Digital Fluoroscopic Imaging:
Acquisition, Processing & Display

J. Anthony Seibert, Ph.D.
University of California Davis
Medical Center
Sacramento, California

Outline of presentation

- Introduction to digital fluoroscopy
- Digital fluoroscopy components
- Analog and digital image characteristics
- Image digitization (quantization/sampling)
- Image processing
- Summary

History of digital fluoroscopic imaging

- ……. mid 1970's
  - Modified II/TV system with "fast" ADC
  - Temporal and energy subtraction methods
- ……. 1980's
  - Clinical DSA angiography systems
  - Qualitative and quantitative improvements
  - Image processing advances
  - Temporal and recursive filtering

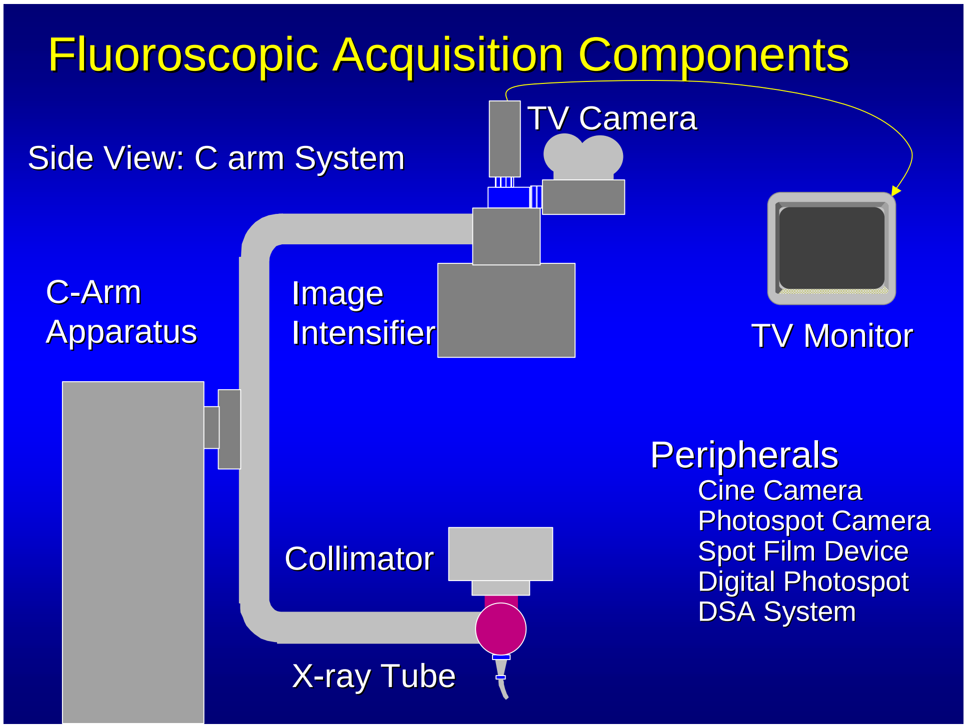
History of digital fluoroscopic imaging

- ……. 1990's
  - Quantitative correction of image data
  - Rotational fluoroscopic imaging
  - Micro-fluoroscopic imaging capabilities
  - CT fluoroscopy (using fan-beam scanners)
  - Cone-beam CT reconstructions
- ……. 2000 - present
  - Introduction of real-time flat-panel detectors

Why digital fluoroscopy / fluorography?

- Low dose fluoroscopic imaging
  (digital averaging, last frame hold)
- Pulsed fluoroscopy and variable frame rate
- DSA and non-subtraction acquisition and display
- Digital image processing and quantitation
- Image distribution and archiving, PACS

- Introduction to digital fluoroscopy
- **Digital fluoroscopy components**
- Analog and digital image characteristics
- Image digitization (quantization/sampling)
- Image processing
- Summary


Fluoroscopic Acquisition Components
Side View: C arm System
TV Camera
C-Arm
Apparatus
Image
Intensifier
TV Monitor
Peripherals
Cine Camera
Photospot Camera
Spot Film Device
Digital Photospot
DSA System
Collimator
X-ray Tube

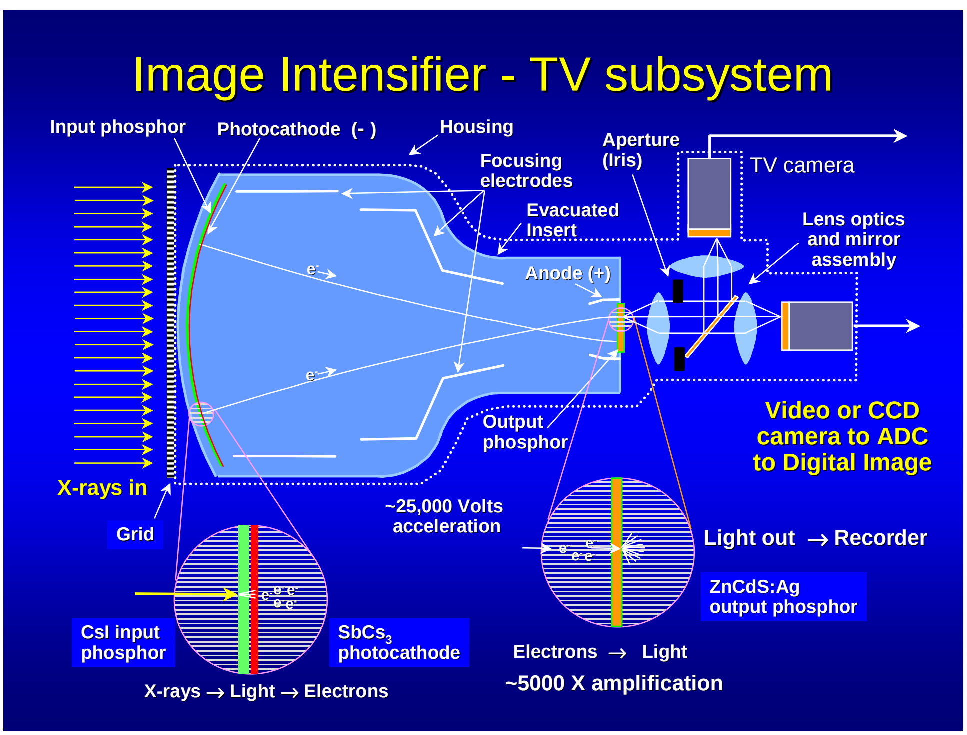
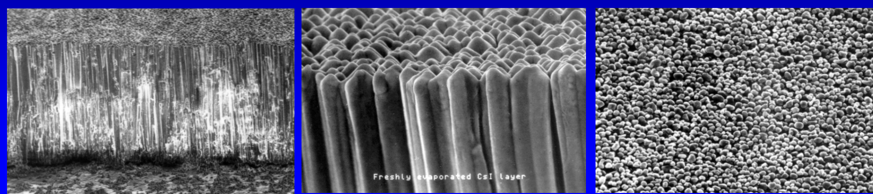


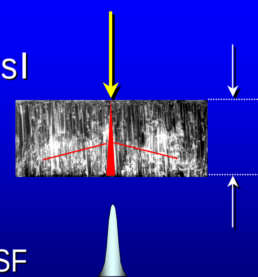
Image Intensifier - TV subsystem
Input phosphor
Photocathode (-)
Housing
Focusing
electrodes
Aperture
(Iris)
TV camera
Evacuated
Insert
Lens optics
and mirror
assembly
Anode (+)
Output
phosphor
Video or CCD
camera to ADC
to Digital Image
X-rays in
Grid
~25,000 Volts
acceleration
Light out → Recorder
ZnCdS:Ag
output phosphor
CsI input
phosphor
$SbCs_3$
photocathode
Electrons → Light
~5000 X amplification
X-rays → Light → Electrons

Structured Phosphor: Cesium Iodide (CsI)

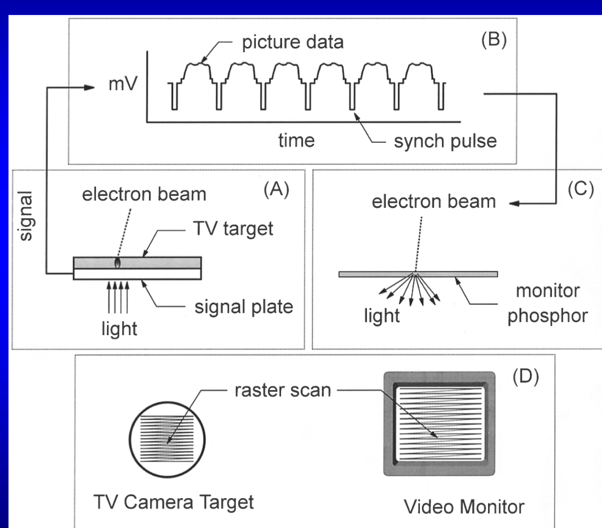
Crystals grow in long columns that act as light pipes



Light Pipe (Optical Fiber)



TV camera readout and output video



TV camera specifications

- Low resolution:
  - 525 line, interlaced, 30 Hz (RS-170)
- High resolution:
  - 1023 - 1049 line, interlaced, 30 Hz (RS-343)
- Highest resolution
  - 2048 line systems
- Progressive scan a must for short pulse-width digital applications

II-TV digital systems

- Two decades+ of availability
- Video signal is convenient for digitization
- Low noise performance of II's: ↑SNR
- Well-developed capabilities
  - IA, DSA, digital photospot
  - Rotational CT
- CCD camera implementations
- II is Big and bulky; image distortions prevalent

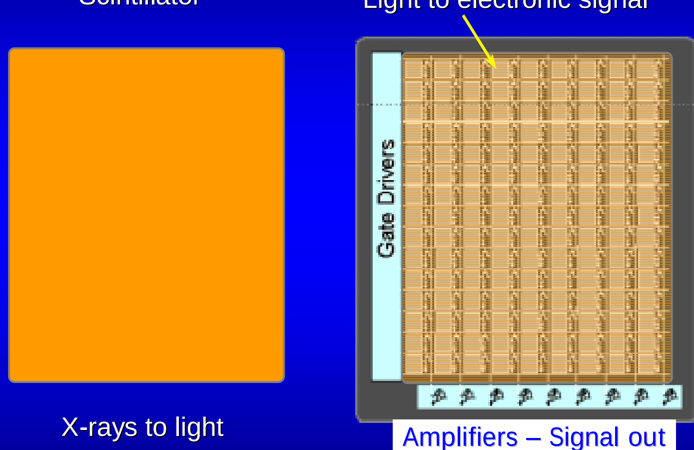
Flat-panel Fluoroscopy / Fluorography

- Based upon TFT charge storage and readout technology
- Thin-Film-Transistor arrays
  - Proven with radiography applications
  - Just becoming available in fluoroscopy
    - CsI scintillator systems (indirect conversion)
    - a-Se systems (direct conversion)

