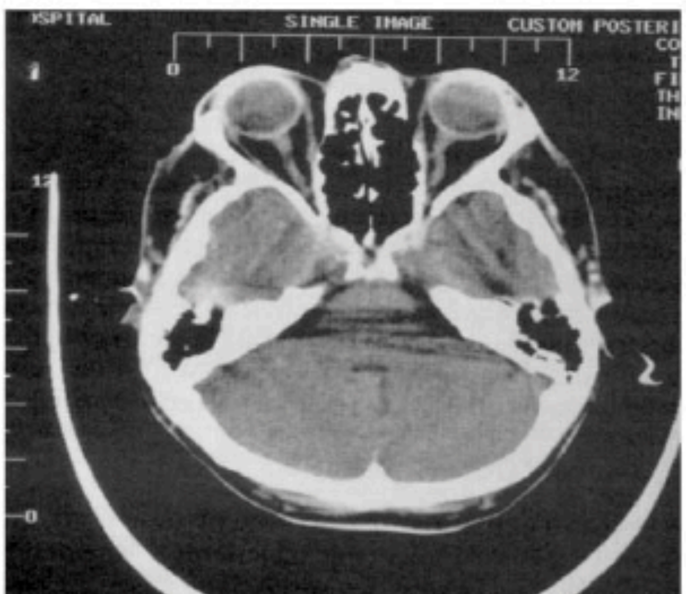
(a)



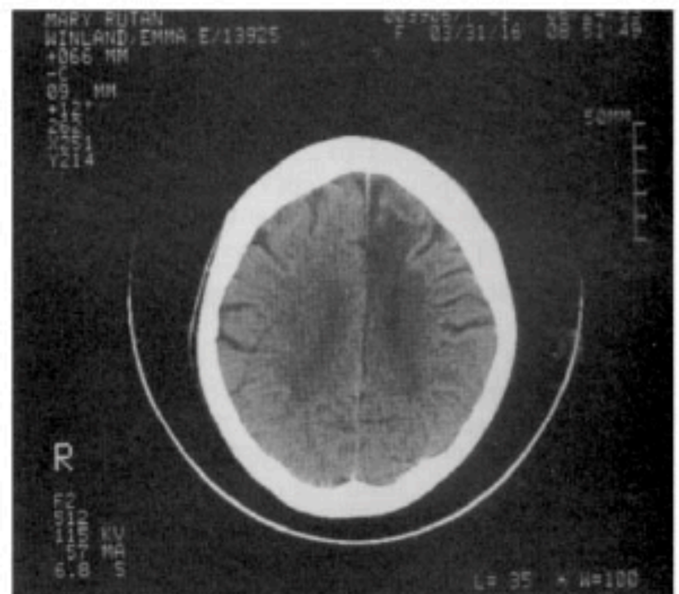
(b)

Star artifact

Beam hardening



(c)



(d)