Photodetector: *a* - Si TFT active matrix array

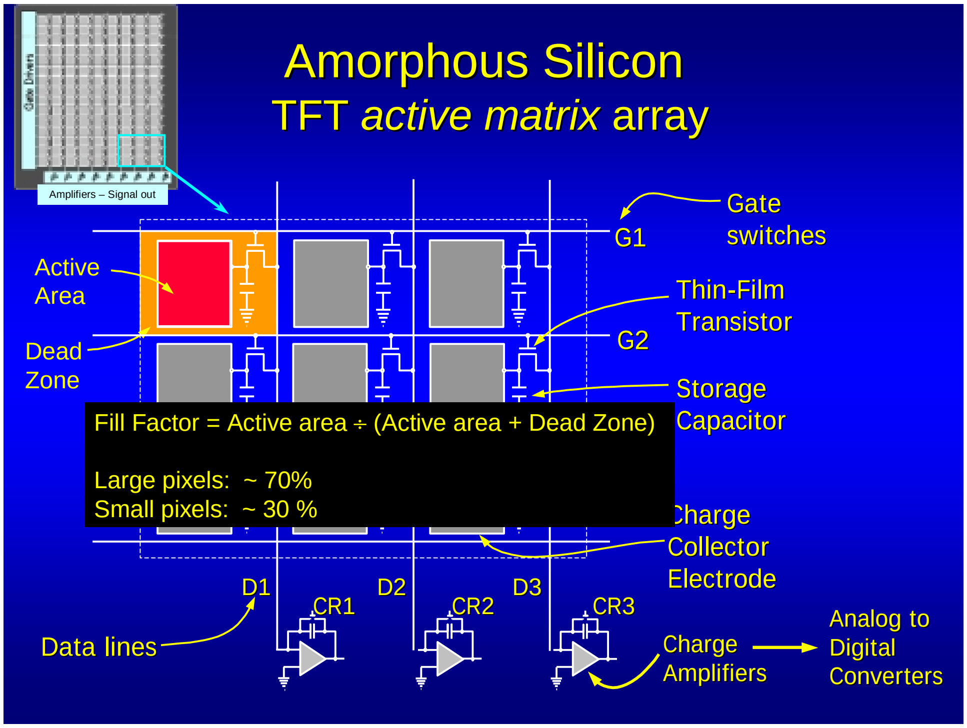
Scintillator

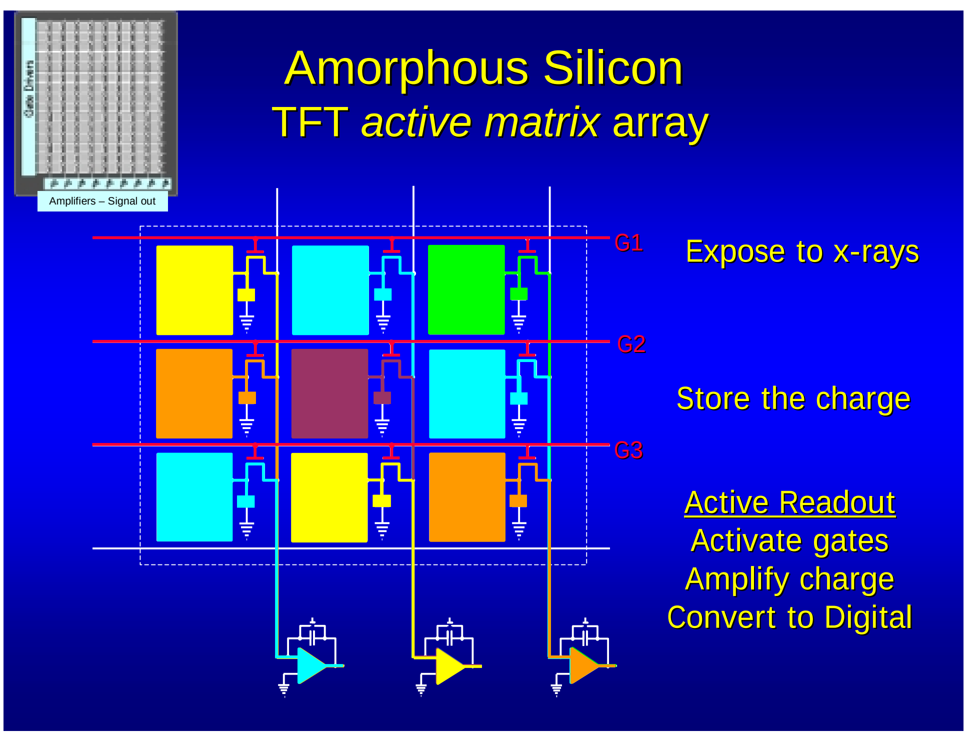
Photodiode:
Light to electronic signal



X-rays to light

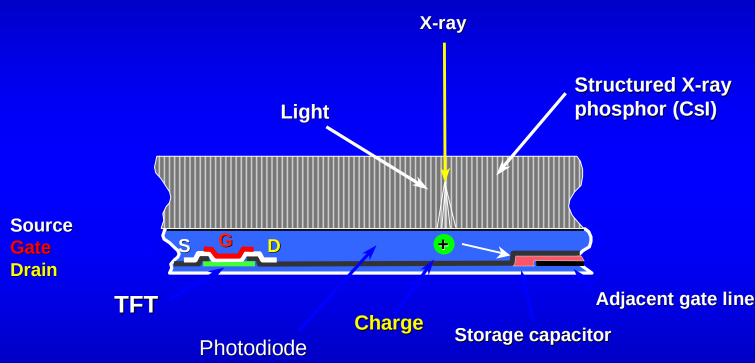
TFT: Storage and readout


Amorphous Silicon
TFT *active matrix* array
Gate Drivers
Amplifiers – Signal out
Gate
switches
G1
G2
Active
Area
Dead
Zone
Thin-Film
Transistor
Storage
Capacitor
Fill Factor = Active area ÷ (Active area + Dead Zone)
Large pixels: ~ 70%
Small pixels: ~ 30 %
Charge
Collector
Electrode
D1
D2
D3
CR1
CR2
CR3
Data lines
Charge
Amplifiers
Analog to
Digital
Converters


Amorphous Silicon
TFT *active matrix* array
Gate Drivers
Amplifiers – Signal out
G1
G2
G3
Expose to x-rays
Store the charge
Active Readout
Activate gates
Amplify charge
Convert to Digital

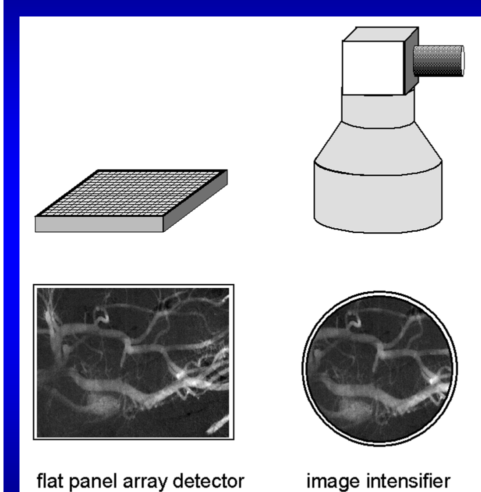
Cross section of detector:

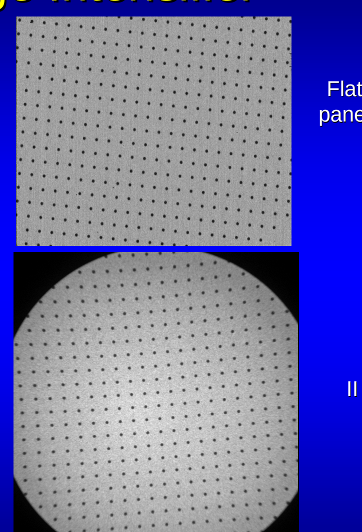
a-Si TFT/ CsI phosphor



X-rays to light to electrons to electronic signal:
Indirect digital detector

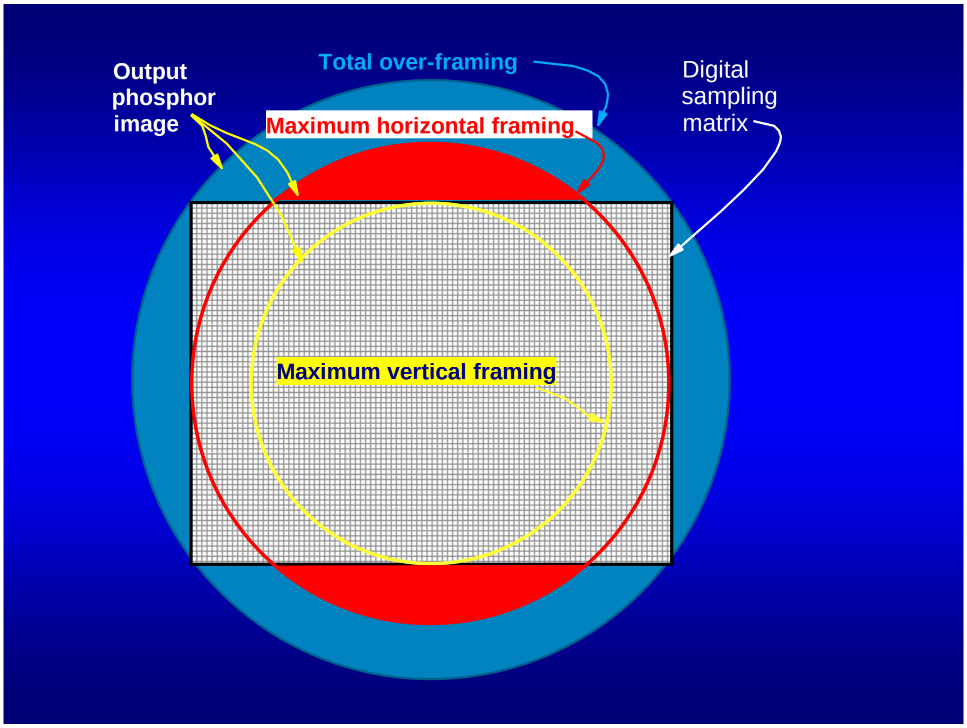
Flat panel vs. Image Intensifier





Field coverage / size advantage to flat panel

Image distortion advantage to flat panel



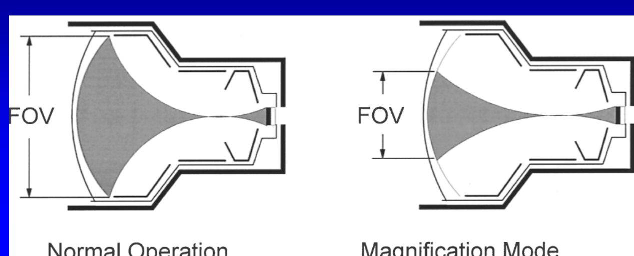
Framing of digital matrix:

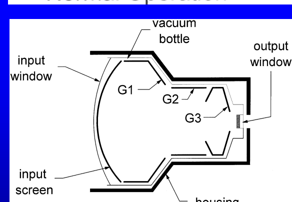
FOV vs. spatial resolution vs. x-ray utilization

framing	FOV	spatial resolution	% recorded area
4:3 aspect ratio	23 cm nominal input diameter	512 × 480 matrix 1023 x 960 matrix	(% digital area used)
Maximum vertical framing	22 cm	0.46 mm 1.09 lp / mm	100 % (41%)
Maximum horizontal framing	19 cm	0.43 mm 1.16 lp / mm	74% (78%)
Maximum overframing*	15 cm	0.33 mm 1.5 lp / mm	61% (100%)

Flat-panel fluoro detector:
efficient use of x-ray detector / x-ray field

Flat panel vs. Image Intensifier





II conversion gain: ~5000:1

-- Electron acceleration flux gain

-- Minification gain

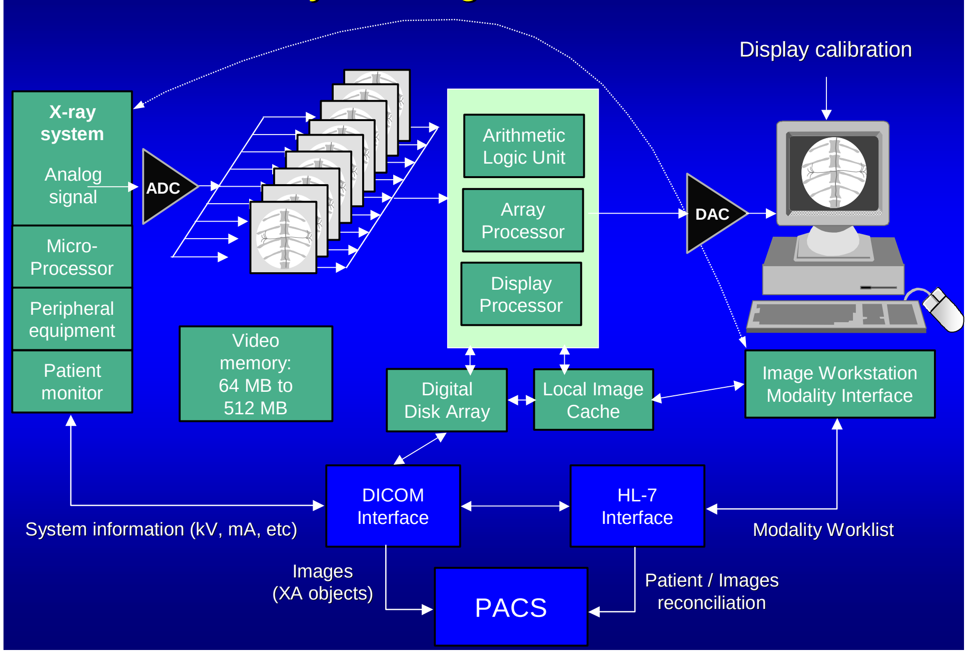
FOV variability (mag mode) and sampling advantage to II

Gain / noise advantage to II

Flat panel vs. Image Intensifier

- Electronic noise limits flat-panel amplification gain at fluoro levels (1-5 μR/frame)
- Pixel binning (2x2, 3x3) lowers noise; “mag-mode” equivalent changes pixel bin sampling
- Low noise TFT’s are being produced (low yield); variable gain technologies are needed
- Prediction:
  – II’s will likely go the way of the CRT…….

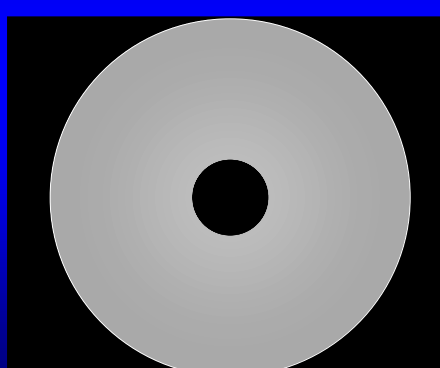
Interventional system digital hardware architecture



- Introduction to digital fluoroscopy
- Digital fluoroscopy components
- **Analog and digital image characteristics**
- Image digitization (quantization/sampling)
- Image processing
- Summary

Fluoroscopic Analog Image

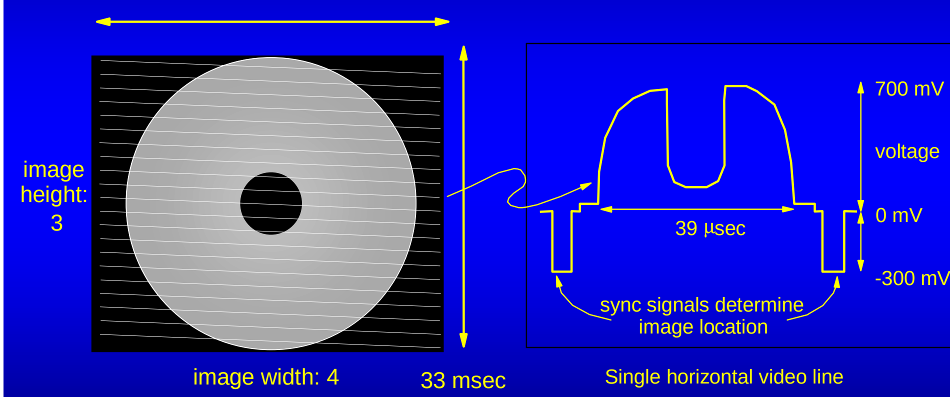
- Continuous brightness variation corresponding to differential x-ray transmission of the object



Uniformly irradiated II with lead disk

Conventional raster scan: RS-170

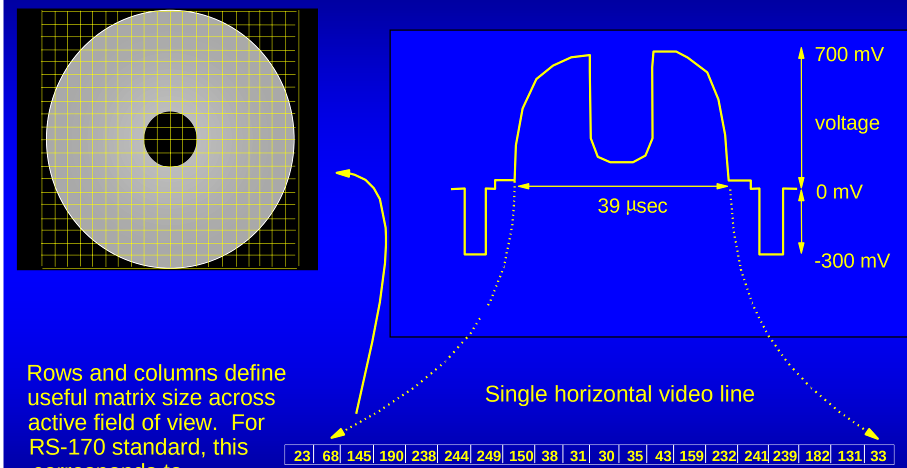
4:3 aspect ratio, 525 lines, 483 active



Digital Image Requirements

- Contrast resolution
  - Ability to differentiate subtle differences in x-ray attenuation (integer numbers)
- Spatial Resolution
  - Ability to discriminate and detect small objects (typically of high attenuation)

Digital Image Matrix



Rows and columns define useful matrix size across active field of view. For RS-170 standard, this corresponds to ~480 x 480.

Digitized video signal corresponding to horizontal line

A better match now often available is 640x480 (VGA)

Digital Acquisition Process

- Conversion of continuous, analog signal into discrete digital signal
- Digitization
  - Sampling (temporal / spatial)
  - Quantization (conversion to integer value)

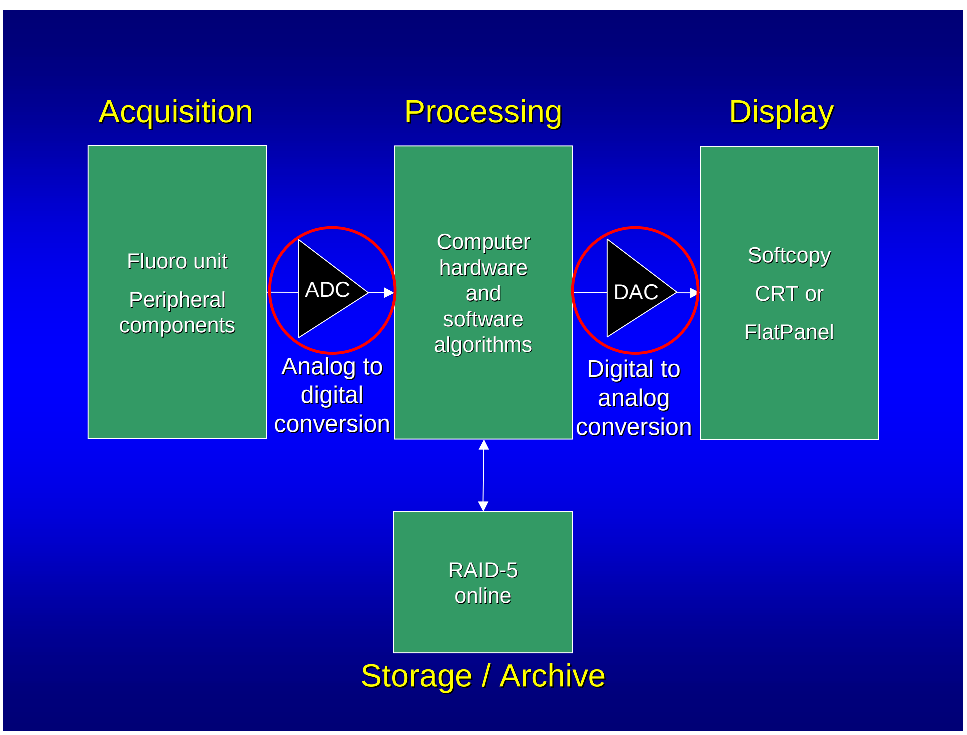
Digital Image Characteristics

- Advantages
  - Separation of acquisition and display
  - Image processing applications
  - Electronic display, distribution, archive
- Disadvantages: noise and data loss
  - Quantization
  - Sampling
  - Electronic (shot)

Consequences of digitization

- Negative:
  - Loss of spatial resolution
  - Loss of contrast fidelity
  - Aliasing of high frequency signals
- Positive:
  - Image processing and manipulation
  - Electronic distribution, display and archive
  - Quantitative data analysis

- Introduction to digital fluoroscopy
- Digital fluoroscopy components
- Analog and digital image characteristics
- **Image digitization (quantization/sampling)**
- Image processing
- Summary

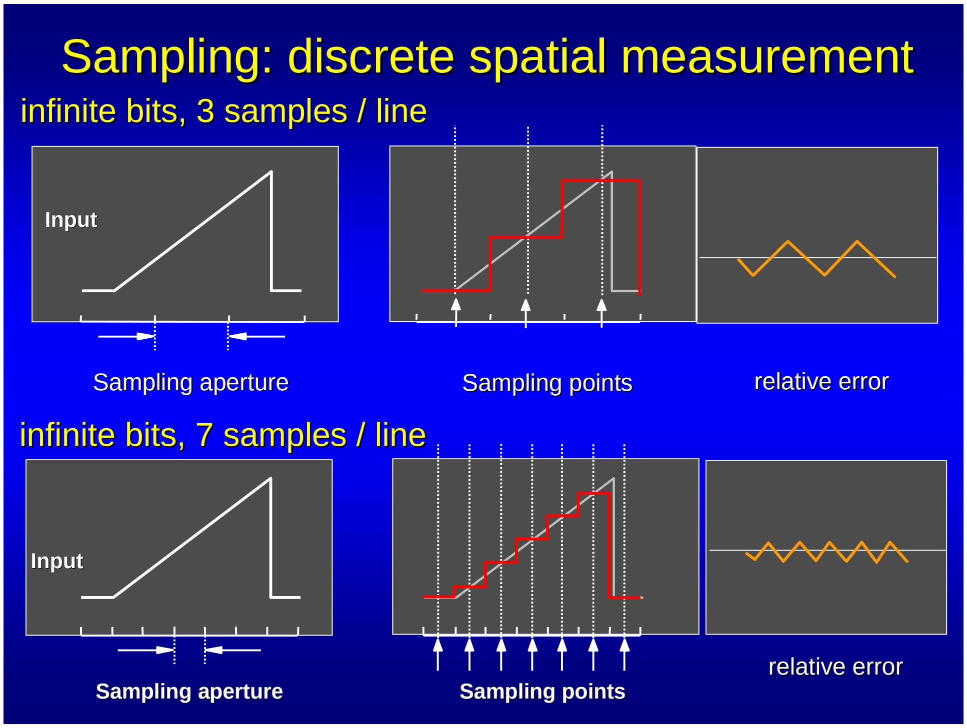


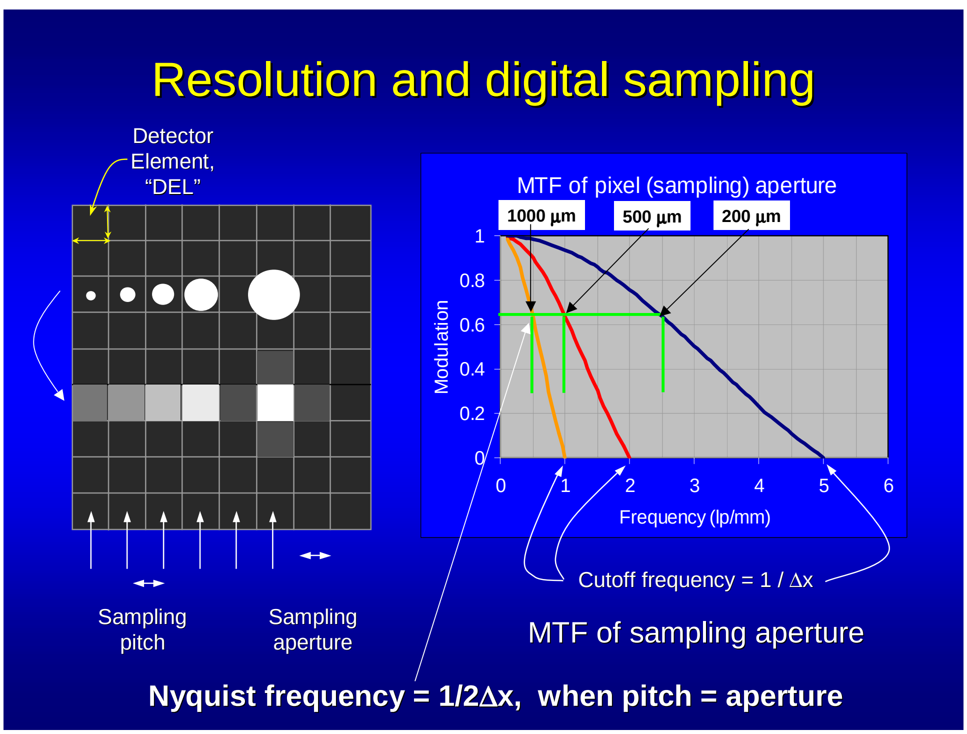
Analog to Digital Conversion: Digitization

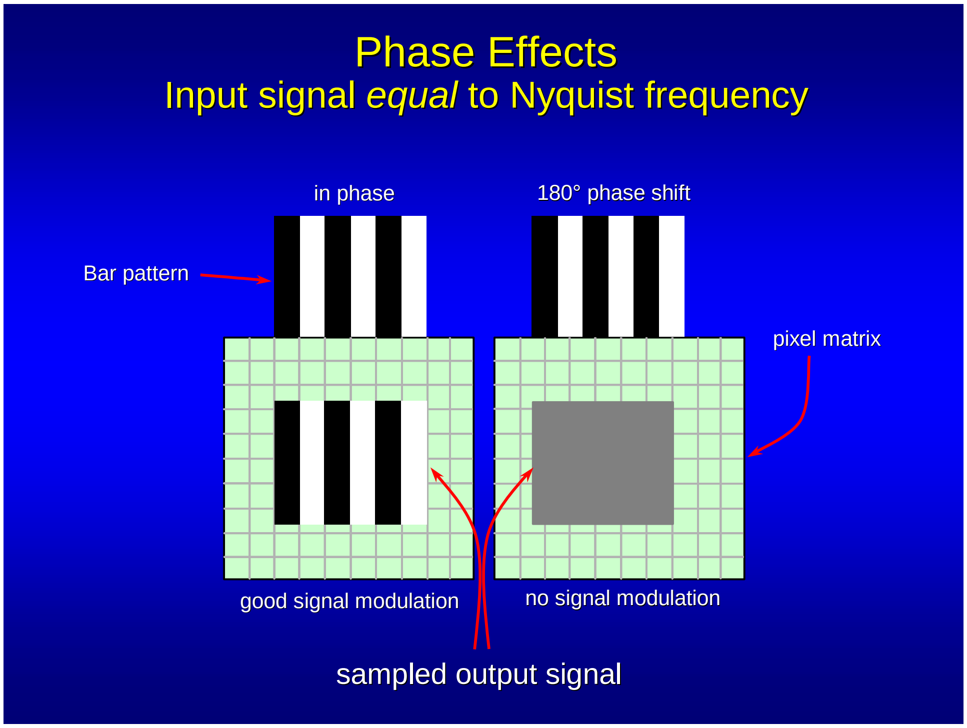
- Sampling: measuring the analog signal at discrete time intervals
  - @ 2x frequency of video bandwidth
- Quantization: converting the amplitude of the sampled signal into a digital number
  - Determined by the number of ADC bits