Ring artifact

# Geometric distortions

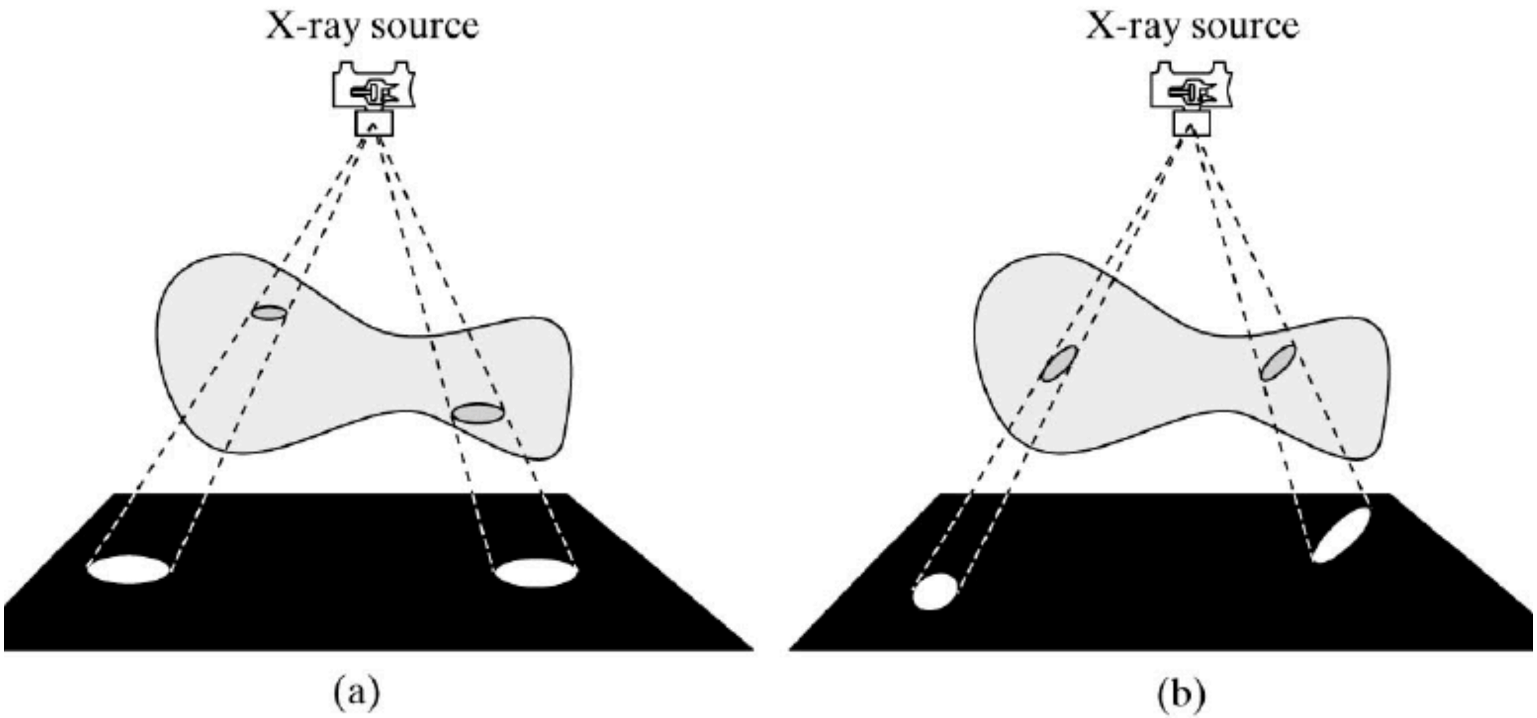



Figure 3.13

*Medical Imaging Signals and Systems*, by Jerry L. Prince and Jonathan Links.
ISBN 0-13-065353-5. 

- In (a): two objects with different sizes appear to have the same size
- In (b): two objects with same shape appear to have different shapes

# Accuracy

Accuracy:

- conformity to truth
  - quantitative accuracy
- clinical utility
  - diagnostic accuracy

- Quantitative accuracy:
  - numerical accuracy: accuracy in terms of signal value
    - bias (systematic, e.g. due to miscalibration), imprecision (random)
  - geometric accuracy: accuracy in terms of object size/shape

# Diagnostic Accuracy

- Contingency table:

a = # w/ disease & test result disease

b = # w/o disease & test result disease

c = # w/ disease & test result normal

d = # w/o disease & test result normal

| | | Disease | |
|---|---|---|---|
| | | + | - |
| Test | + | a | b |
| | - | c | d |

$$sensitivity = \frac{a}{a+c}$$

(true positive)

$$specificity = \frac{d}{b+d}$$

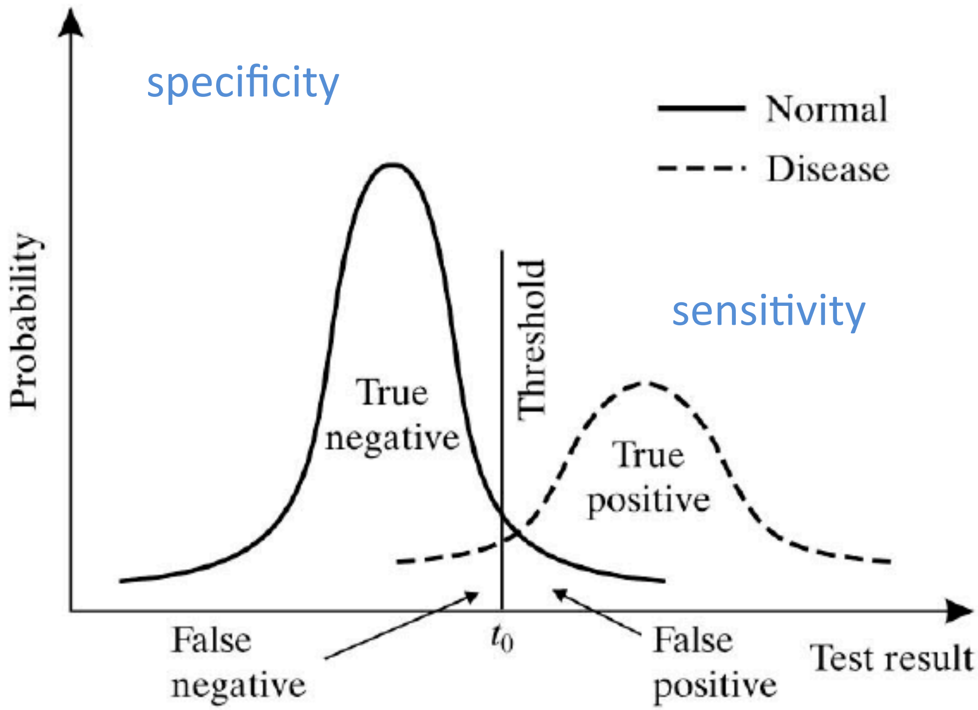
(true negative)

Diagnostic accuracy:

$$DA = \frac{a+d}{a+b+c+d}$$

# Diagnostic Accuracy

If the diagnosis is based on a single value of a test result
and the decision is based on a chosen threshold,
the sensitivity and specificity can be visualized as:



# Watch out for statistics

Case study on 100 patients (10 diseased, 90 normal):

We use an image detector with no sensitivity to the disease

➔ Test result = 100 patients normal

| | | Disease | |
|---|---|---|---|
| | | + | - |
| Test | + | 0 | 0 |
| | - | 10 | 90 |

➔ a=b=0 , c=10, d=90

$$sensitivity = \frac{a}{a+c} = 0$$

$$specificity = \frac{d}{b+d} = 1.0$$

$$DA = \frac{a+d}{a+b+c+d} = 0.9$$

One gets a large diagnostic accuracy even with no sensitivity to the disease, if the sample w/o disease is the majority

# Summary

- Image quality: degree to which an image allows a radiologist or a nuclear medicine physician to accomplish the clinical goal of the imaging study

- We saw six parameters that can be used to quantify the image quality of a medical image: *contrast, resolution (space, time, frequency), noise, artifacts, distortions, accuracy (quantitative, diagnostic)*

- The correction of artifacts and distortions is part of image reconstruction.
- Noise can be reduced either from the hardware or during image reco.
- Contracts can be enhanced with image correction techniques.
- Resolution is in general a fix property of a given system.