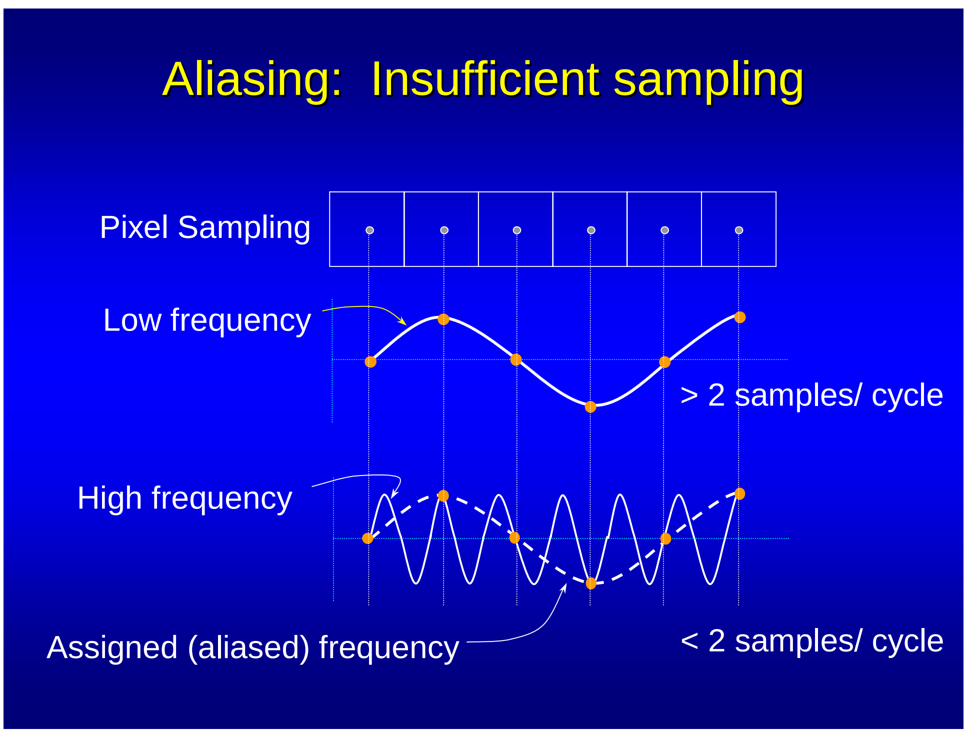
Sampling

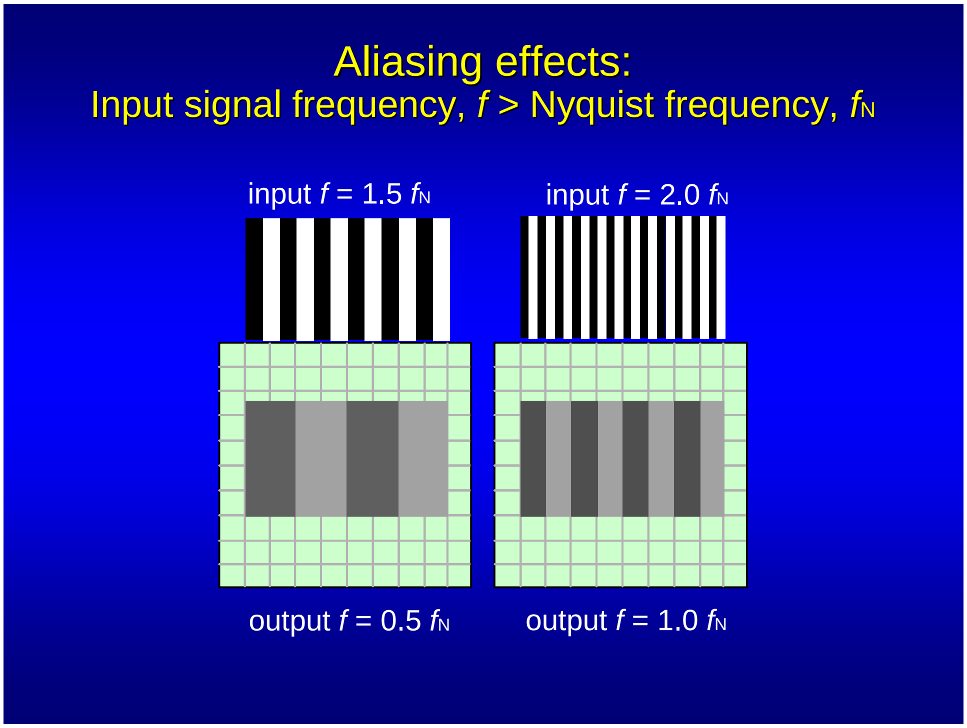
- Signal averaging within detector element (del) area = $\Delta x \times \Delta y$
- Cutoff sampling frequency = $1 / \Delta x$
- Nyquist frequency = $1 / 2\Delta x$
- Minimum resolvable object size (mm) = $1 / (2 \times$ Nyquist frequency$)$

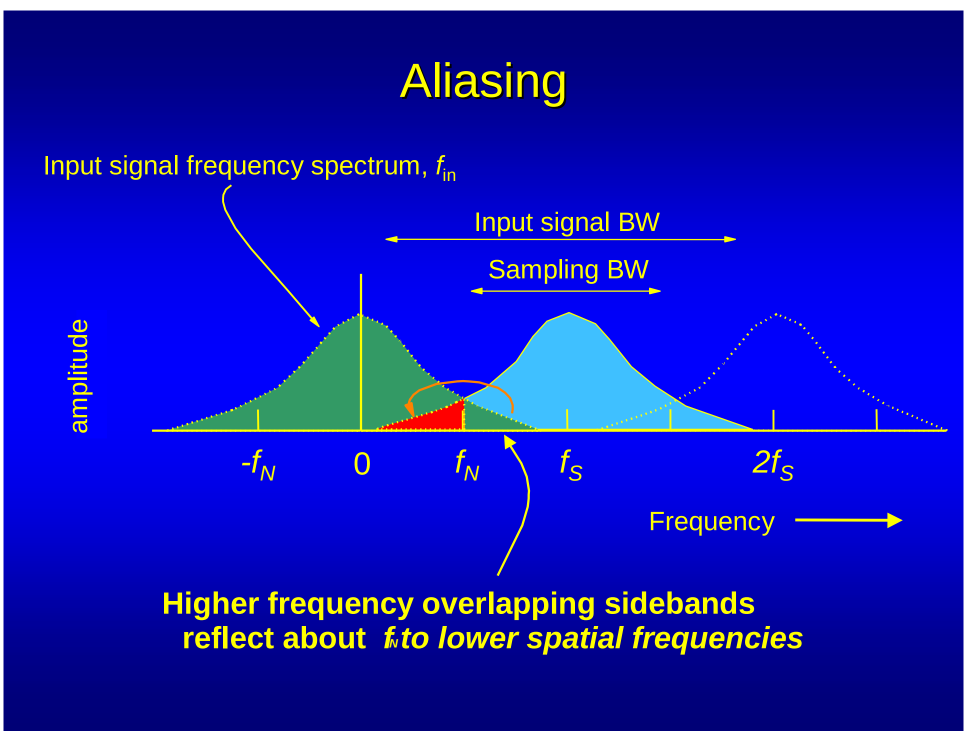

Sampling: discrete spatial measurement
infinite bits, 3 samples / line
Input
Sampling aperture
Sampling points
relative error
infinite bits, 7 samples / line
Input
Sampling aperture
Sampling points
relative error


Resolution and digital sampling
Detector Element, "DEL"
Sampling pitch
Sampling aperture
MTF of pixel (sampling) aperture
1000 µm
500 µm
200 µm
Modulation
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
Frequency (lp/mm)
Cutoff frequency = 1 / Δx
MTF of sampling aperture
Nyquist frequency = 1/2Δx, when pitch = aperture


Phase Effects
Input signal *equal* to Nyquist frequency
in phase
180° phase shift
Bar pattern
pixel matrix
good signal modulation
no signal modulation
sampled output signal

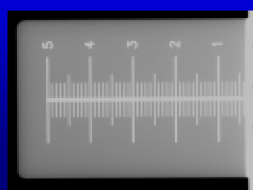

Aliasing: Insufficient sampling
Pixel Sampling
Low frequency
> 2 samples/ cycle
High frequency
Assigned (aliased) frequency
< 2 samples/ cycle

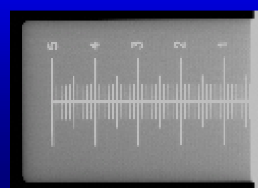

Aliasing effects:
Input signal frequency, f > Nyquist frequency, fN
input f = 1.5 fN
input f = 2.0 fN
output f = 0.5 fN
output f = 1.0 fN


Aliasing
Input signal frequency spectrum, fin
Input signal BW
Sampling BW
amplitude
-fN
0
fN
fS
2fS
Frequency
Higher frequency overlapping sidebands
reflect about fN to lower spatial frequencies

How important is aliasing?

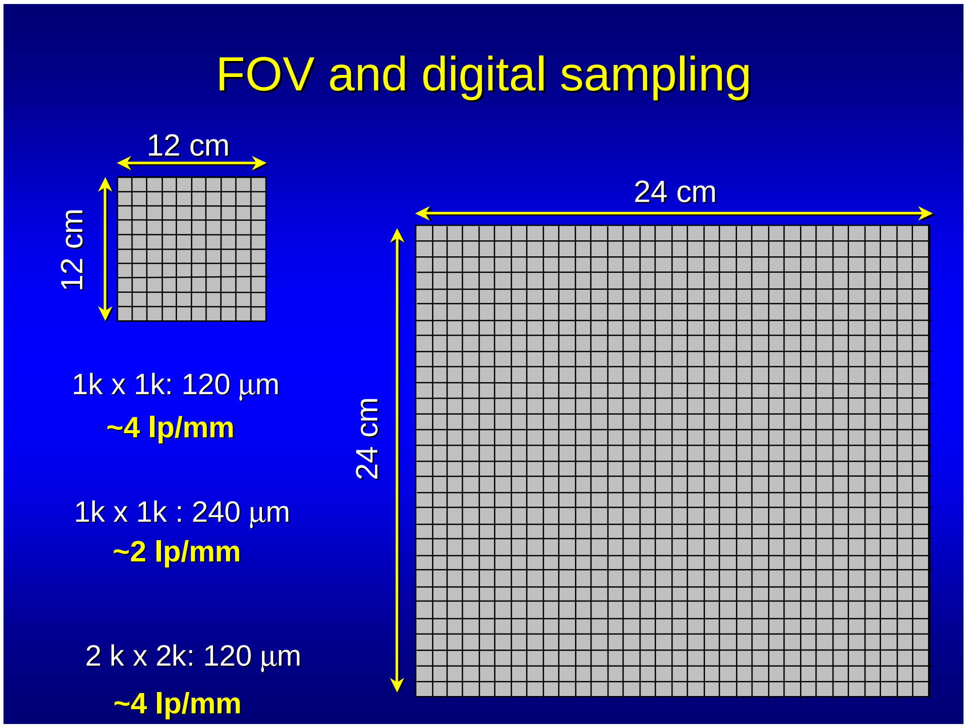
- Most objects have relatively low contrast
- High frequency noise lowers DQE(f) in the clinically useful frequency range
- Clinical impact is probably minimal, except with stationary anti-scatter grids and sub-sampled images
- Image size reduction can cause aliasing
  - Subsampling retains high frequencies, violating Nyquist limit

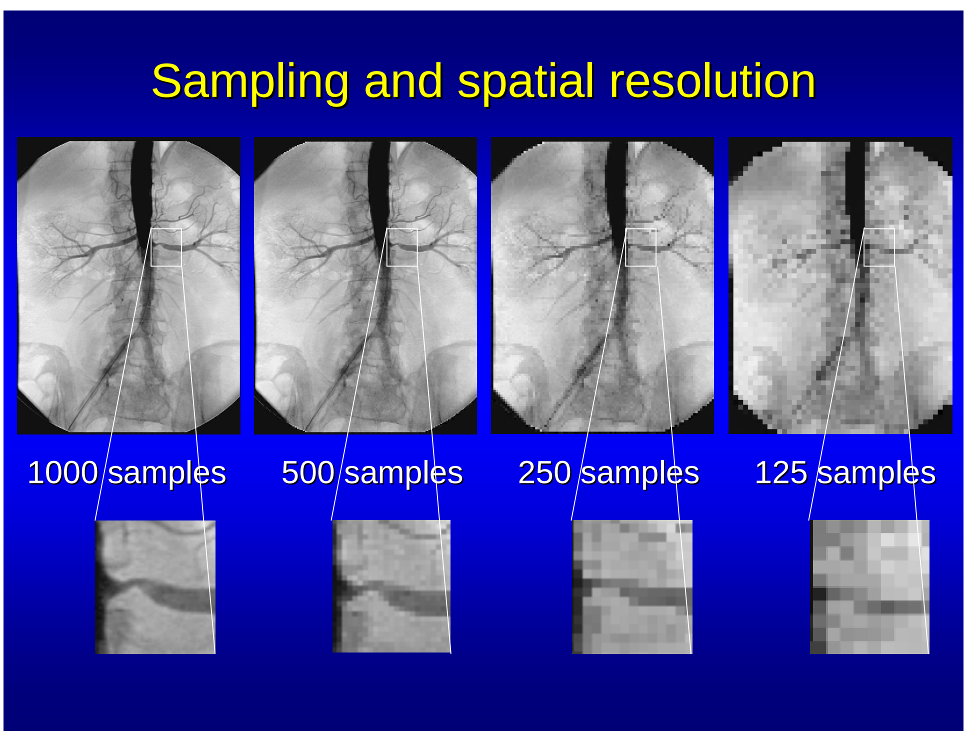


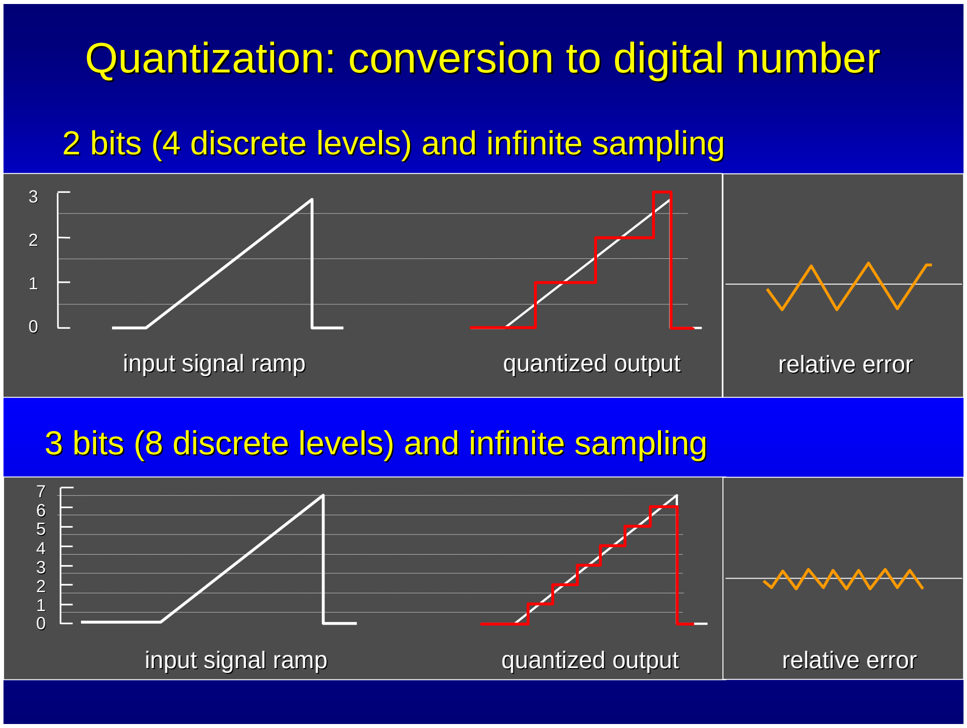


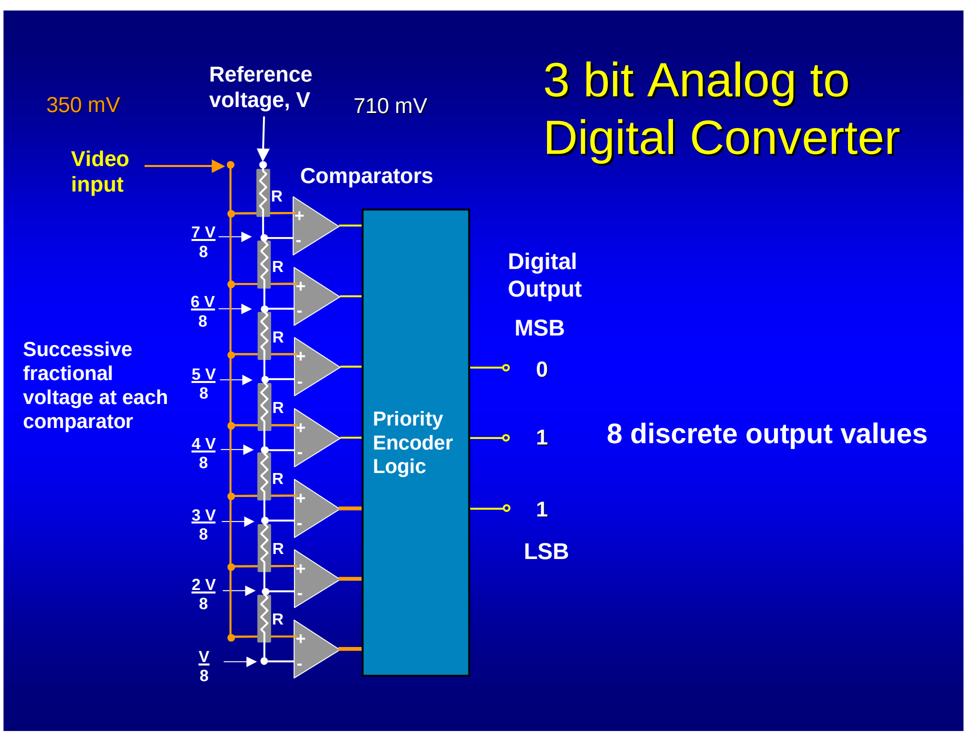
Resolution and image blur

- Sources of blur
  - Light spread in phosphor
  - Geometric blurring: magnification / focal spot
  - Pixel aperture of detector and display
- Goal: match detector element size with anticipated spread to optimize sampling process


FOV and digital sampling
12 cm
12 cm
24 cm
24 cm
1k x 1k: 120 µm
~4 lp/mm
1k x 1k : 240 µm
~2 lp/mm
2 k x 2k: 120 µm
~4 lp/mm


Sampling and spatial resolution
1000 samples
500 samples
250 samples
125 samples

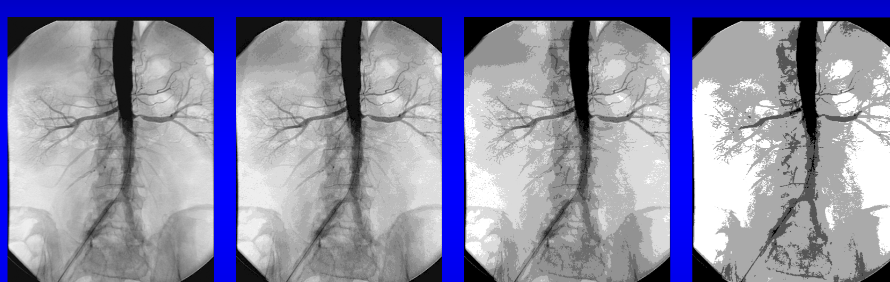

Quantization: conversion to digital number
2 bits (4 discrete levels) and infinite sampling
3
2
1
0
input signal ramp
quantized output
relative error
3 bits (8 discrete levels) and infinite sampling
7
6
5
4
3
2
1
0
input signal ramp
quantized output
relative error


3 bit Analog to Digital Converter
350 mV
Reference voltage, V
710 mV
Video input
Comparators
R
7 V / 8
6 V / 8
5 V / 8
4 V / 8
3 V / 8
2 V / 8
V / 8
+
-
Successive fractional voltage at each comparator
Priority Encoder Logic
Digital Output
MSB
0
1
1
LSB
8 discrete output values

Quantization

- Threshold to next level is ½ step size
- Larger # bits provide better accuracy
- Quantization noise causes “contouring”
- Typical bit depths:
  – Fluoroscopy: 8 bits
  – Angiography: 10 – 12 bits
  – CR / DR: 10 – 14 bits

Quantization Effects



8 bits 4 bits 3 bits 2 bits

“Contouring” is a problem in areas slowly varying in contrast.

Dynamic range considerations

- Maximum usable signal determined by:
  - Saturation of detector (TV camera)
  - Light aperture (determine entrance exposure)
  - Analog to digital converter (ADC)
- Minimum usable signal determined by:
  - Number of bits in ADC
  - Quantum noise
  - System noise
  - Electronics

bits	graylevels
8	256
10	1024
12	4096
14	16384

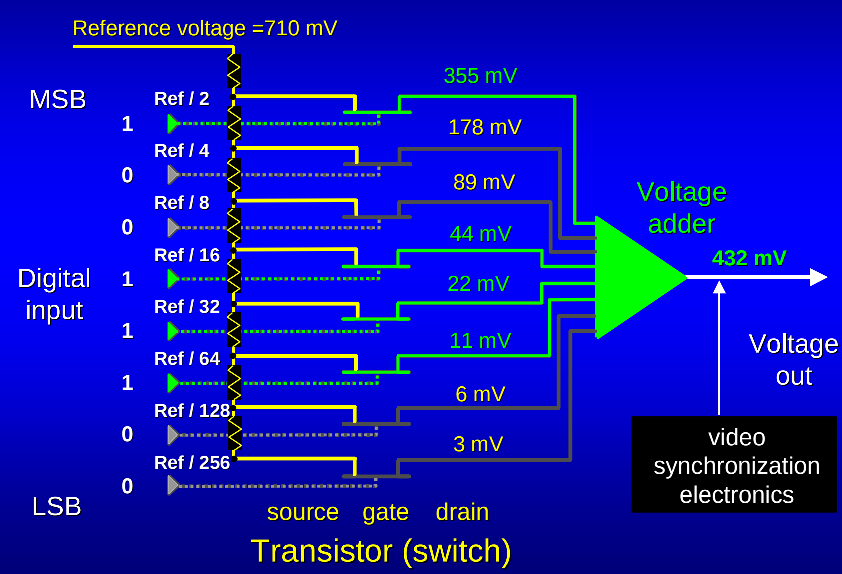
Resolution and Image Size

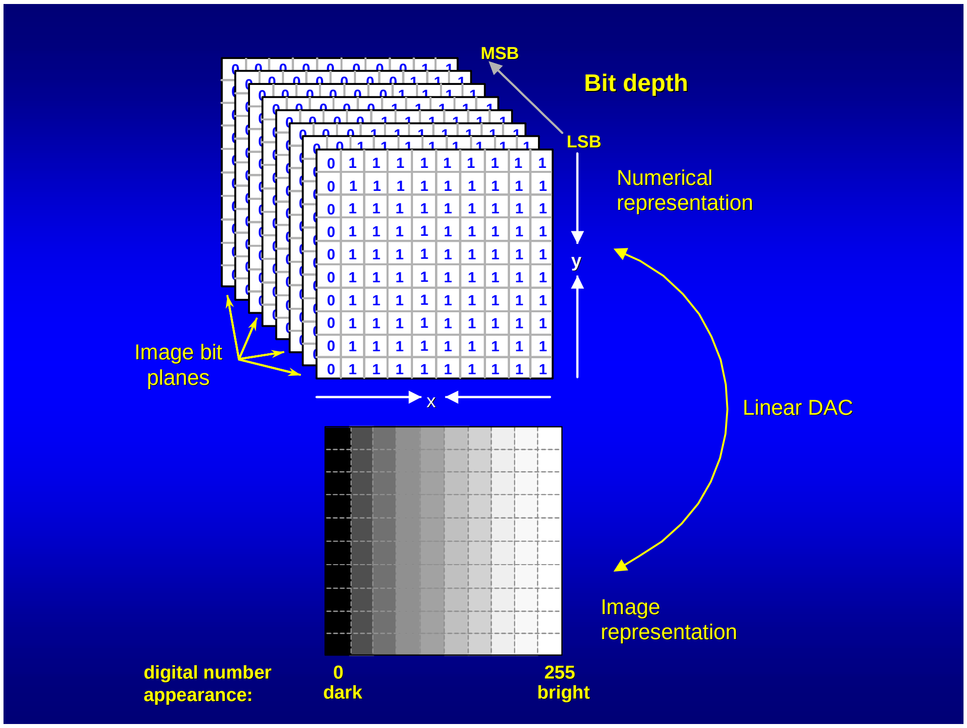
- 2 bytes / pixel uncompressed for digital fluoro
- 512 x 512 matrix (1/2 MB/image, 15 MB/s*)
- 1024 x 1024 matrix (1 MB/image, 30 MB/s*)
- 2048 x 2048 matrix (4 MB/image, 120 MB/s*)
  - *At 30 frame/s acquisition rate
- Overall storage requirement / Interventional Angiography study: 200 to 1000 MB
  - Image compression; selected key images

Digital Image Display

- Digital to Analog Converter (DAC)
- Estimate of original analog signal amplitude
- Image fidelity determined by
  - Frequency response (bandwidth)
  - Number of converter bits (usually 8 or 10 bits)
  - Image refresh rate (# updates / sec)

Digital to Analog Converter: DAC

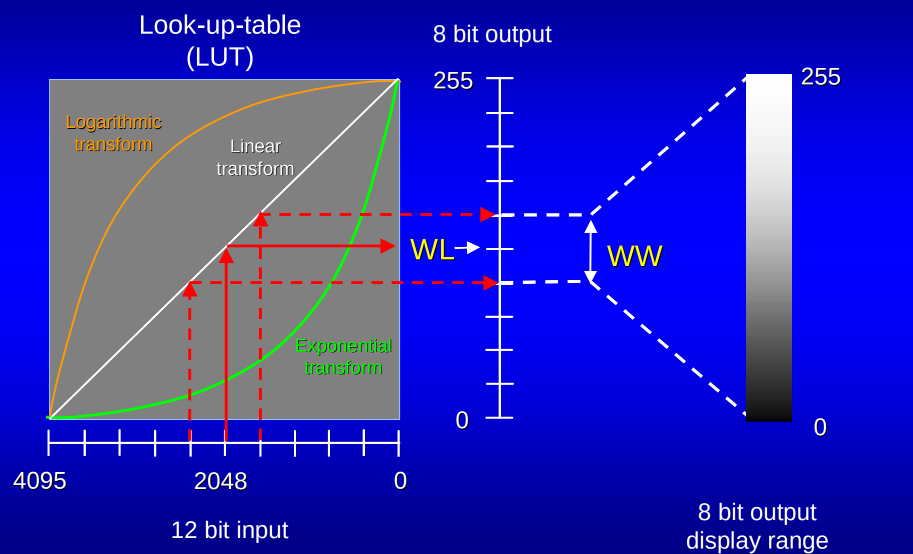




Display adjustments

- LUT: Look up table
  - Dynamic conversion of digital data through a translation table
  - Non-destructive variation of image brightness and contrast
  - Reduced display dynamic range requires compression of image range data (to 8 bits)

Display of digital data



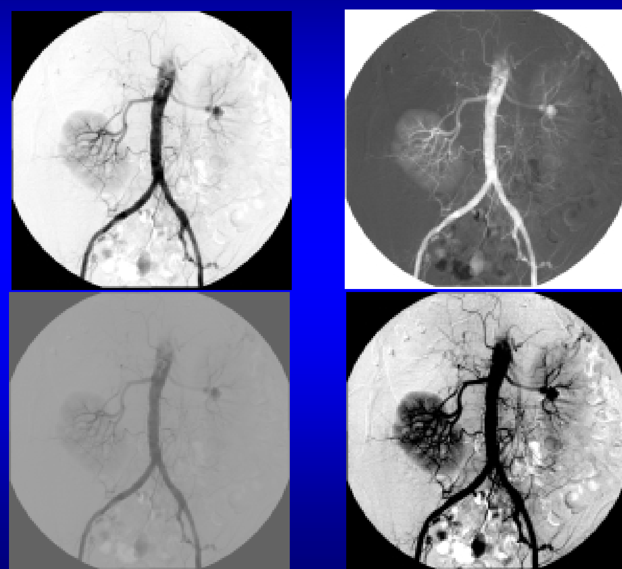
Grayscale Processing

- Look-up-table Transformation
  - Window (contrast, c) and level (brightness, b)

$$I_{out}(x,y) = c \times I_{in}(x,y) + b$$

- Histogram equalization
  - Redistribution of grayscale frequencies over the full output range

Window Width / Window Level



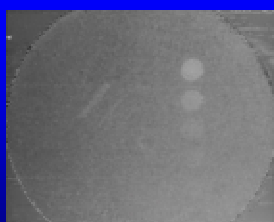
Contrast Resolution

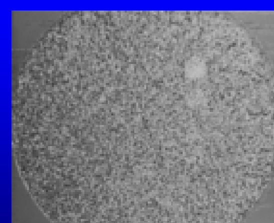
- Fluoroscopic Speed
  - Dependent on light-limiting aperture (f-stop)
  - Variable for digital flat-panel detectors
  - ? secondary quantum sink at higher frequencies
- Electronic noise
  - shot noise, dark noise, fixed pattern noise
- Structured noise
  - Anatomy, overlying objects
- “Useful” dynamic range
  - minimum detectable contrast with additive noise

Low Contrast Resolution

Temporal Averaging 4 frames

No Temporal Averaging





1 mR

0.1 mR

0.01 mR

Image subtraction low contrast phantom

Noise Sources

- Digital acquisition: *SNR-limited* detection
  - quantum mottle and secondary quantum sink
  - fixed pattern (equipment) structured noise
  - electronic and shot noise
  - digitization: sampling and quantization noise
  - anatomic (patient) noise
- Imaging system should always function in x-ray *quantum-limited* range
  - With II/TV, gain is sufficient
  - With flat-panel, electronic noise is limiting factor

- Introduction to digital fluoroscopy
- Digital fluoroscopy components
- Analog and digital image characteristics
- Image digitization (quantization/sampling)
- Image processing
- Summary

Image Processing

- Reduce radiation dose through image averaging
- Enhance conspicuity of clinical information
- Provide quantitative capabilities
- Optimize image display on monitors

Image Processing Operations

- Point
  - Pixel to pixel manipulation
- Local
  - Small pixel area to pixel manipulation
- Global
  - Large pixel area to pixel manipulation

Temporal Averaging

$I_{out}(x,y) = N \Sigma I_i(x,y)$

- Reduces noise fluctuations by $N^{0.5}$
- Increases SNR
- Decreases temporal resolution

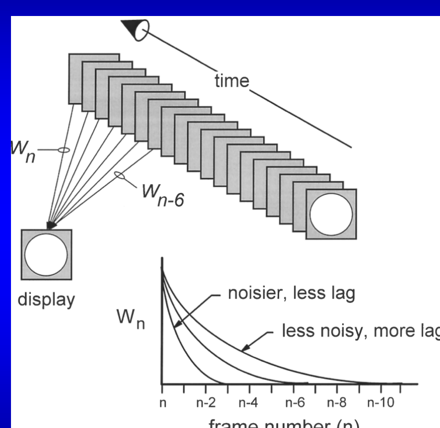


Image Subtraction (DSA)

- Pixel by pixel operation:

$$I_{out(i)}(x,y) = I_m(x,y) - I_i(x,y) + \text{offset}$$

- Time dependent log difference signal
- Window / level contrast enhancement

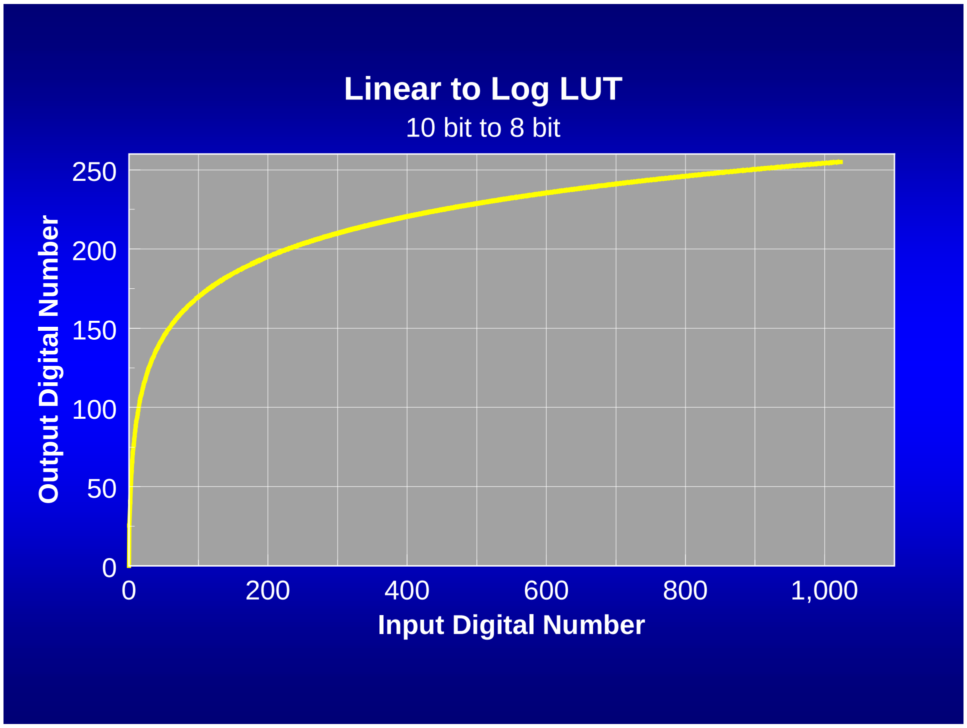
Logarithmic amplification

- Linearizes exponential x-ray attenuation
- Difference signal is independent of incident x-ray flux

Mask image: $I_m = N_0 e^{-\mu_{bg} t_{bg}}$

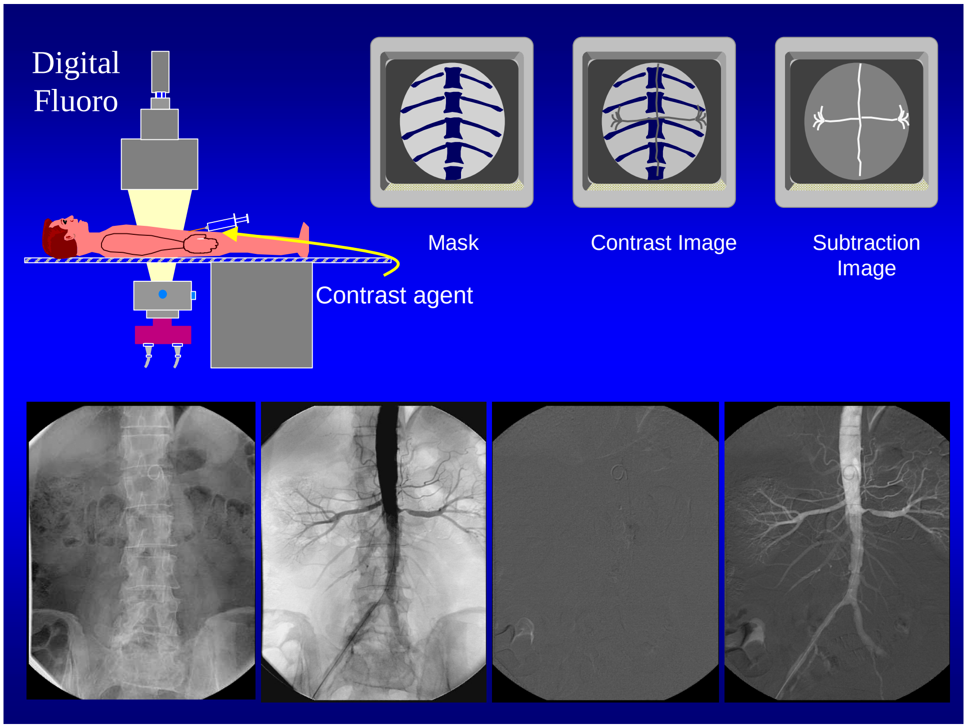
Contrast image: $I_c = N_0 e^{-\mu_{vessel} t_{vessel} - \mu_{bg} t_{bg}}$

Subtracted image: $I_s = \ln(I_m) - \ln(I_c) = \mu_{vessel} t_{vessel}$

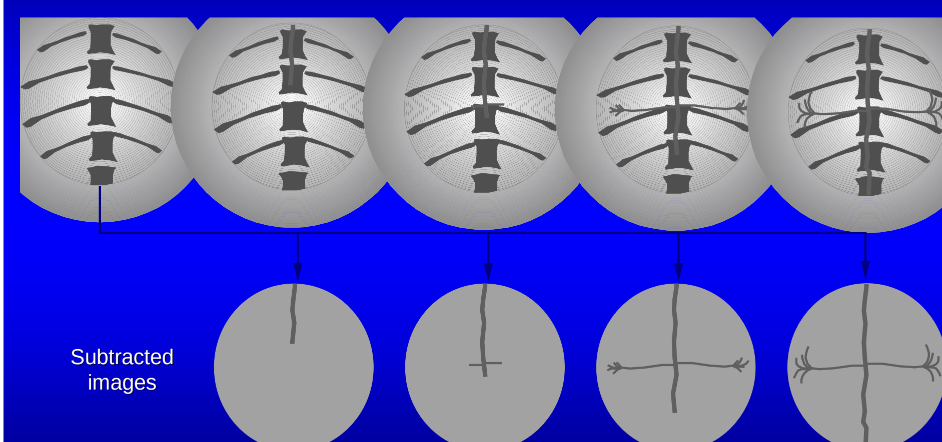


Digital Subtraction Angiography

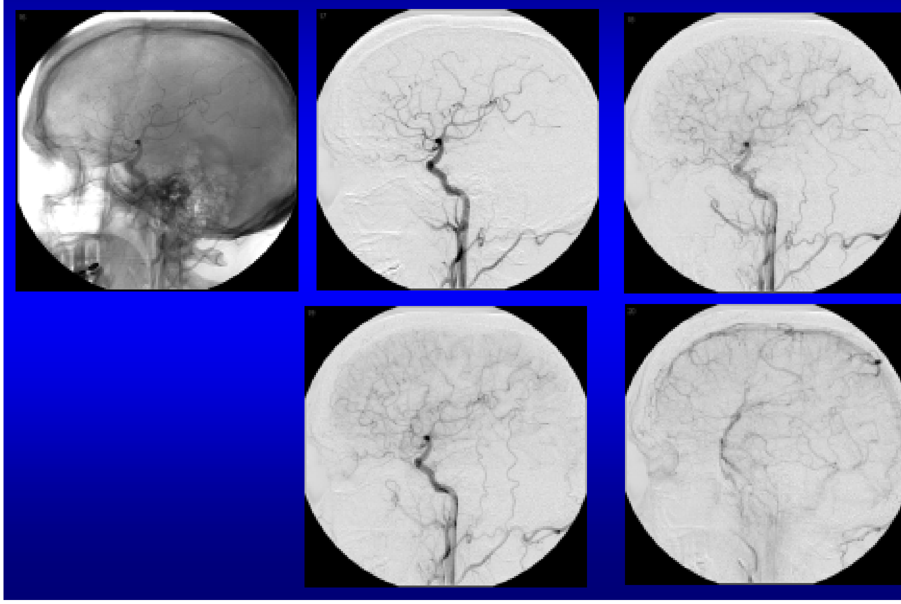
- Temporal subtraction sequence
  – First implemented mid 1970’s
- Eliminate static anatomy
  – Increase conspicuity
- Isolate and enhance contrast
  – Lower contrast “load”



Time-dependent subtraction (DSA)

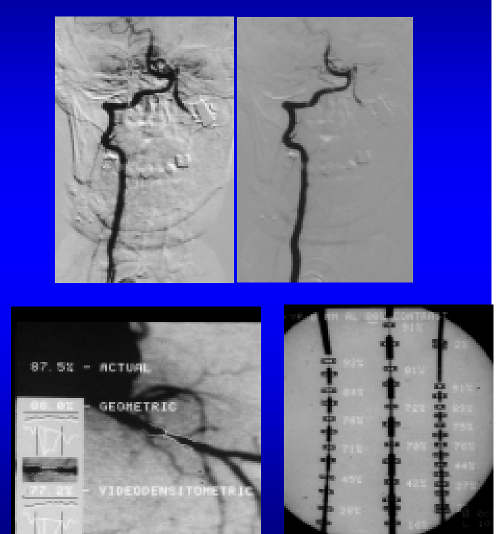


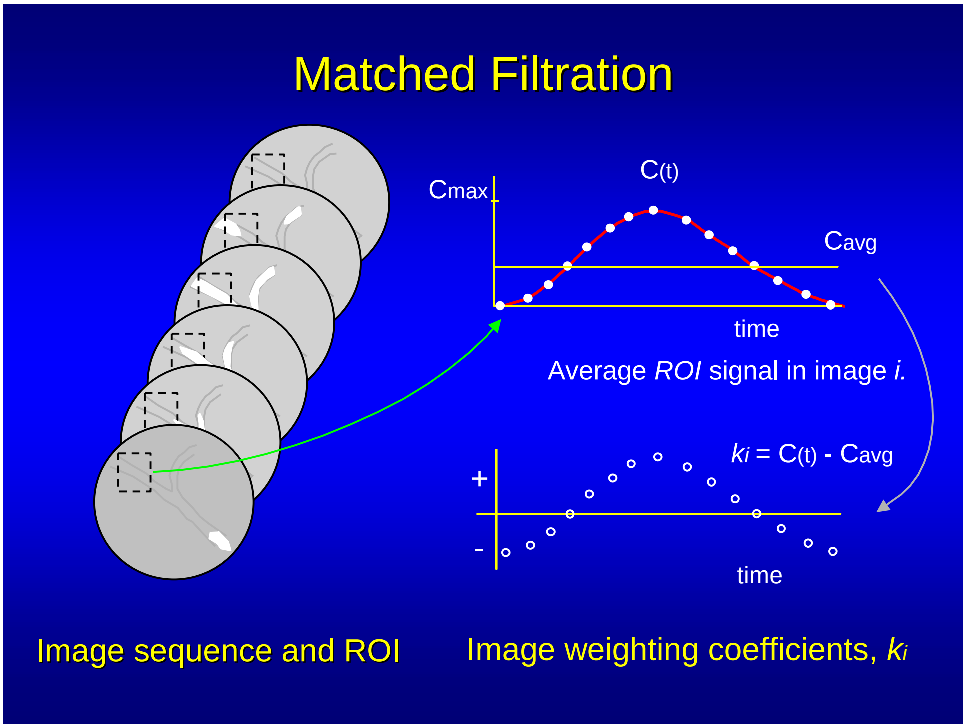
DSA examples



DSA image manipulation / quantitation

- Pixel shifting (correct for misregistration)
- Add anatomy (visualize landmarks)
- Measurements / densitometry




Matched Filtration
Cmax
C(t)
Cavg
time
Average ROI signal in image i.
ki = C(t) - Cavg
+
-
time
Image sequence and ROI
Image weighting coefficients, ki

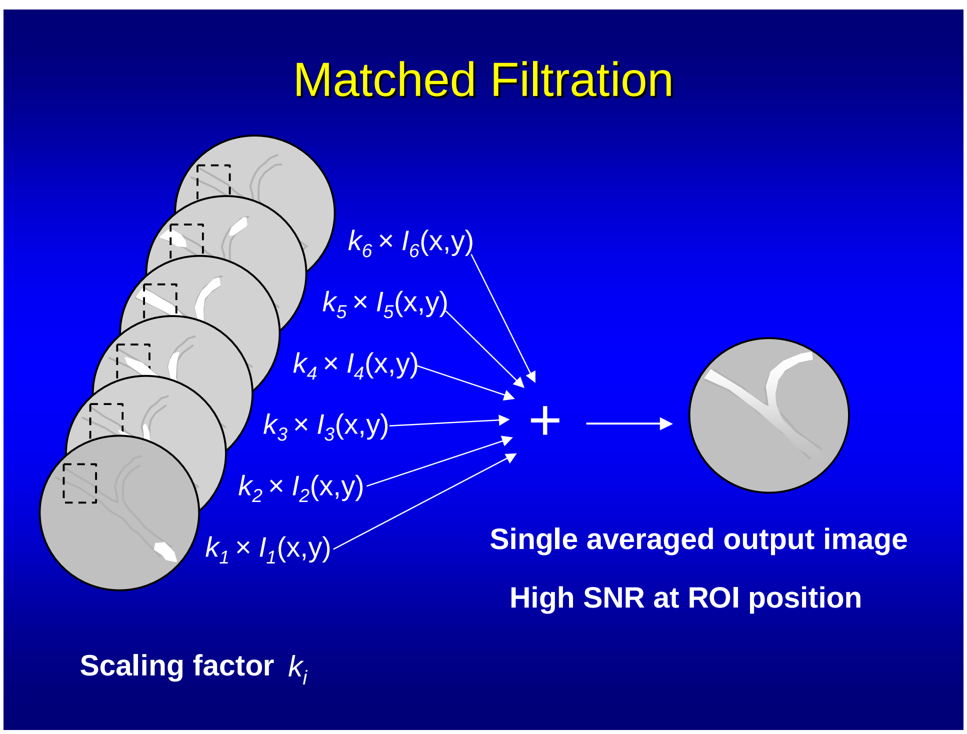

Matched Filtration
k6 × I6(x,y)
k5 × I5(x,y)
k4 × I4(x,y)
k3 × I3(x,y)
k2 × I2(x,y)
k1 × I1(x,y)
+
Single averaged output image
High SNR at ROI position
Scaling factor ki

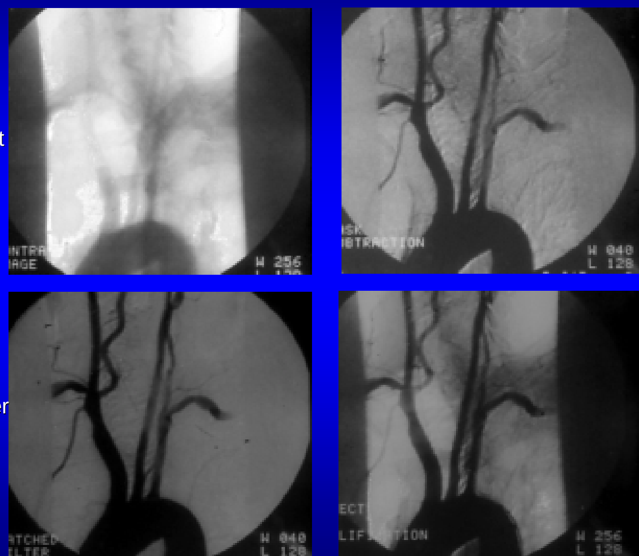
Image comparisons

Contrast Image

Mask subtract Image

Matched filter Image

Selective dye Image



Recursive filtration

- Digital image buffer adds a fraction, k, of the incoming image to the previous output image; temporal averaging with exponentially decreasing signal

$$I_{out}(n) = k\, I_{in}(n) + (1-k)\, I_{in}(n-1) + (1-k)^2\, k\, I_{in}(n-2) + \ldots.$$

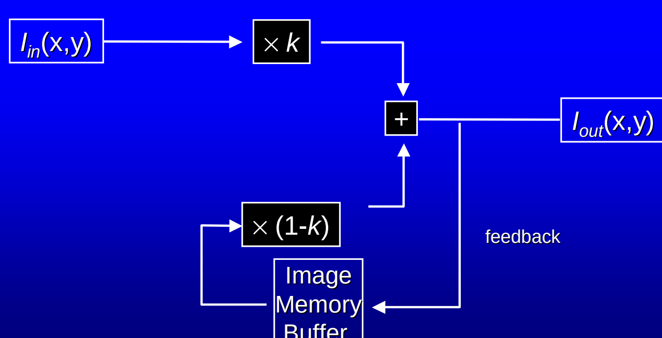


Image Processing Operations

- Point
  - Pixel to pixel manipulation
- Local
  - Small pixel area to pixel manipulation
- Global
  - Large pixel area to pixel manipulation

Spatial Filtration

- Low pass (smoothing)
- High pass (edges)
- Bandpass (edge enhancement)
- “Real-time” filtration uses special hardware and filter kernels of small spatial extent

Convolution

- Pixel by pixel multiplication and addition of filter kernel with image:

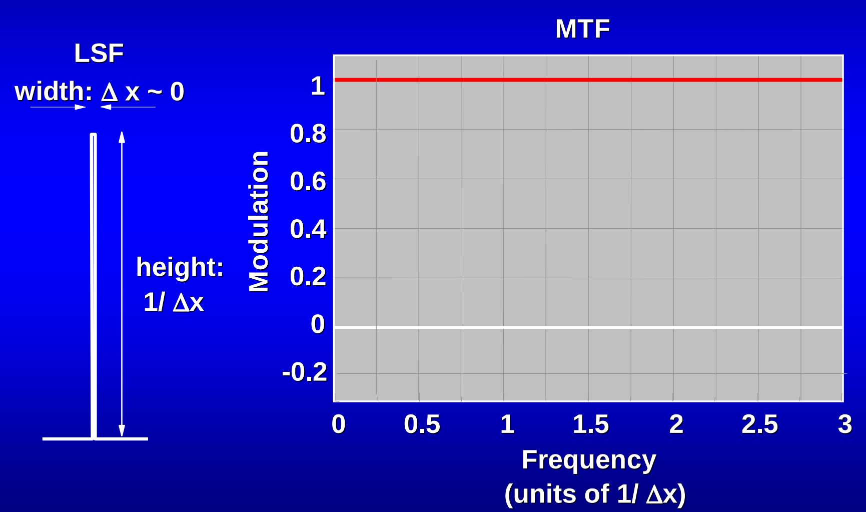
$$I_{out}(x) = \sum_{i=-(N-1)/2}^{(N-1)/2} g(i)\, I_{in}(x+i)$$

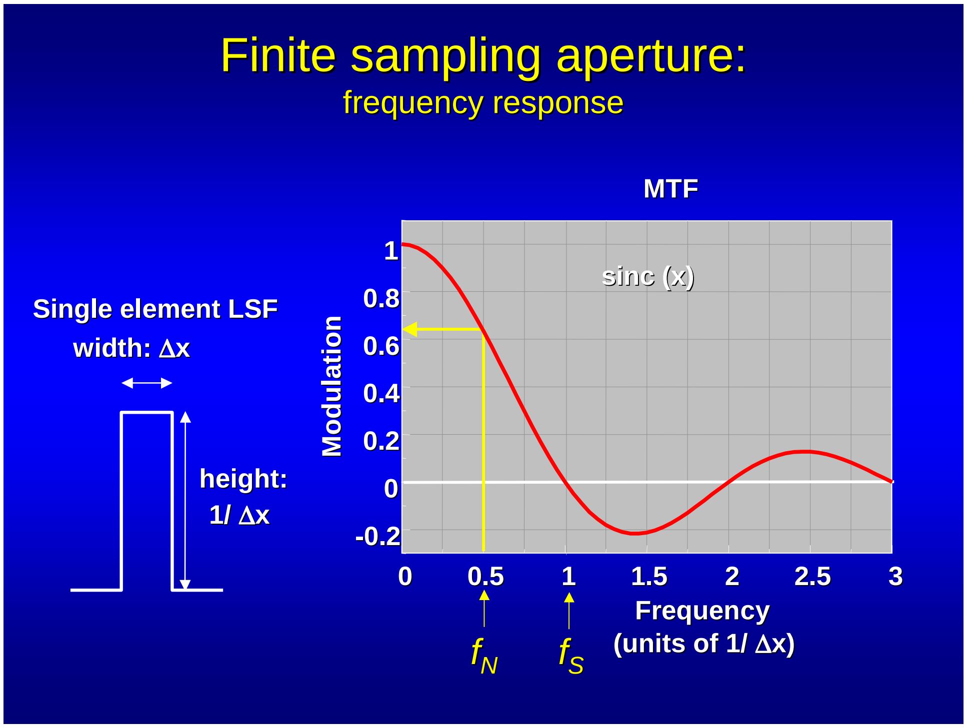
$$I_{out}(x) = g(-1) \times I_{in}(x-1) + g(0) \times I_{in}(x) + g(1) \times I_{in}(x+1)$$

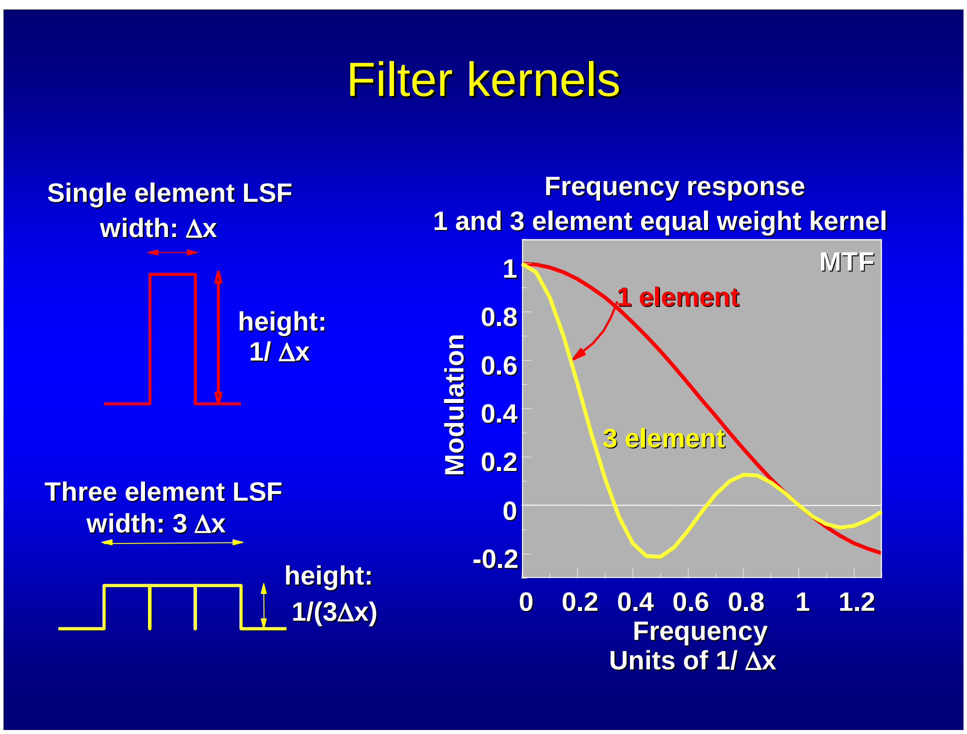
$$I_{out}(x) = g(x) * I_{in}(x)$$

Point sampling aperture:

frequency response




Finite sampling aperture:
frequency response
MTF
Single element LSF
width: Δx
height:
1/ Δx
Modulation
1
0.8
0.6
0.4
0.2
0
-0.2
sinc (x)
0
0.5
1
1.5
2
2.5
3
Frequency
(units of 1/ Δx)
fN
fS


Filter kernels
Single element LSF
width: Δx
height:
1/ Δx
Three element LSF
width: 3 Δx
height:
1/(3Δx)
Frequency response
1 and 3 element equal weight kernel
MTF
1 element
3 element
Modulation
1
0.8
0.6
0.4
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
1.2
Frequency
Units of 1/ Δx

Low pass filtration – smoothing

- Convolve “normalized” filter kernel with image
- Reduces high frequency signals
- Reduces noise variations
- Reduces resolution

2D Low pass filter kernel

- Convolve “normalized” filter kernel with image

1	1	1
1	1	1
1	1	1

÷ 9

**

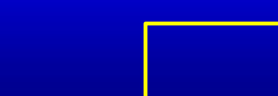
Input

1	1	1	10	10	10
1	1	1	10	10	10
1	1	1	10	10	10
1	1	1	10	10	10
1	1	1	10	10	10
1	1	1	10	10	10

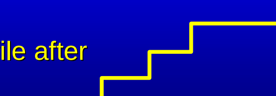
Output

1	1	4	7	10	10
1	1	4	7	10	10
1	1	4	7	10	10
1	1	4	7	10	10
1	1	4	7	10	10
1	1	4	7	10	10

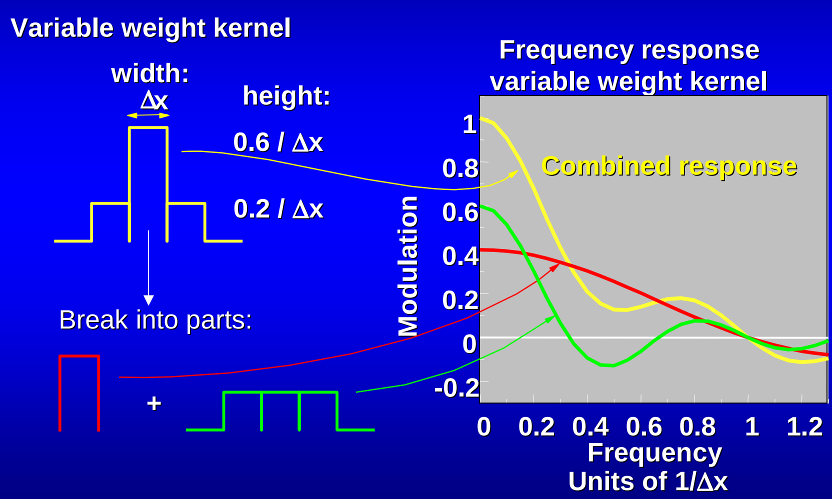
Profile before



Profile after



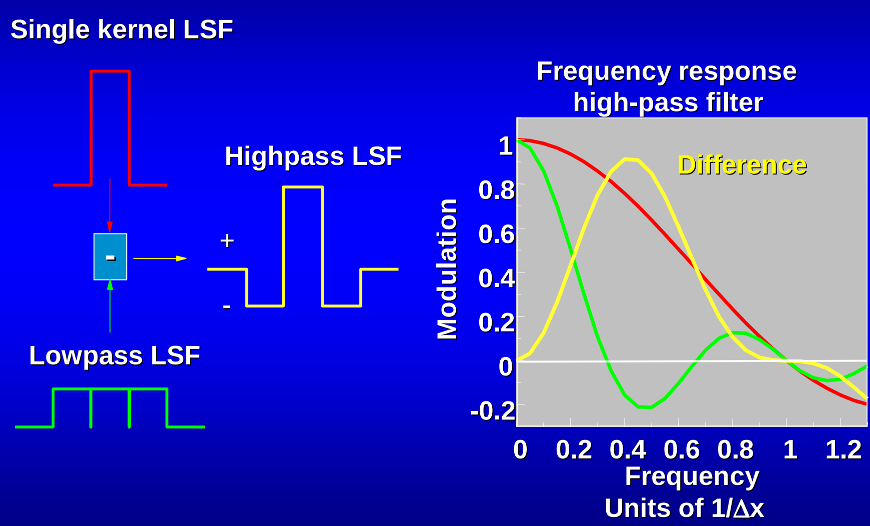
Variable weight low-pass filter kernel



High pass filtration

- Low pass filtered signal subtracted from original signal
- High frequencies (edges) remain in image
- Noise is increased

High-pass filter kernel



2D high pass filter kernel

•Convolve "normalized" filter kernel with image

Kernel:

-1	-1	-1
-1	9	-1
-1	-1	-1

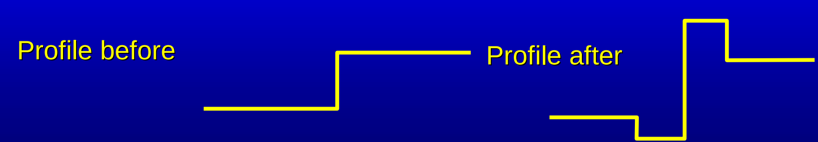
**

Input

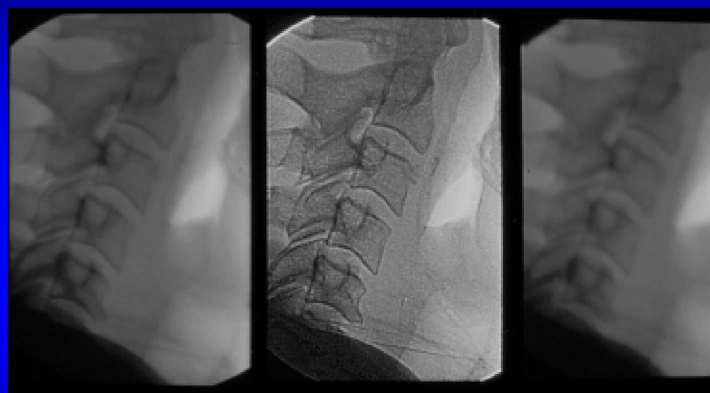
1	1	1	10	10	10
1	1	1	10	10	10
1	1	1	10	10	10
1	1	1	10	10	10
1	1	1	10	10	10
1	1	1	10	10	10

Output

1	1	-26	35	10	10
1	1	-26	35	10	10
1	1	-26	35	10	10
1	1	-26	35	10	10
1	1	-26	35	10	10
1	1	-26	35	10	10



Example filtered images



Unfiltered — Edge enhanced — Smoothed

Image Processing Operations

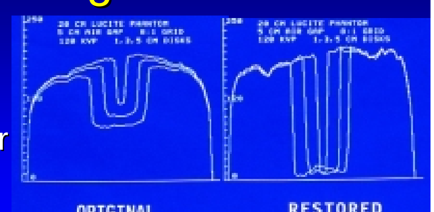
- Point
  - Pixel to pixel manipulation
- Local
  - Small pixel area to pixel manipulation
- Global
  - Large pixel area to pixel manipulation

Global Image Processing

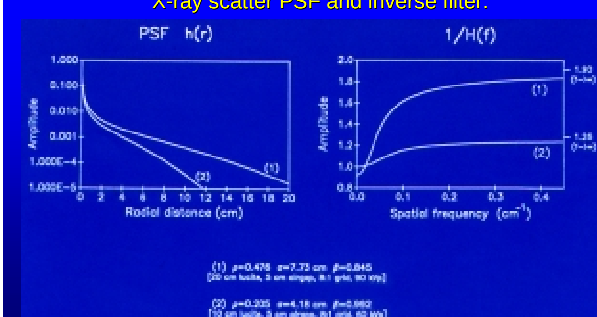
- Frequency domain processing
  - Fourier transform of kernel and image
  - Convolution → Multiplication
  - More efficient for convolution kernels > 9x9
- Inverse filtering (deconvolution)
  - e.g., veiling glare, scatter corrections
- Image translation, rotation and warping
  - Correction of misregistration artifacts, pincushion distortion, vignetting, non-uniform detector response

Inverse filtering

- 2D – FT methods:
  - Measure PSF
  - Generate FT of inverse filter
  - Multiply by 2D-FT of image
  - Re-inverse transform



X-ray scatter PSF and inverse filter:



Quantitative Algorithms

- Stenosis sizing: length, area, densitometry
- Distance measurements
- Density – time curve analysis
- Perfusion – functional studies
- Relative flow and volumetric assessment
- Vessel tracking
- CT with cone-beam reconstruction

Limits to Quantitation

- Non-linear / non-stationary degradations
  - Beam Hardening
  - Scatter
  - Veiling Glare
  - Non-uniform bolus / diffusion
- Geometric effects
  - Pincushion distortion
  - Vignetting
  - Rotational accuracy (CT)

Summary

- Digital imaging is an ***essential*** part of fluoroscopic and angiographic systems
- Limitations and advantages of fluoro digital acquisition and processing must be understood for maximum utilization
- DICOM standards are a must for the integration of digital fluoroscopy in the clinical environment and PACS

Summary

- Fluoroscopic / Fluorographic image processing can provide
  - Significant improvement of image quality
  - Reduced dose (radiation and contrast)
  - Enhanced image details
  - DSA, roadmapping, quantitative densitometry
  - Functional imaging, cone-beam fluoro CT

References / further information

- Seibert JA. Digital Image Processing Basics, in A Categorical Course in Physics: Physical and Technical Aspects of Interventional Radiology, Balter S and Shope T, Eds, RSNA Publications, 1995
- Bushberg et.al. Essential physics of Medical Imaging, Lippincott, Williams & Wilkens, Philadelphia, 2002
- Balter S, Chan R, Shope T. Intravascular Brachytherapy / Fluoroscopically Guided Interventions, Medical Physics Monograph #28, Medical Physics Publishing, Madison, WI, 2002.

……The End……